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Economic comparison of renewable heating systems in two different European countries in consideration of refurbishment of buildings –

Cost/Energy Curves

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by

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Abstract

Total final energy consumption used for the building sector of the European Union is about 40% and buildings are the biggest single contributor (about 26%) to European CO_2 emissions. Therefore, the refurbishment of different buildings, increase of total energy efficiency and support of renewable energies is becoming a very important concern for European countries.

The aim of the thesis is the analysis, evaluation and development of cost-optimality curves in two different European countries (Sweden and Slovenia) for the renovation of single- and multi-family houses. Furthermore, it will be analysed under which circumstances the cost-optimality point can be set in order to support refurbishment choices depending on energy consumption, building refurbishment and heating systems.

As an outcome of the work, enormous potentials for energy savings regarding building envelope and heating systems (use of solar energy and heat pumps) are explored. To select effective refurbishment measures and to quantify the energy saving potentials, a specific methodology is performed on reference buildings in the form of case studies. This methodology defines how to compare measures in relation to their energy performance and implementation costs, and how to adopt these to chosen reference buildings with the target of setting cost-optimal levels. A sensitivity analysis for unclear parameters (service factor and discount rate) is carried out and the deviation of the results are investigated in order to find out whether a general statement is valid or how much the actual result may differ.

The results show heat pumps as the most-effective heating systems with the highest primary energy savings, which allow up to 58% in energy savings. However, heat pump depends on the COP achieved under real conditions which can vary quite significantly among buildings. For the application of solar thermal systems, the geographical location and thus solar radiation plays a prominent role.

Energy characteristics of the buildings have an evident impact on the energy performance of the building. To find the cost-optimal level, all possible options of refurbishment need to be studied in detail. In this context, the results of the Slovenian multi-family house correspond to results typically obtained in the literature. In all other case studies (single- and multi-family houses) this typical pattern could not be reproduced. Reasons are applied energy prices, investment costs, interest rate, not including external costs etc. In this thesis, change of the discount rate and service factors were considered for the sensitivity analysis. Therefore, another reason may be the parameters used for the sensitivity analysis, as exactly this combination cannot be found in the literature.

Finally, as expected, the increase of the discount rate leads to a cost decrease between different heating systems and moves the cost-optimal level from lower net primary energy to a higher one.

Kurzfassung

Für den Gebäudesektor werden etwa 40 % des gesamten Endenergieverbrauchs der Europäischen Union gebraucht und somit sind Gebäude die größten Beteiligten (ca. 26 %) zu den europäischen CO_2-Emissionen. Daher spielen heutzutage die Sanierung der bestehenden Gebäudetypen, die Steigerung der Gesamtenergieeffizienz und die Förderung von erneuerbaren Energien eine sehr bedeutende Rolle für die europäischen Länder.

Das Ziel der Arbeit ist die Analyse, Bewertung und Erstellung von Kostenoptimalitäts-Kurven in zwei verschiedenen europäischen Ländern (Schweden und Slowenien) für die Sanierung von Ein- und Mehrfamilienhäusern. Im Weiteren wird analysiert, unter welchen Umständen die Kosten-Optimalitätspunkte gesetzt werden können, um Sanierungsentscheidungen abhängig von Energieverbrauch, Gebäudesanierung und Heizungssystem zu unterstützen.

Als Ergebnis der Arbeit wurden enorme Potenziale für Energieeinsparungen in Bezug auf die Gebäudehülle und Heizungssysteme (bei Nutzung von Solarenergie und Wärmepumpen) erforscht. Um wirksame Sanierungsmaßnahmen auszuwählen und die Energiesparpotentiale zu quantifizieren, wird eine spezifische Methodik in Form von Fallstudien an den Referenzobjekten angewendet. Diese Methodik definiert, wie Maßnahmen in Bezug auf ihre Energieperformance und Umsetzungskosten mit der Zielsetzung, die Kostenoptimalitätsniveaus festzustellen, an den Referenzgebäuden umgesetzt werden.

Für unklare Parameter (Servicefaktor und Zinssatz) wird eine Sensitivitätsanalyse durchgeführt und die Abweichungen der Ergebnisse untersucht, um eine gültige Aussage zu finden bzw. festzustellen, um wie viel die tatsächlichen Ergebnisse abweichen können.

Die Ergebnisse zeigen, dass Wärmepumpen das effizienteste Heizungssystem mit den höchsten Primärenergieeinsparungen sind, welche Energieeinsparungen von bis zu 58 % ermöglichen. Wärmepumpen hängen jedoch von den Jahresarbeitszahlen ab, welche unter realen Bedingungen für verschiedene Gebäuden ganz erheblich variieren. Für den Einsatz von solarthermischen Anlagen, spielen die geographische Lage und damit die Sonnenstrahlung eine herausragende Rolle.

Die Energieeigenschaften der Gebäudeteile haben eine deutliche Auswirkung auf die Gesamtenergieeffizienz des Gebäudes. Um die kostenoptimalen Niveaus festzustellen, müssen alle Möglichkeiten der Sanierung im Detail untersucht werden. In diesem Zusammenhang entsprechen die Ergebnisse des slowenischen Mehrfamilienhauses jenen Ergebnissen, welche wir aus der Literatur kennen. In allen anderen Fallstudien (Ein- und Mehrfamilienhäuser) konnte dieses typische Muster nicht reproduziert werden. Die Gründe dafür sind die angewandten Energiepreise, Investitionskosten, Zinssätze, Nichtberücksichtigung der externen Kosten usw. In dieser Arbeit wurden die Änderung des Zinssatzes und des Servicefaktors für die Sensitivitätsanalyse berücksichtigt. So können die Parameter für die Sensitivitätsanalyse ein weiterer Grund sein, da genau diese Kombination in der Literatur nicht vorkommt.

Schließlich führt die Erhöhung des Zinssatzes wie erwartet zu einer Verringerung der Kosten zwischen verschiedenen Heizsystemen und die Kostenoptimalitätspunkte werden von niedrigeren Nettoprimärenergien zu höheren verschoben.

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Abbreviations

HDD	*heating degree days*
SFH	*single-family house*
MFH	*multi-family house*
DHW	*domestic hot water*
EPBD	*Energy Performance of Buildings Directive*

Nomenclature

t_{ir}		*indoor temperature*
t_{im}		*set-point (of the indoor) temperature*
t_a		*outdoor temperature*
t_{an}		*standard outdoor temperature*
HDD	[Kd]	*heating degree days*
A	$[\mathrm{m}^2]$	*surface of construction component*
R	$[\mathrm{m}^2\mathrm{K/W}]$	*thermal resistance*
BT		*construction component*
V_r	$[\mathrm{m}^3]$	*volume of the room*
Z_R		*number of rooms in a building*
P_T	[kW]	*transmission heat transfer coefficient*
P_L	[kW]	*ventilation heat transfer coefficient*
H_0	$[\mathrm{kWh/m}^2]$	*annual global horizontal irradiation*
Q(solar)	[kWh]	*annual collector output*
f_s		*service factor*
U	$[\mathrm{W/m}^2\mathrm{K}]$	*thermal transmittance*
$\alpha_{i,a}$	$[\mathrm{W/m}^2\mathrm{K}]$	*surface coefficient of heat transfer (internal and external)*
λ	[W/mK]	*linear thermal transmittance*

d	[m]	*layer thickness*
n_L		*air exchange* *(depending on the room volume, it is between 0.2 and 0.5)*
c_{PL}	[kJ/kg K]	*specific thermal capacity of the air (approx. 1.009)*
ρ_L	[kg/m^3]	*air density (approx. 1.3)*
COP		*coefficient of performance*

1 Introduction

1.1 Motivation

Nowadays, for the refurbishment of different building types, increase of total energy efficiency and support of renewable energies is starting to play a very important role for European countries. 40% of the European Union's total final energy consumption is used for the building sector. (Fernando Pacheco Torgal, 2013) Buildings are the biggest single contributor (about 26%) to European CO_2 emissions that amount to approximately 5 gigatonnes (Gt) for all sectors. Reaching the declared long-term aim of reducing greenhouse gas emission levels by 80-95% by 2015 can be achieved with a big effort by improving building energy efficiency. Therefore, existing buildings have a big potential for reducing consumption. In fact, they suffer from lack of insulation and poor performance of heating systems. Most of the buildings which were built after World War II have a poor energy performance. The condition of a building is not only influenced by its age but also by the technological choices of the period in which it was built.

The 2002 version of the Energy Performance of Buildings Directive (EPBD) did not address the target levels for the energy performance of buildings. The EPBD recast of 2010 introduced the principles of cost-optimal energy performance that are decisive to move national requirements to more effective levels.[1]

The achievement of cost-optimal levels can be performed by applying a harmonised calculation methodology (Directive 2010/31/EU, Article 5 and Annex III). This methodology can be used by Member States as an appropriate example for their national plans for increasing nearly zero-energy buildings. (Project ENTRANZE, 2014)

This thesis is dealing with suitable actions for energy saving in building refurbishment, regarding building envelope and heating systems (use of solar energy and heat pumps) for existing buildings.

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[1] Cost optimality, Discussing methodology and challenges within the recast Energy Performance of Buildings Directive, Buildings Performance Institute Europe –BPIE, 2010

1.2 Essential questions

The essential question for this thesis is: How do the total costs of different renovation options for different building types in various European countries compare in consideration of

- Renewing the heating systems

  and

- Refurbishing the building envelope?

The aim of this thesis is the analysis, evaluation and development of cost-optimality curves in two different European countries for single- and multi-family houses. Furthermore, it will be analysed under which circumstances the cost-optimality point can be set in order to support refurbishment choices depending on energy consumption, building refurbishment and heating systems.

The analysis and calculations shall enable the comparison of renewable heating systems, heat pumps and solar systems under various pre-conditions and variable energy consumptions.

1.3 Structure of the thesis

After the introduction, the second chapter deals with the disaggregated description of costs for several measures on building envelopes and renewal of heating systems regarding their relevant components, which are considered in the calculations. In addition, energy price changes based on the “Poles” model as part of the ENTRANZE Project are presented.

The focus of chapter 3 is the methodology of cost-optimality calculations. First of all, system boundaries and meanings of different terms are clarified. Next, different packages of measures as basis for the creation of energy/cost curves are described. To set the framework conditions, the main assumptions are explained. A closer look into climatic input parameters as well as output parameters for the cost-optimality calculations is illustrated to show the expected parameters. As part of the energy performance calculation based on the standard (EN 12831, Heating systems in buildings – Method for calculation of the design heat load, 2003), simplified calculation steps of the energy need for conditioned space is demonstrated. For the creation of more variants for the determination of cost-optimal levels, the correlation of thermal transmittance (U-value) with insulation thickness has been analysed. Next, the need for the service factor is explained in order to understand its impact on the sensitivity analysis. Finally, the cost-optimality method is described.

Chapter 4 shows case studies where the cost-optimality method is applied to calculate cost-optimal levels for single- and multi-family houses in Sweden and Slovenia.

In the final chapter, conclusion and quintessence of the results are summarised.

1.4 Fundamental literature

The most important entry literatures for the thesis are “Cost optimality publications” (Discussing methodology and challenges within the recast Energy Performance of Buildings Directive) from the Building Performance Institute Europe – BPIE and Reports on Cost/Energy curve calculations of the ENTRANZE Project. The objective of the ENTRANZE project is to actively support policy-making by providing the required data, analysis and guidelines to achieve a fast and strong penetration of nearly zero-energy buildings and renewable energy sources within the existing national building stocks. (Marco Pietrobon, 2013). Both literatures facilitate the entry into the field of cost-optimality calculations.

Another important source for the thesis is the “TABULA WEbTool”. This web tool s developed within the framework of the Intelligent Energy Europe projects TABULA and EPISCOPE. With the help of this web tool, all required data about the existing buildings could be retrieved and used for the case studies.

The book “Erneuerbare Energien” by Martin Kaltschmitt, Wolfgang Streicher and Andreas Wieser has to be mentioned, because it was used to define the costs related to the renewal of heating systems.

(EN 15603:2008, 2008), (ÖNORM M 7500, 1980) and (ÖNORMB8135, 1983) are used for the energy performance calculations. In addition, the lecture documentation of “Wirtschaftliche und Ökologische Optimierung der Heizenergieversorgung” by Prof. Reinhard Haas simplifies the application of energy performance calculations to the reference buildings.

Several case studies about implementing the cost-optimal methodology in EU countries like Germany and Austria from BPIE could be used as comparative examples for the thesis. (Andreas Enseling, 2010) (Klemens Leutgöb, 2012)

1.5 Methodology

At the beginning of the thesis, several literatures were analysed to create a general overview of the field of cost-optimality calculations. For this purpose, cost-optimality publications from BPIE and Cost/Energy curve calculations by ENTRANZE Project proved useful.

Next, it was very important to use actual cost data for the calculations and therefore a big effort was made to research the market in the chosen countries. Several installation companies and energy agencies in different countries like Sweden, Hungary, Slovakia and Slovenia were contacted to perform the calculations based on practical values. Since the required data could not be acquired, the values were taken from the book (Martin Kaltschmitt, 2013).

As case studies, single- and multi-family houses were considered to cover all private residences. To see the impact of geographical location, Sweden and Slovenia were chosen, a northern European country and a central/semi-southern country, as the focus of this thesis.

To determine the cost-optimal levels, a comparative framework methodology needs to be introduced. The methodology defines how to compare measures in relation to their energy performance and costs related to their implementation and how to adopt these to chosen reference buildings with the target of setting cost-optimal levels.

The following Figure 1-1 shows a schematic description of the process for setting cost-optimal levels.

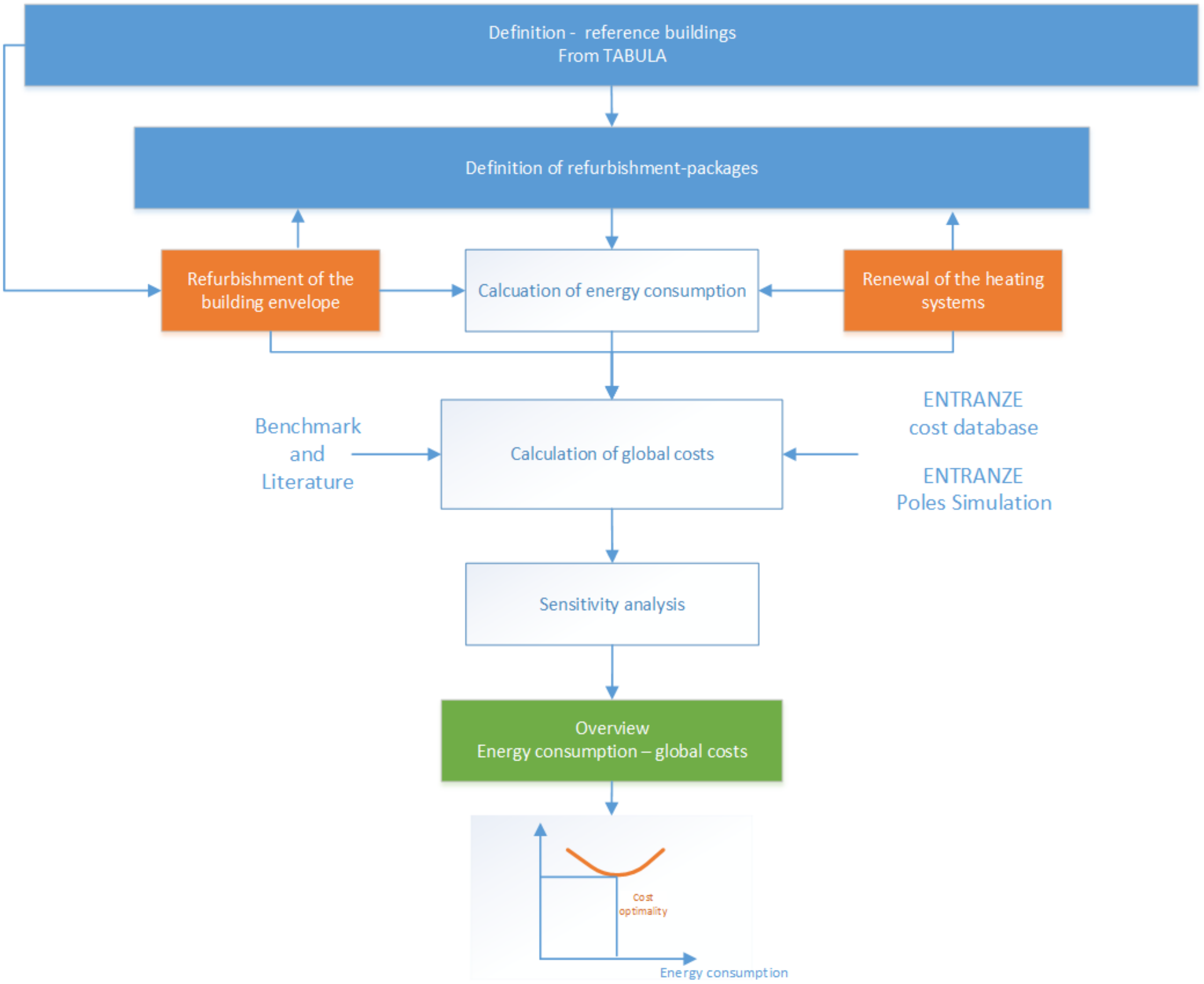

Figure 1-1 Schematic description of the process for setting cost-optimal levels for the reference buildings

For the determination of cost-optimal levels for residential buildings, the following procedures were carried out:

1. **Definition of reference buildings**

   Based on the data available in the TABULA WebTool[2], reference buildings are chosen. For the selected countries, single-family and multi-family houses have been considered. The characteristics of the reference buildings are explained in chapter 4.

2. **Definition of refurbishment packages and heat supply systems**

   By defining different thermal protection standards, different insulation measures and use of renewable heating systems the cost-optimal level for the reference buildings could be determined.

3. **Energy performance calculation**

   For the calculation of the energy performance of the buildings, the Austrian standard ("*ÖNORM M 7500*") have been applied. (ÖNORM M 7500, 1980). Based on the defined refurbishment packages and heat supply systems, the primary energies were calculated. Terminologies, system boundaries and definition of primary energy according to EN standards are described in chapter 3.1.

4. **Calculation of global cost**

   From a private financial viewpoint, specific cost categories and assumptions are defined and global costs are calculated. For the verification of the costs, a market research for the chosen countries and analysis of the available literature is performed. The structure of global costs, which are considered in the performed calculation, is specified in chapter 2.

5. **Sensitivity analysis – Identification of scenarios**

   The calculation is complemented by a sensitivity analysis. Here, the unclear parameters are going to be varied and the deviation of the results investigated in order to find out whether the general statement is valid or how much the actual result may differ.
   In the thesis, a sensitivity analysis is performed by varying service factor and discount rate (interest rate).

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[2] http://webtool.building-typology.eu/ (last accessed on 23rd December 2015)

6. **Determination of cost-optimal levels**

   As a result of the steps described above a graph representing the global costs over the net primary energy is generated for each reference building. The results are discussed separately for each study case.

A detailed description of the methodology is illustrated in chapter 3.8.

2 Cost topology

2.1 Structure of the costs

The figure below gives an overview of the make-up of global costs, which are considered in the calculation.

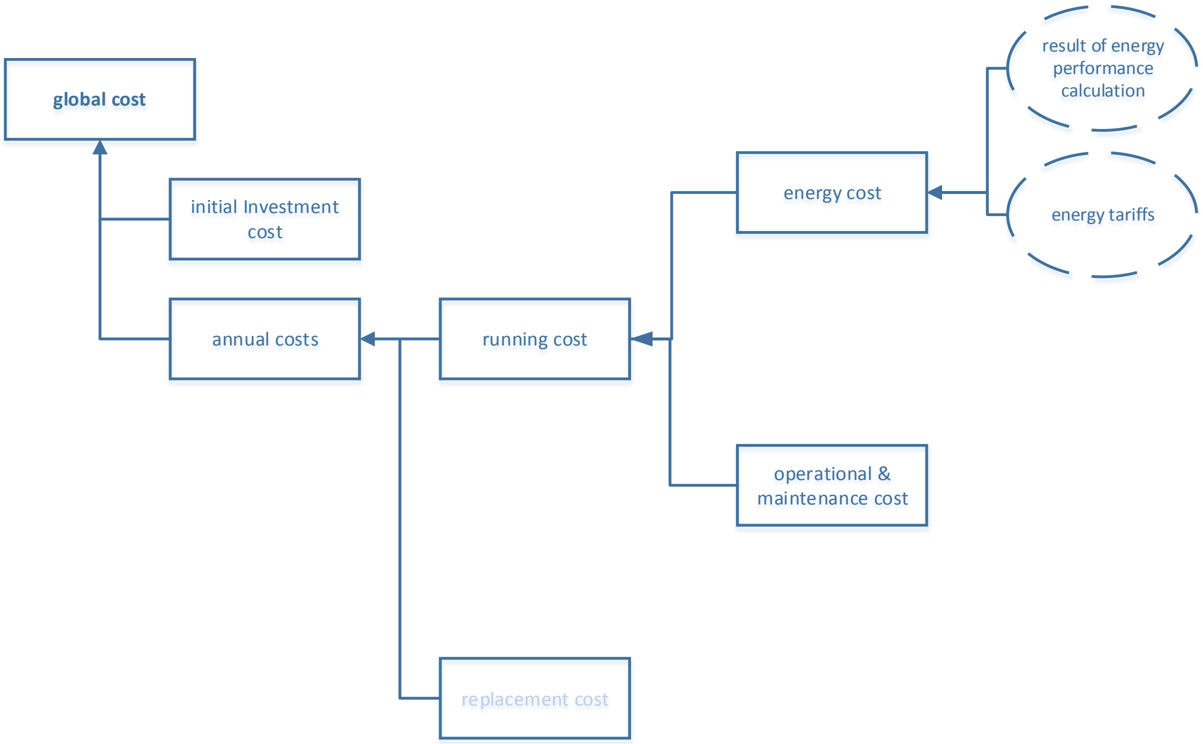

Figure 2-1 Structure of all costs considered in the global cost calculation

Initial investment costs include:

- **Construction costs related to the quality of the building envelope**
  These costs are taken from the ENTRANZE cost database (last updated: January 2014). As a basis for the calculation, only available costs from Germany are considered. All available costs are listed in Annex 4. For the missing costs, an interpolation process was developed for the estimation.

- **Investment costs related to the renewal of heating systems**
  A market research was done for these costs. Several installation companies and energy agencies in different countries like Sweden, Hungary, Slovakia and Slovenia were contacted via email. The email contained a table and requested material and installation costs for heating systems (heat pumps, solar thermal systems and biomass) for different heat loads. The idea was to request further information like

maintenance costs if a company or agency replied. Unfortunately, almost no information could be received or the provided data was not sufficient for the analysis and purpose of this work.
E.g. the following average costs were sent from the Swedish Heat Pump Association (SVEP) for different heat pump systems in Sweden for a typical single-family house with an annual energy consumption for heat and tap water of 20,000 kWh/year. Further costs for different energy consumptions or heat loads could not be provided. These costs were not sufficient to be taken into consideration for this thesis.

Table 2-1 Average costs for a typical single-family house with an annual energy consumption for heat and tap water of 20,000 kWh/year

	Air-to-air	Geothermal (vertical)	Geothermal (horizontal)	Ground water	Air-to-water	Exhaust air
Average cost (SEK)	23,832	144,032	127,143	137,863	108,006	64,691

Therefore, (Martin Kaltschmitt, 2013) is used as a basis for all costs; for all missing data an interpolation process was developed for the estimation.

As displayed above (Figure 2-1), annual costs are divided into running and replacement costs:

- **Running costs**
  Due to energy costs, these costs are on the one hand dependent on the heating systems, and on the other hand on operational and maintenance costs. Energy costs are calculated based on the result of the energy performance calculation and applicable national energy tariffs. Operational and maintenance costs include inspections, adjustments, cleaning, small repairs and cyclical regulatory costs related to specific heating systems.

- **Replacement costs**
  These costs are not considered in the thesis. To facilitate the calculation, the period of the cost-optimality calculation and life time of building components is set to 30 years. For more accurate calculations, the life time of each building component and heating (sub-) system should be taken into account and applicable costs added to global costs.

Please note that all construction costs which are not directly related to energy (e.g. polluting emissions and external costs) are not part of this work. Costs of land, property taxes, subsidies, etc. are also not included.

2.2 Costs related to heating systems

The aim of this chapter is to give detailed descriptions about all the related costs of the heating systems. A special focus lies on heat pumps and solar thermal systems.

2.2.1 Heat pumps

2.2.1.1 Investments costs

The amount of the investment costs for heat pumps generally depends on the technology used (e.g. ground source/air source heat pumps, etc.) and system size. By increasing the system size, specific costs are decreasing. For technology, only electrical ground source heat pump is used. Electrical means that electricity is used as support energy. Optionally, gas may be used. Air source heat pumps are not considered in this thesis.

Investments costs of electrical ground source heat pumps can be divided into (Martin Kaltschmitt, 2013):

- **Heat source systems**
  Heat source systems with earth collectors vary between €550 and 2,600 per kW; models with borehole heat pipes vary between €1,000 and 2,400 per kW.

- **Heat pumps**
  The costs for heat pumps vary a lot and are between €500 and 5,000 per kW. By increasing the system size, heat source systems make up the main part of the costs.

- **Storage**
  The charge for the solar storage depends on the volume stored.

- **Installation and initial operation**
  All labour costs for the setup, relocation of pipelines, construction works, installation and initial operation are included.

Based on the available investment costs in (Martin Kaltschmitt, 2013), all missing data was estimated by using interpolation. The following figure shows the investment costs by varying the energy need for a single-family house.

In general, investment costs for heating systems are displayed based on heating power, i.e. in kilowatt. In this thesis, a relation between investment costs and energy need based on the reference buildings used in the book (Martin Kaltschmitt, 2013) were determined to illustrate the investment costs for heating systems.

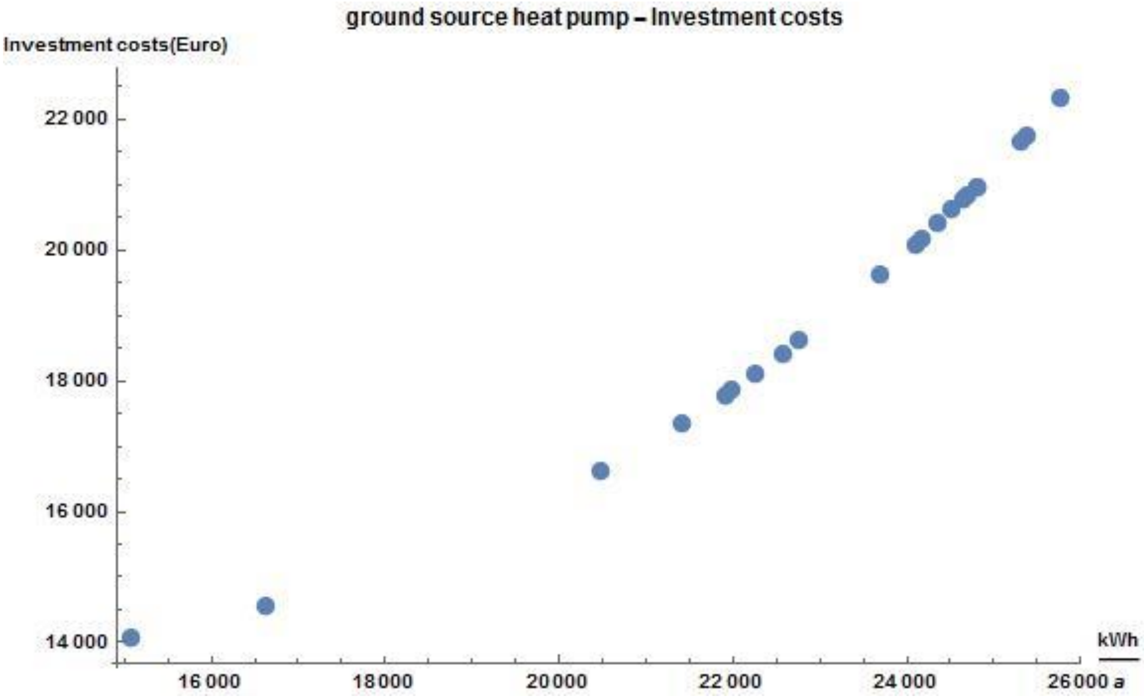

Figure 2-2 Investment costs of ground source heat pump for a single-family house

For higher energy needs, the available cost data was limited. Therefore, the costs were estimated in a linear way. Please find below the investment costs by varying the energy need for a multi-family house.

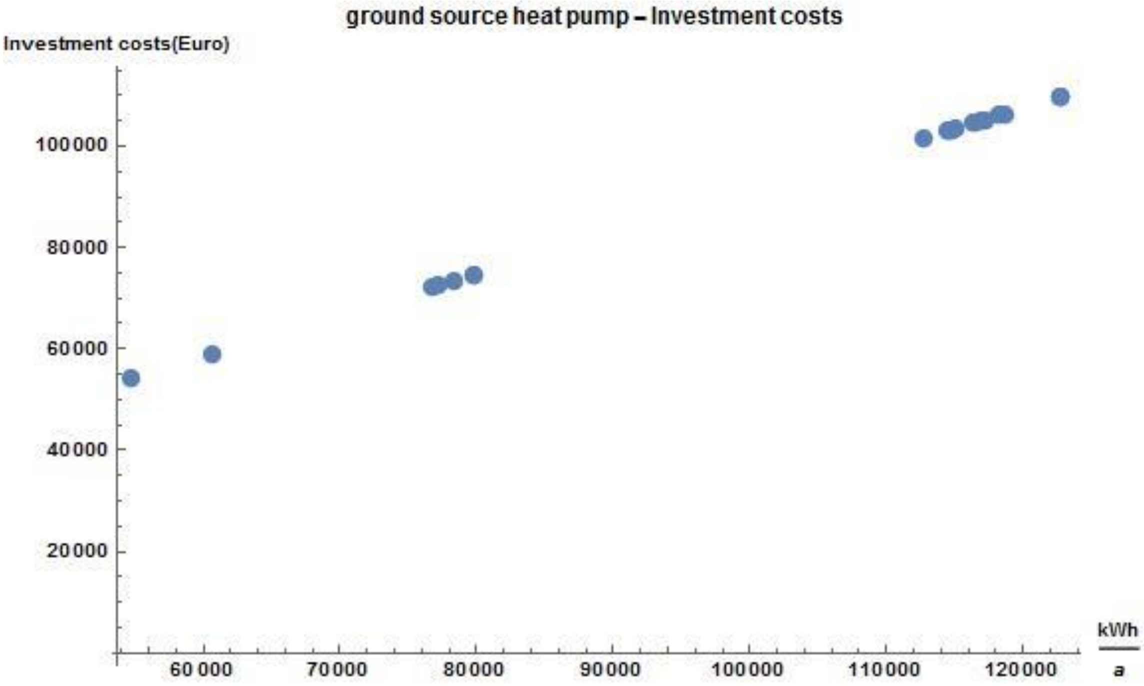

Figure 2-3 Investment costs of ground source heat pump for a multi-family house

2.2.1.2 Operation and maintenance costs

Only small repairs like exchanging seals are included. Bigger replacements, such as exchanging the entire heat pump, are not factored into these costs.

2.2.1.3 Energy costs

For the operation of the heat pumps, only electricity is needed as support energy. The applicable energy tariff is shown in chapter 2.4.

2.2.2 Solar thermal system

2.2.2.1 Investments costs

The investments costs for a solar thermal system can be divided into (Martin Kaltschmitt, 2013):

- **Collector**
  The collector prices on the market vary between €50 and €1,200 per m² depending on their characteristics. The collector type is crucial. Unglazed collectors are used for pool heating. Glazed collectors are used for domestic hot water or combined space heating and domestic hot water. Prices increase with the glazing quality and collector size.

- **Storage**
  The charge for the solar storage depends on the volume to be stored and storage principle. The latter are domestic hot water, buffer for hot water heating, combined storage tank for heating and domestic hot water, and storage with loading unit.
  Depending on the technology used, costs vary between €1.5 and 7 per litre.

- **Other system components**
  These include costs related to pipelines, measuring and control devices, pump antifreeze and all safety equipment.

- **Installation and initial operation**
  All labour costs for the installation, relocation of pipelines, connection of solar storage and initial operation is included. This part is about 20-40% of the initial investment costs. (Martin Kaltschmitt, 2013)

Similar to the investment cost of heat pumps, based on the available investment cost in (Martin Kaltschmitt, 2013), all missing cost data for the solar thermal system were estimated by using interpolation. The following figure shows the investment cost by varying the energy need for a single-family house.

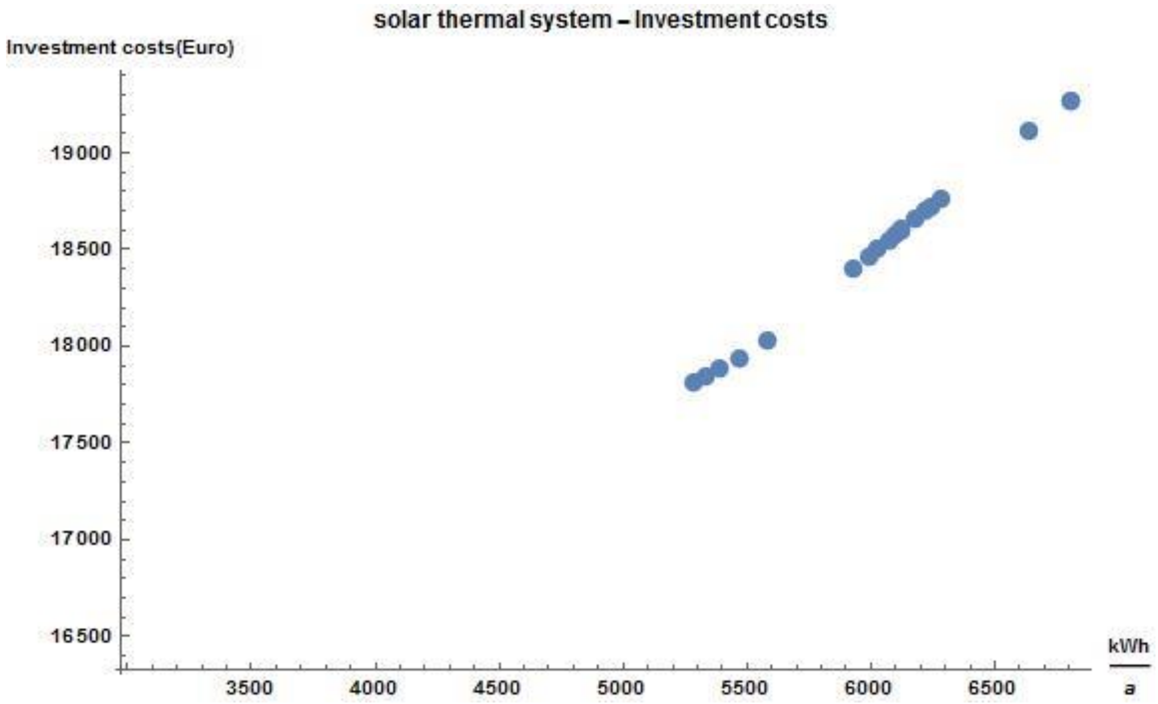

Figure 2-4 Investment cost of solar thermal system for a single-family house

Please note that due to the required energy need for the reference buildings (as demonstrated in chapter 4) the use of solar thermal systems is only considered in combination with conventional heating systems.

For multi-family houses, the correlation of collector area and energy production (at the collector output) is used as described in chapter 3.5.2. Based on the available data in (Martin Kaltschmitt, 2013), the price per collector m² is estimated at €805.

2.2.2.2 Operation and maintenance costs

Small repairs like exchange of seals are included. Bigger replacements such as exchange of collectors or storage are not part of these costs.

2.2.2.3 Energy costs

For the operation of the solar thermal system, support energy (electricity) is needed. Due to the divalent operation with conventional heating systems, cost-related consumption of gas is required. The applicable energy tariffs are displayed in chapter 2.4.

2.3 Refurbishment costs

As already mentioned in chapter 2.1, the basis for the calculation of refurbishment costs is the ENTRANZE cost database (last updated: January 2014).

Irrespective of the location of the reference building, available envelope costs for Germany were applied for the calculation. All costs for each kind of measurement are listed in Annex 4. The costs are gathered from evaluations of recent construction projects, analysis of standard quotations of construction companies and use of current cost databases which are created from market-based researches. (María Fernández Boneta (CENER), 2013)

The costs are subdivided into specific measures, which are described in the following chapters:

- Roof insulation
- External wall insulation
- Floor slab or framework insulation (when in direct contact with the outside ambient air or with unconditioned spaces)
- Insulation of the ground floor in contact with the ground
- Perimeter insulation
- Improving the air permeability of the envelope
- Improving the thermal quality of windows / doors

The detailed descriptions with different thermal insulations (e.g. 5 cm, 15 cm and 30 cm thermal insulation for the roof) for each refurbishment level are shown in Annex 4.

For each variant of the measures,

- material costs,
- labour costs,
- business profit and
- general expenditure and professional fees (if applicable)

are listed in Euros per m² in Annex 4.

For the missing data on the ENTRANZE cost database, a linear interpolation process was developed for the estimation.

2.4 Energy price scenarios

As part of the ENTRANZE Project, the “Poles” model has been applied by Enerdata (Project ENTRANZE, 2014). The Poles simulation shows energy price scenarios for 57 countries or regions. Energy price changes for the case studies were based on the published scenarios by (Project ENTRANZE, 2014).

The following tables list the energy scenarios for Sweden and Slovenia. All listed prices are listed in $05/toe, which means that the prices are calculated with US dollar prices from 2005. This data is real (not nominal) data according to the prices from 2005. For the calculation of the prices from 2014, the price from 2005 need to be multiplied with 1+ interest rates for the period between 2006 and 2014.

Table 2-2 Sweden – Energy price scenarios, Domestic Prices ($05/toe) (average), Residential – Services, Source: (Project ENTRANZE, 2014)

	2000	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2040**	**2050**
Domestic Prices ($05/toe) (average)									
Residential – Services									
Oil	908	1438	1598	1555	1752	1986	2235	2534	2814
Gas	700	1111	1416	1430	1475	1614	1705	1788	1859
Coal	638	649	886	842	907	1109	1263	1356	1387
Biomass	701	709	783	783	691	697	702	722	758
Electricity	1313	1678	2193	2226	2267	2385	2456	2420	2351

Table 2-3 Slovenia – Energy price scenarios, Domestic Prices ($05/toe) (average), Residential – Services, Source: (Project ENTRANZE, 2014)

	2000	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2040**	**2050**
Domestic Prices ($05/toe) (average)									
Residential – Services									
Oil	705	815	913	971	1153	1379	1614	1889	2142
Gas	498	548	788	869	914	1050	1140	1220	1284
Coal	434	506	809	770	834	1036	1189	1281	1311
Biomass	695	1097	1103	927	735	795	839	865	873
Electricity	1947	1559	1758	1775	1808	1871	1941	1968	1958

For the use of the applicable energy prices in this theses, the following steps were followed for data preparation:

1. Conversion from \$05/toe to \$14/toe
   2005-2014: Inflation rate[3] = 25.39%

2. Conversion from \$14/toe to €14/toe
   Exchange rate from website oanda[4] on 31st December 2014

3. Conversion from €14/toe to €14/kWh (and €14/GJ)

The energy price scenarios are available in 5-year intervals. For the years in between, the data was estimated by using an interpolation process.

Based on the Poles simulation, the electricity and gas prices for Sweden and Slovenia are shown in the following chapters (2.4.1 and 2.4.2).

2.4.1 Sweden

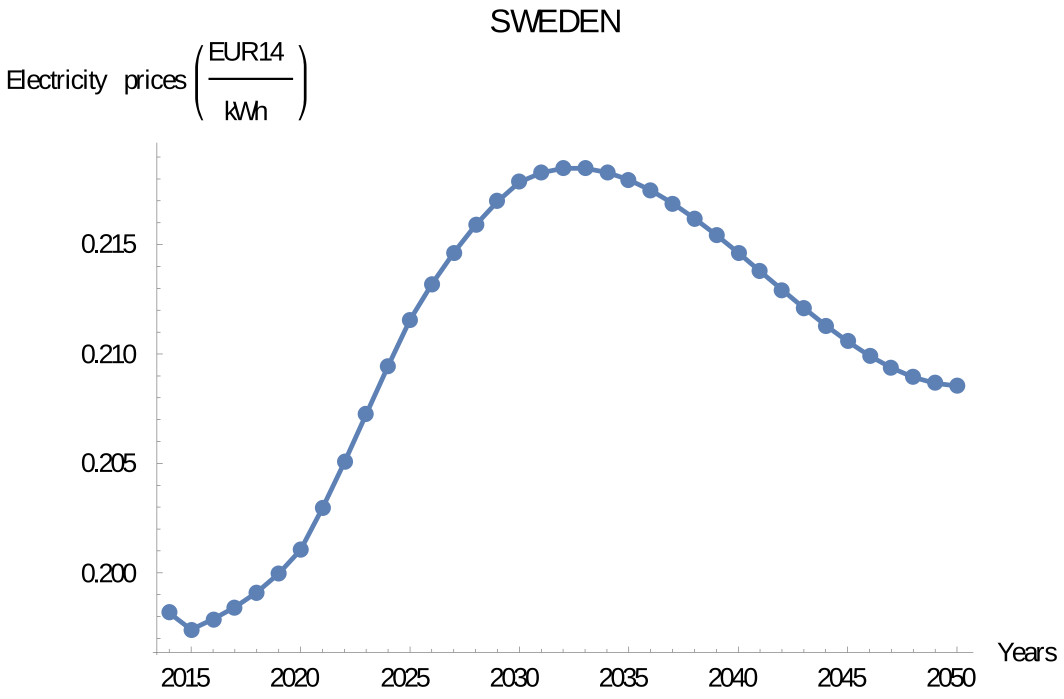

Figure 2-5 Sweden – Retail electricity prices based on ENTRANZE Poles simulation

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[3] Source: http://inflationdata.com/Inflation/Inflation_Rate/HistoricalInflation.aspx, last accessed on 3rd February 2016

[4] Source: www.oanda.com, last accessed on 3rd February 2016

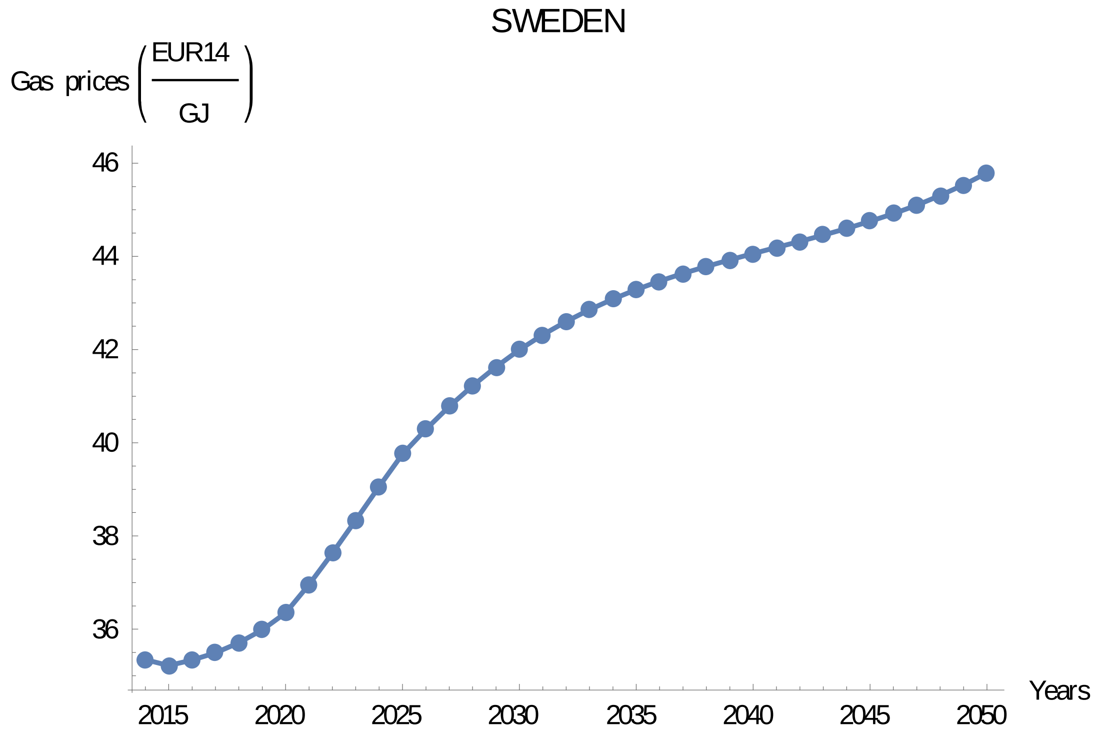

Figure 2-6 Sweden – Retail gas prices based on ENTRANZE Poles simulation

2.4.2 Slovenia

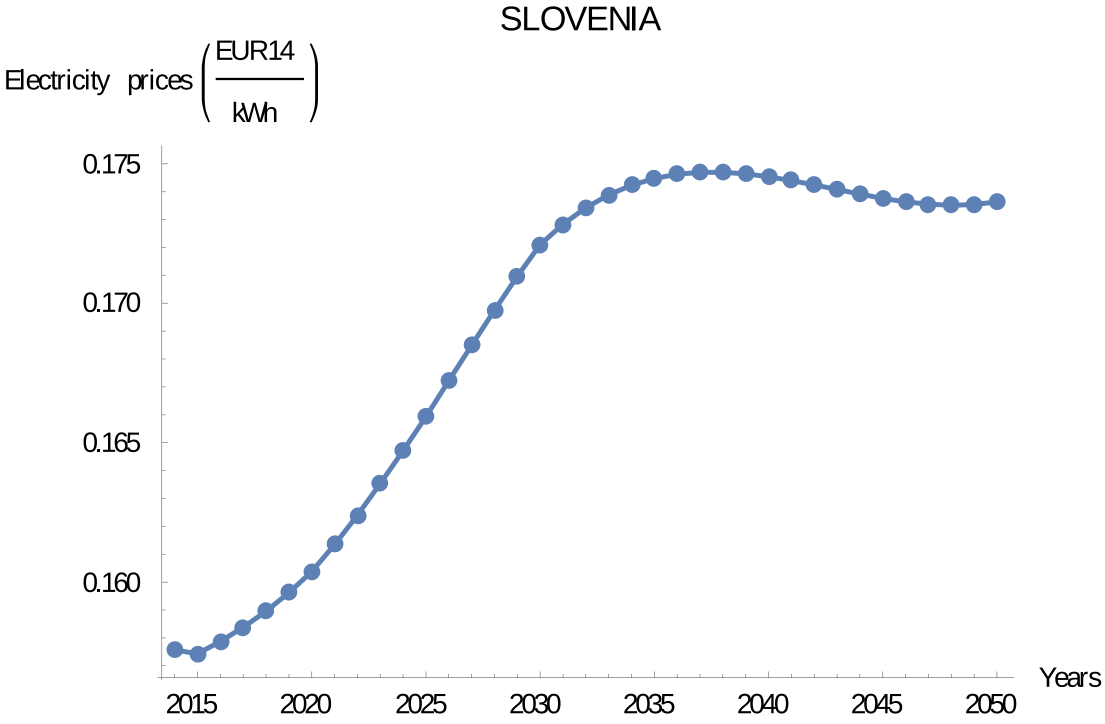

Figure 2-7 Slovenia – Retail electricity prices based on ENTRANZE Poles simulation

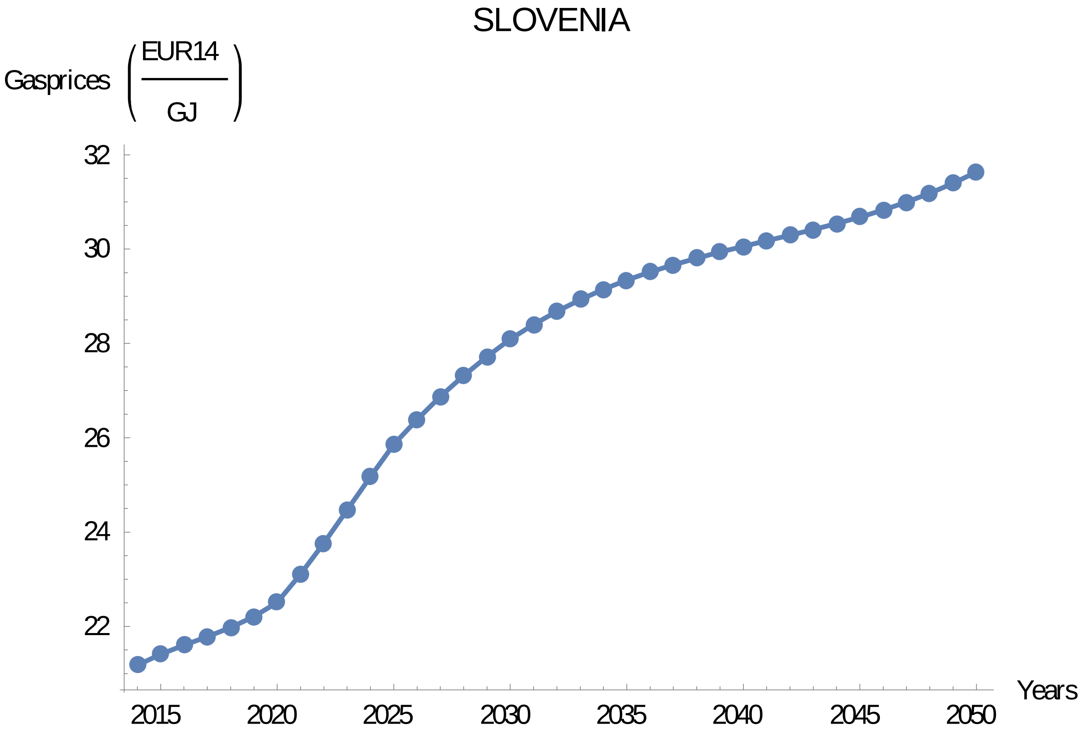

Figure 2-8 Slovenia – Retail gas prices based on ENTRANZE Poles simulation

3 Methodology of cost-optimality calculation

3.1 Energy terminology according to EN standards

Due to a larger number of different terms in the literature used to describe the energy demand and energy consumption in buildings, the aim of this chapter is to clarify the system boundaries and meanings of different terms. However, these terms will then be used consistently in this thesis. For better understanding, the following figure (*Figure 3-1 System boundaries with all energy terms used in this thesis*) defines all related energy terms and their boundaries used in this thesis. (Müller, 2015)

All other terms, like space cooling, are not the focus of this work and therefore these terms are neither shown in the figure nor are they defined.

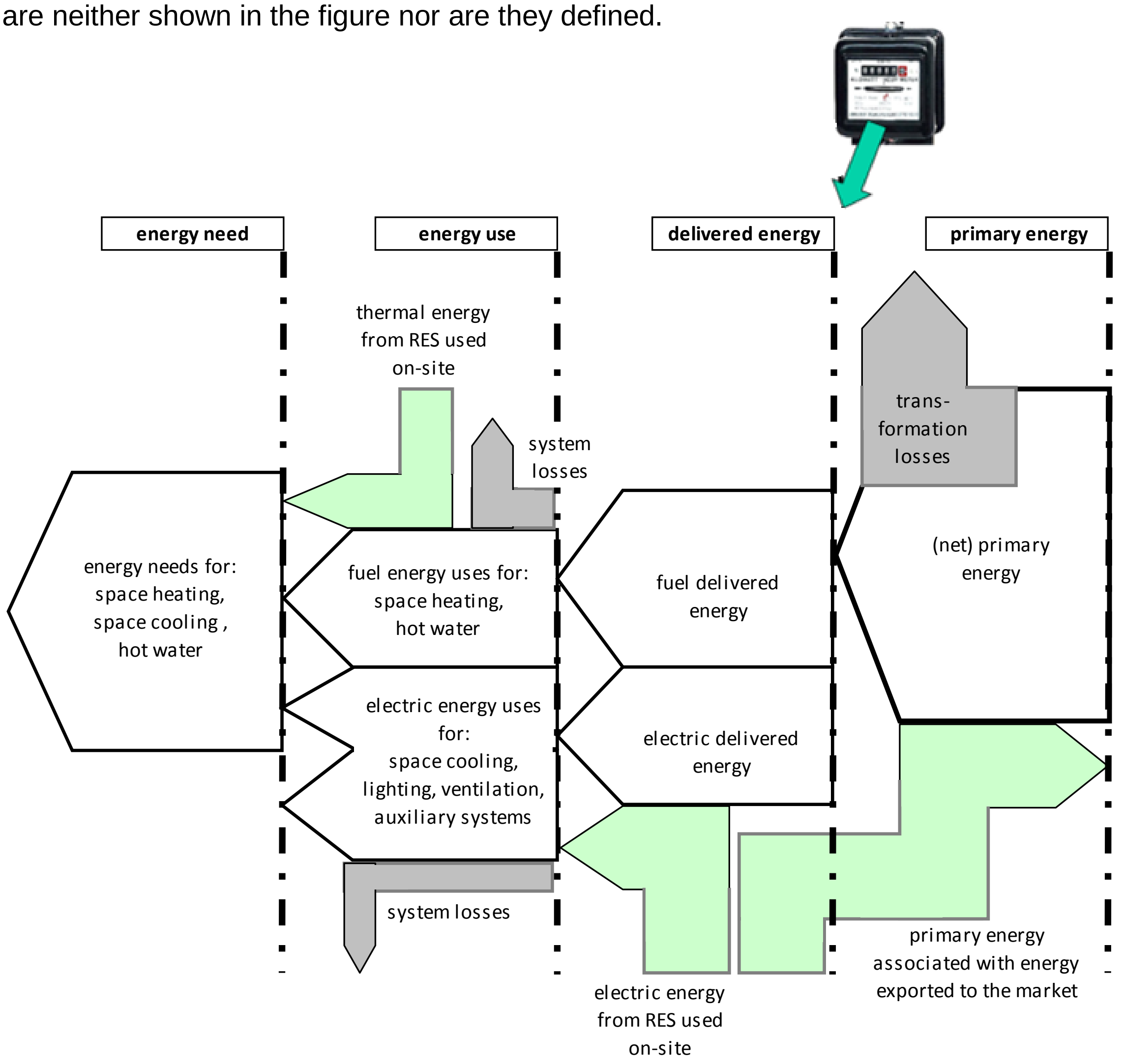

Figure 3-1 System boundaries with all energy terms used in this thesis and scheme of the net primary energy demand[5]

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[5] Source: ENTRANZE, Report on Cost/Energy curves calculation, D3.3. of WP3 of the Entranze Project (primary based on (EN 15603:2008, 2008)), September 2013

The definitions of the mentioned terms in (Figure 3-1) are taken from [EN 15603:2008] and [EN 15615:2007] standards (Marco Pietrobon, 2013). These standards are well known in building physics and therefore used as a basis for this thesis. (EN 15603:2008, 2008)

- System boundary
  Boundary considers all areas in connection with the building (inside and outside the building) where energy is consumed or produced.

- Energy need for heating
  The heat which needs to be supplied for a conditioned space to keep the temperature conditions during a specific period of time.
  Please note that for the purpose of this work the energy need is only calculated.

- Energy need for domestic hot water
  Heat to be supplied for the needed amount of domestic hot water (according to calculation) to change its temperature from the cold water temperature to the preset temperature at the delivery point. The heating technology of the building is not considered

- Energy use for lighting
  Electrical energy input to operate the lighting system.

- Energy use for space heating or domestic hot water
  Energy input to the heating or hot water system to cover the energy need for heating or hot water. If the energy is used for both heating and domestic hot water, it is difficult to break it down according to its specific purpose. Therefore, the energy use is listed as a combined quantity.

- Delivered energy
  The energy supplied to the building through the system boundary to comply with the uses taken into account (heating, domestic hot water, lighting, appliances etc.) or to produce electricity, listed by energy carrier.

- System thermal loss
  The loss of the system for heating or domestic hot water, which does not benefit system output.

- Auxiliary energy
  Electrical energy used by systems for heating and domestic water to support energy transformation to comply with energy needs.

- Primary energy
  Energy that is independent from any conversion or transformation process. Primary energy contains non-renewable and renewable energy. Furthermore it is used to produce the energy delivered to the building. By using conversion factors, it is calculated from the delivered and exported amounts.
  The conversion factors are listed below.

Table 3-1 Conversion factors for the calculation of total primary energy from the delivered and exported amounts

solar	0
heat pump	0
gas	1
electricity	2,5

- Renewable energy
  Energy from a source that is not depleted by extraction, such as solar energy (thermal and photovoltaic), wind, water power, renewed biomass, heat pumps.
    - NOTE: In ISO 13602-1:2002, a renewable resource is defined as a “natural resource for which the ratio of the creation of the natural resource to the output of that resource from nature to the techno sphere is equal to or greater than one”.

Terms which are used in this work were explained in the sections and shown in Figure 3-1 System boundaries with all energy terms used in this thesis and scheme of the net primary energy demand above. In closing, I would like to explain the relations between the terms which were applied for the calculations.

$$delivered\ energy = energy\ need - solar\ energy - ambient\ energy$$[6]

The term energy use has already been defined. This thesis is focused on energy need for space heating and domestic hot water. Therefore, energy use is not relevant and will not be used in the next chapters.

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[6] In the case of photo voltaic energy, this relation is not valid anymore.

3.2 Identification of technical refurbishment packages

To improve the energy performance of buildings, different packages of measures need to be compiled. These compiling packages are the basis for creating the energy/cost curves and needed to be calculated for the reference buildings (BPIE, 2010). The definition of this proper baseline is very important for performing the cost-optimal calculations. The baseline has an impact on the results of the calculation. In order to compare different reference buildings, technologies and scenarios, the following groups were considered:

- **Building envelope**
  These are measures which deal with the reduction of heat transmissions and improve the air tightness of the building envelope. The aim is to reduce transmission loss. The following measures are included (BPIE, 2010):

    - thermal insulation products
    - building materials (e.g. construction component with lower thermal transmission)
    - measures to ensure air-tightness
    - measures to reduce the effects of thermal bridges
    - highly efficient glazing for windows and doors

  For the main components of the building, all considered refurbishment measures are listed below. The refurbishments show the disaggregation level to compare various measures. The listed measures range from a base refurbishment level to additional measures with highly efficient insulations. (María Fernández Boneta (CENER), 2013):

<u>Roof insulation</u>

- Refurbishment of the exterior layer of the roof
- Removal of the roof and refit by adding a new layer of insulation
- Addition of a thermal insulation layer over the last slab in contact with conditioned space
- Insulation below the last concrete slab

<u>External wall insulation</u>

- Base refurbishment level of walls (renovation of the exterior layer of the walls for aesthetic, functional and/or security reasons)
- External insulation by adding thermal insulation to the external surface of the façade
- EIFS System – lightweight synthetic wall cladding which includes foam plastic insulation and thin synthetic coatings
- Filling air chamber with thermal insulation
- Adding of thermal insulation layer on the internal surface of the wall

- Removal of the inner skin of the cavity wall and creation of a new skin, separated by an air chamber from the external skin

Floor/basement insulation

- Removal of the existing layers over the concrete slab. Additionally, installation over the insulation of a concrete screed and finally adding a ceramic or wood layer
- Installation of thermal insulation below the first conditioned plant of the building
- For ground floor in contact with the ground; removal of the currently layer over the concrete slab; additionally, installation of thermal insulation and finally adding a ceramic or wood layer

Window/door refurbishment

- Repair of old window components like glass and frames for aesthetic, functional and/or security reasons
- Window glazing substitution without changing of current frames
- Replacement of old windows by double-glazing or more efficient windows
- Adding a new window to the existing one

- **Space heating & domestic hot water**

  To meet the demand for heating, an active system is necessary. To achieve this demand, an efficient and/or renewable energy system can be used. The energy system should be used in combination with a suitable storage and distribution system. (Marco Pietrobon, 2013)

  The heating systems considered are:

  - Conventional heat supply systems – condensing boiler (gas) – currently in use
  - Heat pump (ground source heat pump)
  - Solar thermal heating system

  The following energy efficiency measures were taken into consideration. (María Fernández Boneta (CENER), 2013)

  Generation

  - Removal of the old heating generation system and installation of a standard gas boiler
  - Removal of the old heating generation system and installation of a heat pump
  - Installation of a thermal solar system to meet domestic hot water loads and/or a fraction of heating loads
  - Connection to a district heating system

- Emission
  Installation of an insulated radiant floor emission system
- Installation of a radiator emission system

Distribution

- Pipe insulation

Control

- Installation of an indoor thermostatic control system

Other

- Local electric hot water boiler

In many cases, the same system can be used for the production of domestic hot water and space heating. It can also be supplied by a combined or separate system. To reduce the heat loss, highly efficient storage and distribution systems are very important. (Marco Pietrobon, 2013)

3.3 Assumptions

The applicable calculations are based on the following assumptions:

- Irrespective of the location (country) of the reference houses, ”ÖNORM M 7500” is the applicable standard for the calculation of the energy need.
- All used terms for the calculation have been taken from the “EN ISO 13790” standard.
- For the calculation of the heating degree days (HDD), internal room temperature and outside air temperature are sufficient for the estimation of annual energy consumption. For the accurate calculation of the values for the HDD, that means accurate calculated internal room temperature $\mathrm{t_{im}}$ and heating limit, the exact frequency distribution of the outside air temperature $\mathrm{t_a}$ is required. The preparation of the values with the mentioned accuracy makes sense only in rare cases. (HAAS, Wirtschaftliche und ökologische Optimierung der Heizenergieversorgung, 2012/2013, S. 2-6)

- The energy needs for space heating and hot water are calculated for the selected climate conditions and buildings.

- Space cooling, ventilation systems and lighting are not the focus of this work. Therefore, measure packages or related calculations for this purpose are not considered.

- Internal heat gains are not considered for the calculations. For the sensitivity analysis, internal gains in connection with the service factor are discussed.

- All costs of construction which are not directly related to energy (e.g. polluting emissions and external costs) are not part of this work. Costs of land, property taxes, subsidies, etc. are also not included.

- Some input factors like calculation period, cost categories and starting year of the calculation are fixed for the calculation of global costs.
  - Calculation period for determination of global costs is 30 years.
  - Lifetime of building components and heating (sub-) system is 30 years.
  - Starting year is set to 2014.

3.4 Climatic input parameters

3.4.1 Indoor temperature

For the purpose for our calculation, the relevant values are indoor temperature t_{ir} and average indoor room temperature t_{im} . According to (ÖNORM M 7500, 1980), the set-points of internal temperatures (Table 3-2) for heated rooms are listed below.

The listed temperatures are only valid for rooms with heating systems. (ÖNORM M 7500, 1980)

Table 3-2 Set-point (of the indoor) temperature for heated rooms
Source: (ÖNORM M 7500, 1980)

Room type	Set-point temperature [°C]
Living and bedrooms	+20 °C
Kitchen	+20 °C
Bathroom	+24 °C
Toilet	+15 °C
Heated adjacent rooms (vestibule, corridor)	+15 °C
Staircase	+10 °C

The set-point temperature of unconditioned rooms like basements and/or roofs are defined according to the set-point temperature of adjacent rooms. In this work, +5 °C is set for these types of rooms.

The set-point (of the internal) temperature in households is required for the determination of heating degree days and can be calculated as follows:

$$t_{im} = \frac{\sum_{r=1}^{Z_R} t_{ir} \, * \, V_r}{\sum_{r=1}^{Z_R} V_r}$$

t_{ir} ... *Indoor temperature of the room* r

V_r ... *Volume of the room* r

Z_R ... *Amount of rooms in the building*

The exact recording of indoor temperature is very import for the calculation of the energy consumption of buildings. If t_{im} is changed by only one degree, it increases or decreases the energy consumption by 5 – 7%. (HAAS, Wirtschaftliche und ökologische Optimierung der Heizenergieversorgung, 2012/2013, S. 2-5)

3.4.2 Outdoor (air) temperature t_a

The outdoor temperature is the second important parameter for the heating load and energy need of the building. This parameter changes over the course of the day and also over the course of the year, as shown in the following figure. (HAAS, Wirtschaftliche und ökologische Optimierung der Heizenergieversorgung, 2012/2013, S. 2-5, 2-6)

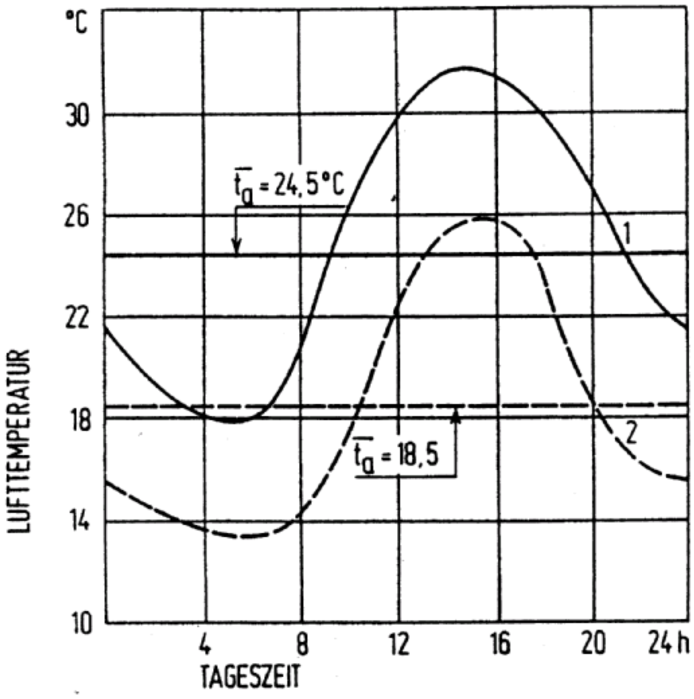

Figure 3-2 Temperature course during a day (Curve 1: July day, Curve 2: September day) Source: (HAAS, Wirtschaftliche und ökologische Optimierung der Heizenergieversorgung, 2012/2013)

3.4.3 Standard outdoor temperature t_{an}

The standard outdoor temperature t_{an} [°C] is the lowest two-day-average of the outdoor air temperature of a location, which has been reached or fallen below 10 times over the past 20 years. It is described in ÖNORM M 7500, part 4. (ÖNORM M 7500-4, 1980)

For locations where no data is available, values of cities with similar climate conditions have been chosen. Standard external temperature for locations above 1000m sea level, can be set as shown in Table 3-3. (HAAS, Wirtschaftliche und ökologische Optimierung der Heizenergieversorgung, 2012/2013, S. 2-7 - 2-9)

Table 3-3 Indicatory value for the standard outdoor temperature according to sea level [m] Source: (HAAS, Wirtschaftliche und ökologische Optimierung der Heizenergieversorgung, 2012/2013)

from [m]	to [m]	t_{an} [°C]
1001	1400	-18
1401	1800	-20
1801	2200	-22
2201	2600	-24
2601	3000	-26

3.4.4 Heating Degree Days (HDD)

Depending on the outdoor temperature as well as the length of this period, the heating energy demand varies. Both of these influencing factors are described by the Heating Degree Days (HDD). Their basis is the indoor temperature set-point of 20°C (e.g. for living and bedrooms) and the heating temperature of 12°C, i.e. heating is mandatory only on days where the outdoor temperature is less than the heating temperature (12°C). For every day this case applies to, the difference between 20°C and the average outdoor temperature is summed up. The result are the heating degree days on the basis (20/12). Heating temperature is estimated based on insulation level. In this thesis, only 12°C is considered. (Siegen, 2002)

Table 3-4 shows the heating degree days for the location, which are required for the calculation of energy needs of the reference buildings. HDD for Stockholm are taken from (Siegen, 2002). Due to the similarities, HDD for Ljubljana are based on the available data for Klagenfurt and are taken from (Heidi Krischan, 2015).

Table 3-4 Heating Degree Days for the selected locations of the reference buildings

Location	Heating degree days [Kd]
Stockholm	4636 Kd
Ljubljana	3675 Kd

Although the equation is applicable for Austria, the following correlation with the sea level can be used in case of insufficient information about the locations (HAAS, Wirtschaftliche und ökologische Optimierung der Heizenergieversorgung, 2012/2013):

$$HDD_{\frac{20}{12}} = 3100 + 0{,}8 \cdot SL \qquad SL \ldots \quad sea\ level\ [m]$$

3.5 Output parameter

The output parameters for the cost-optimality calculations are:

- Calculation of energy need (and Final Primary Energy (FPE))
- Determination of global cost (Costs)
- Definition of scenarios
- Generation of the graph – Cost/Energy Curves

For a detailed illustration of the mentioned output parameters, please refer to the schematic of the setting process for cost-optimal levels. This model is described in chapter 3.8.

3.5.1 Calculation of energy need

Based on the (EN 12831, Heating systems in buildings – Method for calculation of the design heat load, 2003), the following figure gives the simplified calculation steps for the energy need for the conditioned space.

Step 1	Identification of needed values: • standard external (air) temperature • annual average of the external temperature	Meteorological data
Step 2	Definition of each room of the building • Conditioned room • Un-conditioned room • Internal temperature	Status of each room and internal temperature Temperatur of each conditioned room
Step 3	Definition of: • Dimensioning • Characteristic of all construction components of each conditioned and unconditioned rooms	Building data
Step 4	Calculation of transmission heat transfer coefficient	Heat loss caused by: • Building envelpe • Unconditioned room • Neighbor room • ground

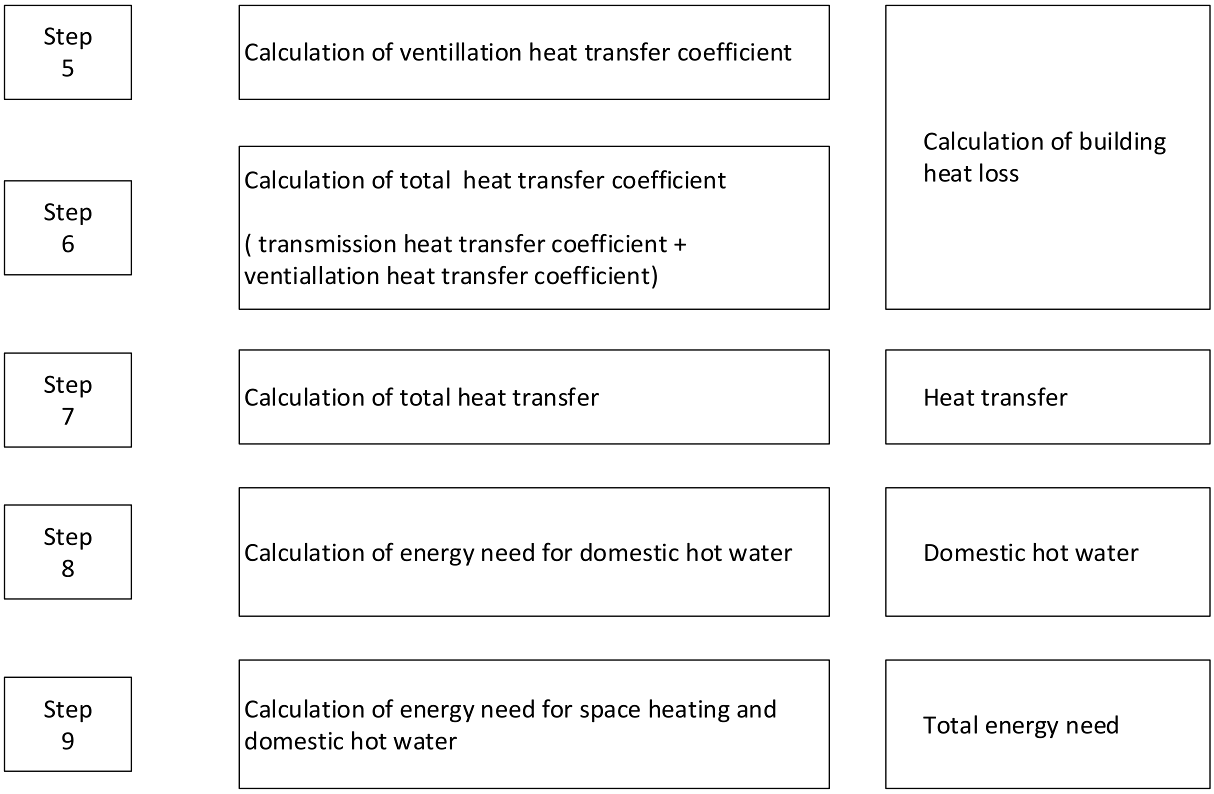

Figure 3-3 Simplified calculation steps for energy need

For the calculation of the energy need, first of all the heating transfer coefficients of the building need to be assessed. Heat transfer $\boldsymbol{P_H}$ of a building is the heat power loss for a specific external temperature t_{an}.

According to ÖNORM M 7500, heat transfer needs to be determined separately for each room. The total heat transfer is calculated by the sum of those heat transfers.

The heat transfer consists of:

- Transmission heat transfer coefficient $\boldsymbol{P_T}$ [kW]
- Ventilation heat transfer coefficient $\boldsymbol{P_L}$ [kW]
  (ÖNORM M 7500, 1980)

Therefore:

$$P_H = P_T + P_L$$

3.5.1.1 Transmission heat transfer coefficient P_T [kW]

This is the heat flow rate due to thermal transmission through the fabric of a building divided by the difference between the environment temperatures on either side of the construction[7].

$$P_{T\_BT} = k_{BT} * A_{BT} * (t_i - t_a)$$

A *… surface of construction component [m²]*

k *… surface coefficient of heat transfer [W/m²K]*

R *… thermal resistance [m²K/W]*

BT *… construction component*

t_a *… external temperature of the construction component*
(for external component bordering on the external (air) temperature:
$t_a = t_{an}$*)*

t_i *… indoor temperature of the construction component*

For building components, which are bordering on earth, the earth norm temperature has to be considered.

3.5.1.2 Ventilation heat transfer coefficient P_L [kW]

The ventilation heat transfer coefficient is the heat emission which is required to heat the entering air to the calculated internal (room) temperature t_i.

According to (ÖNORM M 7500, 1980), it is calculated by the sum of the supplementary heat transfers of the window and room.

$$P_L = P_W + P_R$$

P_W *... Supplementary heat transfer of the window (according to* (ÖNORM M 7500, 1980)*)*

P_R *... Supplementary heat transfer of the room (according to* (ÖNORM M 7500, 1980)*)*

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[7] ISO 13790:2008, Energy performance of buildings – Calculation of energy use for space heating and cooling, Switzerland

There is a simplified calculation according to (ÖNORMB8135, 1983), where the ventilation heat transfer coefficient is calculated by the required minimum air exchange:

$$P_{L_{Min}} = \frac{0{,}75 * n_L * c_{PL} * \rho_L * V_{building} * (t_{im} - t_{aN})}{3600}$$

n_L ... *air exchange (depending on the room volume, it is between 0.2 and 0.5)*

$V_{building}$ ... *building volume [m³]*

c_{PL} ... *specific thermal capacity of the air [kJ/kg K] (ca. 1.009)*

ρ_L ... *air density [kg/m³] (ca. 1.3)*

3.5.2 Solar thermal production

For solar thermal energy, Eurostat considers the first usable form of energy as primary energy. Therefore it is defined as follows: “Solar thermal production is the heat available to the heat transfer medium minus the optical and thermal collector losses”[8].

This chapter explains a simple method for converting installed solar collector area to annual collector output. This means how much energy can be produced depending on the global horizontal irradiation.

Depending on the application, the following collector types are used for solar thermal systems.

- Unglazed collectors → Pool heating
- Glazed collectors → Domestic hot water
  → Combined space heating and domestic hot water

“The annual solar collector heat production is defined as the heat available to the heat transfer medium minus the optical and collector losses”[9], which means the output of the collectors. (Nielsen, 2011)

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[8] Source: Recording the Solar Thermal Contribution, Werner Weiss, (AEE-Insitute for Sustainable Technologies-Austria), Jan Erik Nielsen (PlanEnergie – Denmark) European Solar Thermal Industry Federation

[9] Source: Eurostat and International Energy Agency

As pool heating is not part of this thesis, the collector area equations with solar primary energy below show only domestic hot water and/or space heating requirements (Werner Weiss):

$$Q_{glazed\ collector,domestic\ hot\ water}[kWh] = \mathbf{0,44} \cdot H_0\ \cdot A_a$$

$$Q_{glazed\ collector,combined\ systems}[kWh] = \mathbf{0,33} \cdot H_0\ \cdot A_a$$

Q	*Annual collector output [kWh]*
H_0	*Annual global horizontal solar irradiation [kWh/m²]*
A_a	*Collector area [m²]*

Please note that pipe losses should be taken into account, which are about 11%. (Martin Kaltschmitt, 2013) It should be noted that the described method is an oversimplified calculation.

3.6 Correlation of thermal transmittance with insulation thickness

The basis for the determination of cost-optimal levels is data available on TABULA WebTool[10]. Unfortunately, this data is not comprehensive enough for the analysis. The correlation of thermal transmittance (U-value) with insulation thickness has been analysed and determined as part of the work. As a result, additional refurbishment packages are created, which are implemented into the calculations for the study cases.

Primarily, by using the relations above, it is shown that the thermal transmittance (U) can be described as the function of the insulation thickness (d).

π is defined as the difference between saved energy costs and investment costs (in consideration of the annuity).

$$\pi = \Delta EC - \alpha \cdot IC$$

$$\frac{\partial \pi}{\partial d} = 0$$

$$\Delta EC\ (d) = \alpha \cdot IC\ (d)$$

$$\Delta EC\ (d) = \Delta Q \cdot p$$

$$\rightarrow \Delta Q\ (U)$$

$$\rightarrow U = f\ (d)$$

ΔEC	*... difference of the energy costs*
IC	*... investment costs*
α	*... annuity factor*
d	*... layer thickness of the building component*
p	*... energy price (depending on the heating system)*

Two different approaches were taken into account to find a correlation between thermal transmittance and insulation thickness.

1) Building components (e.g. building wall or roof) bordering on air
2) Building components (e.g. basement/floor) bordering on earth

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[10] http://webtool.building-typology.eu/ (last accessed on 23rd December 2015)

For a better understanding, the calculation of additional variants for a single-family house in Sweden is demonstrated. This house is used as a reference building for the case studies in chapter 4.

In general, the U-value for any building component can be calculated as follows:

$$\boldsymbol{U_{building\ component}} = \frac{1}{\frac{1}{\alpha_i} + \sum\frac{d}{\lambda} + \frac{1}{\alpha_a}}$$

U ... *thermal transmittance*

$\alpha_{i,a}$ ... *surface coefficient of heat transfer (internal and external)*

λ ... *linear thermal transmittance*

d ... *layer thickness*

The thermal transmittance of the building wall for a single-family house in Sweden is calculated as follows:

$$\boldsymbol{U_{wall}} = \frac{1}{\frac{1}{\alpha_i} + \sum\frac{d}{\lambda} + \frac{1}{\alpha_a}}$$

Due to missing information, surface coefficients of the heat transfer are estimated. The actual state of the building wall of the single-family house in Sweden (full extension of the building wall):

$$\frac{1}{\alpha_i} + \frac{1}{\alpha_a} = 0{,}17\frac{m^2K}{W}$$

The following values are taken from the TABULA WebTool. (TABULA, 2012)

$$\mathrm{U}\ (d = 45 * 10^{-3}) = 0.33\ (\text{usual refurbishment})$$
$$\mathrm{U}\ (d = 70 * 10^{-3}) = 0.26\ (\text{advanced refurbishment})$$

Therefore, the following equation can be formed:

$$0.33 = \frac{1}{0.17 + \frac{d_{Wall}}{0.42} + \frac{45 * 10^{-3}}{\lambda}}$$

$$0.26 = \frac{1}{0.17 + \frac{d_{Wall}}{0.42} + \frac{70 * 10^{-3}}{\lambda}}$$

From both equations, the thickness of the building wall and the linear thermal transmittance of the installation measure can be calculated.

$$d_{Wall} = 0.5845 \text{ [m]}$$

$$\lambda = 0.03064 \text{ [W/m}^2\text{K]}$$

After calculating the missing variables (d_{Wall} and λ), the thermal transmittance (U) can be displayed as a function of insulation thickness (d):

$$U = \frac{1}{0.17 + \frac{0.5845440559440559}{0.42} + \frac{d}{0.030642857142857142}}$$

Below, the thermal transmittance depending on the insulation thickness is displayed graphically.

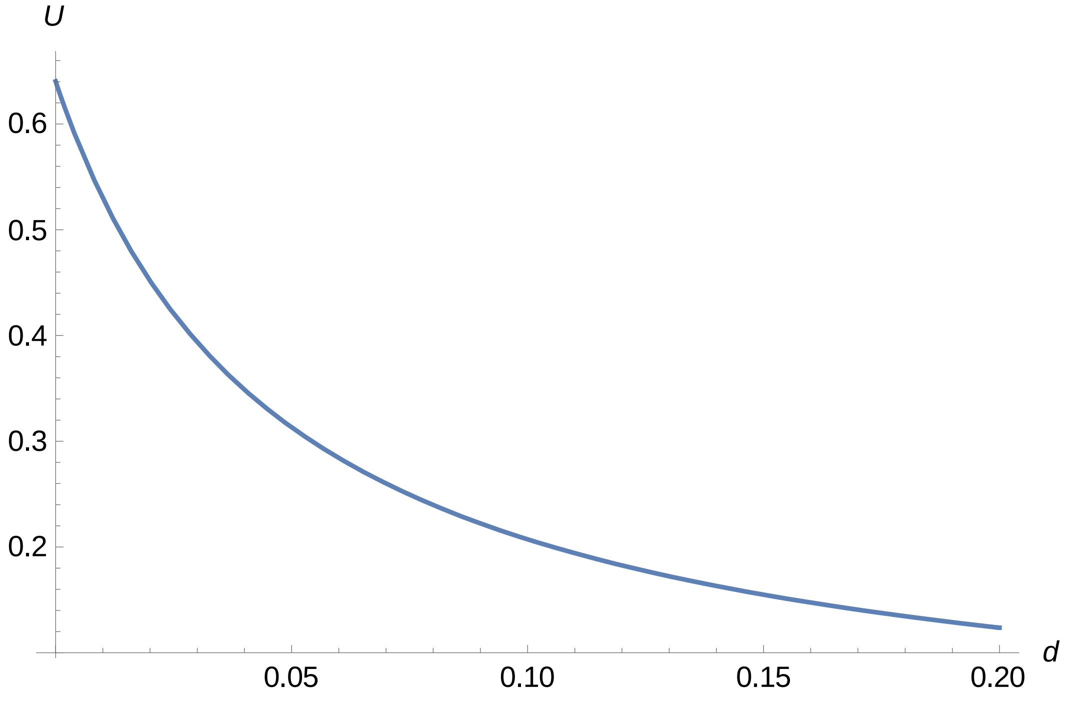

Figure 3-4 Thermal transmittance (U) function depending on the insulation thickness for the single-family house in Sweden

This calculation needs to be performed for each building component bordering on air. Based on the methodology, additional variants are created for the reference buildings. All calculated values are included in chapters 4.1.1.1, 4.1.2.1, 4.2.1.1 and 4.2.2.1 of the case studies.

Furthermore, the calculated thermal transmittance values of the single-family house for the building wall were checked with the website U-Wert Rechner[11] (Plag, 2015).

Below a comparison between both calculations is listed in the table (Table 3-5):

Table 3-5 Thermal transmittance comparison of additionally created variants for a single-family house in Sweden

Layer thickness [mm]	U-value according to calculation as described in this chapter	U-value results according to website "U-Wert Rechner "
50	0,31	0,3
100	0,21	0,2
200	0,12	0,12

For the layer thicknesses of 50 and 100mm, a difference of 0.01 W/m²K is observed, but the deviation is negligible. The details of the assessment from the website "U-Wert Rechner" is illustrated in the Annexes 1 to 3. These annexes are unfortunately in German, as the website is only available in that language.

During the analysis, it has been observed that the model described above is only applicable for building components bordering on air (e.g. building wall and roof). For building components bordering on earth, (e.g. basement/floor) a similar correlation needs to be elaborated.

A different approach is demonstrated as follows. The thermal transmittance (U-value) can be defined as follows:

$$U = \frac{\Delta Q/\Delta t}{\Delta T \cdot A}$$

$$[U] = \frac{J}{s \cdot K \cdot m^2} = \frac{W}{K \cdot m^2}$$

The U-value is the heat quantity which flows through a surface area A within a specific time unit where an air temperature difference ΔT between both sides of a building component applies.

The heat transfer coefficient is defined as follows:

$$H = \lambda \cdot \frac{A}{d} = \frac{\Delta Q}{\Delta t \cdot \Delta T}$$

$$[H] = \frac{W}{K}$$

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[11] www.u-wert.net (last accessed on 1st March 2015)

Therefore, U is the heat transfer coefficient for a specific surface area;

$$U = \frac{H}{A}$$

The heat transfer for two layers which abut each other is:

$$\frac{1}{H} = \frac{1}{H_1} + \frac{1}{H_2} = \frac{d_1}{\lambda_1 \cdot A} + \frac{d_2}{\lambda_2 \cdot A}$$

As a result, the U-value is for two layers:

$$U = \frac{H}{A} = \left(\frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2}\right)^{-1}$$

Now this relation is going to be applied to the floor of a single-family house in Sweden.

The following floor characteristics are estimated below:

- concrete slab with a thickness of 0.2 meters
- U = 0.28
- the floor actually has a perimeter protection

These characteristics lead to the following equation of the floor:

$$0.28 = \left(\frac{0.2}{2.1} + \frac{d_{Perimeter}}{0.037}\right)^{-1}$$

With this, $d_{Perimeter}$ can be calculated.

$$d_{Perimeter} \rightarrow 0.12861904761904763 \text{ [m]}$$

Further insulation measures can be calculated as follows:

$$U_{floor} = \left(\frac{0.2}{2.1} + \frac{0.12861904761904763}{0.037} + \frac{d}{0.037}\right)^{-1}$$

U_{floor} (d= $50 * 10^{-3}) = 0{,}20$
U_{floor} (d =$100 * 10^{-3}) = 0{,}16$
U_{floor} (d =$150 * 10^{-3}) = 0{,}13$

Below, the thermal transmittance of the floor depending on the insulation thickness for the single-family house in Sweden is displayed graphically.

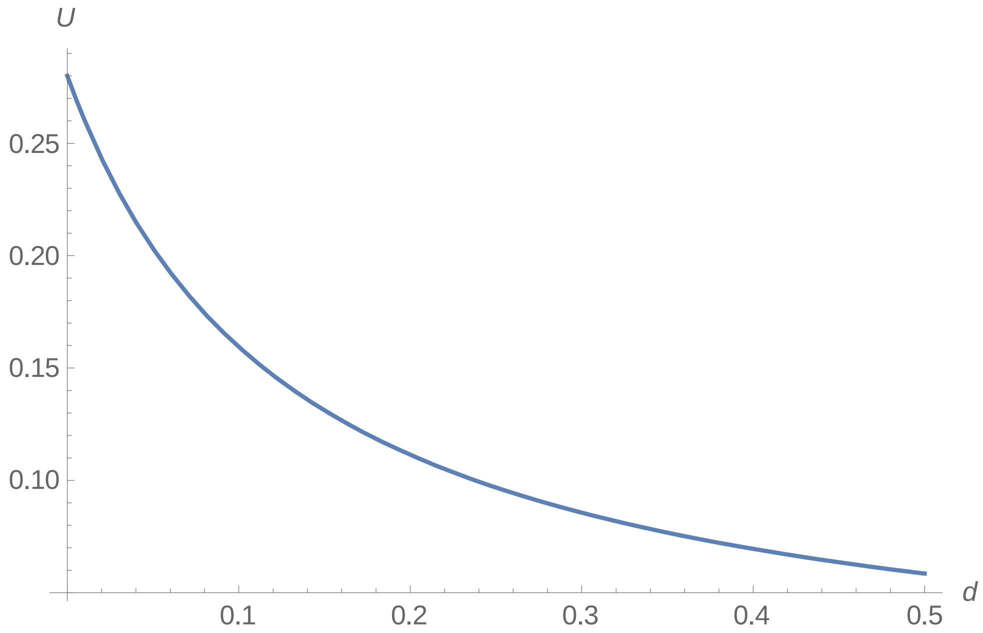

Figure 3-5 Thermal transmittance (U) function of the floor depending on the insulation thickness for the single-family house in Sweden

3.7 Service factor

The energy need calculated according to the standards does not match the measured result. This represents the building's data but doesn't reflect the user behaviour. In general, it is not possible to indicate each resident's exact behaviour.

User behaviour depends on the following characteristics:

- Thermal quality of the building envelope
- Size of the dwelling unit (apartment)
- Centralisation degree of the heating system
- Local climate

The influence of the thermal quality of the building envelope is due to higher heating costs and therefore a conscious usage of heating. This means that energy prices and local climate show a similar effect. (Biermayr, 1998) shows in his dissertation that energy prices do not have a permanent impact on energy need. The user (resident) will not change his behaviour as long as a specific price barrier is not crossed. The influence of this variable is not considered in this work. (Peter Biermayr A. M., 2010)

A similar influence on the service factor can be observed for the local climate. Higher annual temperatures lead to lower space heating which in turn leads to lower heating costs. This variable is to be included into the service factor and has a similar impact on the building envelope as the thermal quality.

The explanations above give an overview about the importance and the need of the service factor. Therefore, all internal and external influences for the calculation of the energy need, such as user behaviour, individual ventilation habits, solar radiation gains and internal heat sources are consolidated into a so-called service factor.

According to (HAAS, Wirtschaftliche und ökologische Optimierung der Heizenergieversorgung, 2012/2013), service factors vary between 0.55 and 0.90 (Status 2006) depending on the heating systems used and type of building (single-family or multi-family houses).

Consequently, three different service factors (0.55, 0.85 and 1) are considered for the case study sensitivity analysis in this thesis.

3.8 Description of the model

The following Figure 3-6 shows a schematic description of the process for setting cost-optimal levels. The detailed steps are described below the figure.

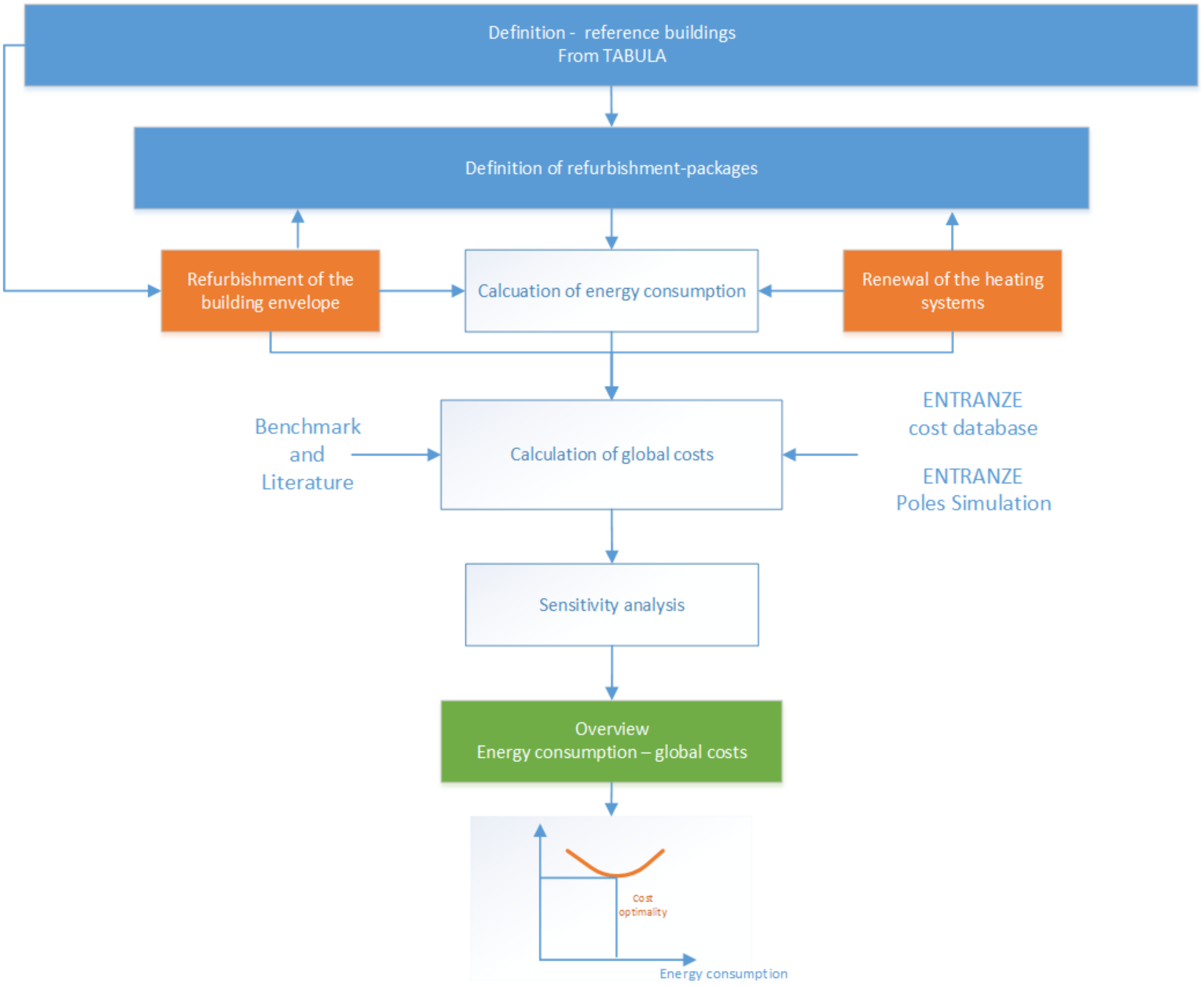

Figure 3-6 Schematic description of the process for setting cost-optimal levels for the reference buildings

For the determination of cost-optimal levels for residential buildings, the following procedures are essential:

1. **Definition of reference buildings**

   Single-family and multi-family houses in Sweden and Slovenia are considered as reference buildings for this thesis. The building data was taken from TABULA

WebTool[12], which has been developed within the framework of the Intelligent Energy Europe projects TABULA and EPISCOPE. Caretakers of National Building Typologies are Mälardalens University (Mälardalens University) and the Building and Civil Engineering Institute ZRMK (Ljubljana, Slovenia). (TABULA, 2012).

The main characteristics of the chosen reference buildings are described in chapters 4.1 and 4.2.

2. Definition of refurbishment packages and heat supply systems

The definition of different thermal protection standards, variants of insulation measures and use of renewable heating systems allows a determination of cost-optimal levels for the reference buildings.

The differentiation elements consist of:

- Insulation of roof
- Insulation of walls
- Insulation of cellar ceiling
- Thermally improved windows
- Thermally improved doors
- Heat supply

The base values were taken from TABULA WebTool. (TABULA, 2012) Additional measures were derived from these values to enable more variants in order to draw meaningful conclusions.

3. Energy performance calculation

For the calculation of the energy performance of the buildings, the Austrian standards ("*ÖNORM M 7500*") have been applied. (ÖNORM M 7500, 1980) Based on the defined refurbishment packages and heat supply systems, the primary energies were calculated.

The conversion factors from final energy to primary energy are not taken from the Austrian standards. The conversion factors used are listed in Table 3-1.

Only energy need for heating and domestic hot water was considered in the calculations. Energy consumption for cooling purposes, lighting, auxiliary systems and electrical household appliances of the building are not part of the calculations. (Andreas Enseling, 2010)

4. Calculation of global cost

From a private financial point of view, the following cost categories are considered for the calculation of global costs:

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[12] http://webtool.building-typology.eu/ (last accessed on 23rd December 2015)

- Initial investment costs
  These costs are based on market- and literature-based analysis. These costs are very important for the cost-optimal levels and include design, purchase of building elements, installation and commissioning processes.

- Running costs (energy, operational and maintenance costs)
  Operational and maintenance costs are based on the book “Erneuerbare Energien”. (Martin Kaltschmitt, 2013).
  Energy costs are taken from ENTRANZE Poles forecasts and adapted for the calculations.

- Replacement costs
  As described in chapter 2.1, these costs are not considered in the thesis. To facilitate the calculation, the period for the cost-optimality calculation and life time of building components was set to 30 years.

VAT is not considered in the calculation of all costs. Furthermore, subsidies are not included. All costs are calculated over a period of 30 years and running costs are discounted to the beginning of the calculation period (to year zero), which means that the net present value method applies. The starting year of the global cost calculation is fixed. For the sake of comparison, a period of 30 years is considered for single-family and multi-family houses. Energy prices and their development are considered on a national level.

5. Sensitivity analysis – Identification of scenarios

The calculation is complemented by a sensitivity analysis where unclear parameters are going to be varied and the deviation of the results is investigated in order to find out whether the general statement is valid or how far the actual result may differ. In this thesis, a sensitivity analysis is performed by varying the service factor and discount rate (interest rate).

6. Determination of cost-optimal levels

As a result of the steps described above, a graph representing the global costs over the net primary energy is generated for each reference building. The results are discussed separately for each study case.

Please note that other assumptions are listed and described in chapter 3.3.

4 Case studies

4.1 Single-family houses

For the purpose of single-family house case studies, two houses in two different countries (Sweden and Slovenia) are used as reference buildings.

4.1.1 Sweden

This chapter illustrates the calculation of cost-optimal levels based on a case study for a single-family house in Sweden. A photo (Figure 4-1) of the single-family house is displayed below.

Figure 4-1 Photo of the single-family house in Sweden which is used as a reference building for the case study

Although the house is located in southern Sweden, the location of Stockholm has been chosen for the calculation to represent the average Swedish climate.

Basic information of the building is as follows:

Location:	Stockholm
Construction year:	1960
Conditioned floor area:	125 m^2
Lifetime of buildings components:	30 years
Calculation period:	30 years
Number of residents:	3

In addition to the general information listed above, the following input data is specified:

Table 4-1 List of input data for the single-family house in Sweden

Input data	Temperature [°C]
Standard external temperature t_{an}	-30 °C
Average internal room temperature t_{im} (conditioned)	+20 °C
Average internal room temperature t_{im} (unconditioned e.g. roof)	-5 °C
Set-point (of the internal) temperature	+12 °C

Based on the general information and input data for the single-family house, heat degree days (HDD) are calculated. Therefore, *HDD* is *4636* [Kd].

Table 4-2 summarises the characteristics for the main building components of the single-family house in Sweden, which is used as a reference building for the calculations. The building data of the current state, usual and advanced refurbishment are taken from TABULA WebTool. (TABULA, 2012). In this context, some adaptations on the building data and refurbishment packages have been elaborated to determine the cost-optimal levels. All refurbishment packages are defined in chapter 4.1.1.1.

Table 4-2 Characteristics of the (existing) single-family house in Sweden

	Building components	Current state	U-value	[m²]
Single-family house in Sweden	Roof	horizontal wind	0.29	125
	Wall	light concrete block	0.6	100
	Basement / Floor	concrete slab	0.28	125
	Window		2.34	22
	Door		3	2

As in further procedures, the usage and influence of solar thermal heating systems will be shown; here, I would like to create an overview of the global horizontal irradiation of Stockholm. (Solar, 2015)

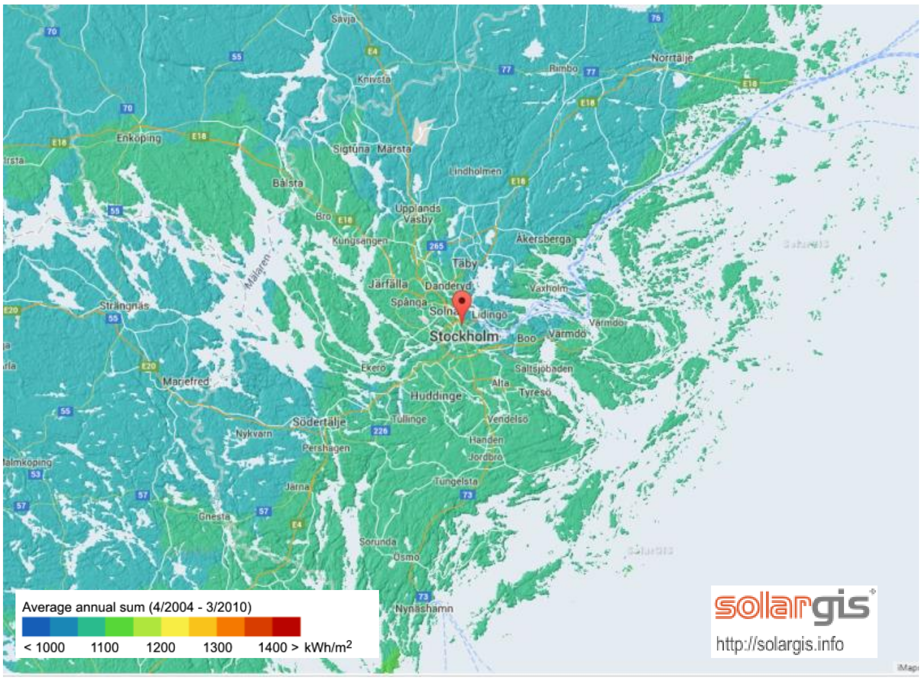

Figure 4-2 Global horizontal irradiation – Stockholm[13]

The figure shows the global horizontal irradiation of Stockholm as $H\,(Stockholm) = 1100$ (Solar, 2015). This value (H) was taken from the solargis website.

For the calculation of the reference building's energy performance, annual global horizontal irradiation needs to be considered. According to (Nielsen, 2011), the annual global horizontal solar irradiation at collector output is $410\ [\frac{kWh}{m^2}]$.

4.1.1.1 Definition of refurbishment measures

The different thermal installation measures are defined in this chapter. In total, five different refurbishment packages are created. Usual and advanced refurbishment packages reflect the values from TABULA WebTool[14]. Other installation measures named "*other refurbishment packages*" were derived from available data on TABULA WebTool and calculated. Each package includes various installation measures like installation of roof, walls, cellar ceiling and thermally improved windows/doors. In addition to the defined refurbishment packages, the renewal of heat supply systems was taken into consideration. For the determination of cost-optimal levels, each installation measure is taken into account separately.

The tables listed below give an overview about the protection standards of the building components and improved U-values after refurbishment.

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[13] http://solargis.info/imaps/#loc=59.344395,18.061523&c=58.636935,22.791138&z=6 (last accessed on 25th December 2015)

[14] http://webtool.building-typology.eu/ (last accessed on 23rd December 2015)

Table 4-3 SE-SFH Variant 1 – Usual refurbishment with respective insulation measures and U-values[15]

Building component	U-value	Insulation measure
Roof	0.11	add 200 mm of insulation, loose wool
Wall	0.33	add 45 mm of insulation and wood panel
Basement / Floor	0.21	add 40 mm of insulation
Window	0.9	new window, 3 glazed
Door	1.2	new door

Table 4-4 SE-SFH Variant 2 – Advanced refurbishment with respective insulation measures and U-values[16]

Building component	U-value	Insulation measure
Roof	0.06	add 500 mm of insulation, loose wool
Wall	0.26	add 70 mm of insulation and wood panel
Basement / Floor	0.21	add 45 mm of insulation
Window	0.76	new window, 2 + 2 glazed
Door	0.9	new door

U-values for variants 3-5 were calculated according to the correlation of U-values with insulation thickness. For calculation details, please refer to chapter 3.6.

Table 4-5 SE-SFH Variant 3 – Other refurbishment 1 with respective insulation measures and U-values

Building component	U-value	Insulation measure
Roof	0.13	add 150 mm of insulation, loose wool
Wall	0.31	5 cm of thermal insulation
Basement / Floor	0.20	5 cm of thermal insulation

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[15] Source: http://webtool.building-typology.eu/ (last accessed on 23rd December 2015)
[16] Source: http://webtool.building-typology.eu/ (last accessed on 23rd December 2015)

Table 4-6 SE-SFH Variant 4 – Other refurbishment 2 with respective insulation measures and U-values

Building component	**U-value**	**Insulation measure**
Roof	0.09	add 300 mm of insulation, loose wool
Wall	0.21	10 cm of thermal insulation
Basement / Floor	0.16	10 cm of thermal insulation

Table 4-7 SE-SFH Variant 5 – Other refurbishment 3 with respective insulation measures and U-values

Building component	**U-value**	**Insulation Measure**
Wall	0.12	20 cm of thermal insulation
Basement / Floor	0.13	15 cm of thermal insulation

Furthermore, the impact of different heating systems in combination with each insulation measure has been assessed. The considered heating systems are listed below:

- Conventional heat supply systems – condensing boiler (gas) – currently in use
- Heat pump (ground source heat pump)
- Solar thermal heating system

Due to the fact that a solar thermal system alone is not sufficient to comply with the energy need of the whole reference building (a solar coverage ratio of 20% has been estimated), this system is combined with a conventional heating system, meaning that this system needs to be considered divalent. The other two heating systems are rated as monovalent in the calculation.

4.1.1.2 Calculation of energy performance

Based on the general information, input data, refurbishment packages and chosen heating system, the following values for the net primary energy demand are calculated.

Table 4-8 Energy performance of the single-family house in Sweden

Refurbishment measures	Heat transfer [W]	Energy need – space heating [kWh/a]	Energy need – domestic hot water [kWh/a]	Total energy need [kWh/m²a]	Net primary energy per m² – heat pump [kWh/m²a]	Net primary energy per m² – solar thermal [kWh/m²a]	Net primary energy per m² – conventional gas [kWh/m²a]
Roof – usual refurbishment	10,103	22,481	2,039	196	123	197	231
Roof – advanced refurbishment	9,946	22,134	2,039	193	121	194	227
Roof – other refurbishment 1	10,158	22,605	2,039	197	123	198	232
Roof – other refurbishment 2	10,028	22,315	2,039	195	122	195	229
Wall – usual refurbishment	9,315	20,729	2,039	182	114	182	213
Wall – advanced refurbishment	8,965	19,950	2,039	176	110	176	205
Wall – other refurbishment 1	9,231	20,541	2,039	181	113	181	211
Wall – other refurbishment 2	8,701	19,363	2,039	171	107	171	199
Wall – other refurbishment 3	8,283	18,433	2,039	164	102	163	189
Basement / Floor– usual refurbishment	10,228	22,759	2,039	198	124	199	233
Basement / Floor– advanced refurbishment	10,228	22,759	2,039	198	124	199	233
Basement / Floor– other refurbishment 1	10,185	22,664	2,039	198	124	198	232

Refurbishment measures	Heat transfer [W]	Energy need – space heating [kWh/a]	Energy need – domestic hot water [kWh/a]	Total energy need [kWh/m²a]	Net primary energy per m² – heat pump [kWh/m²a]	Net primary energy per m² – solar thermal [kWh/m²a]	Net primary energy per m² – conventional gas [kWh/m²a]
Basement / Floor– other refurbishment 2	9,911	22,055	2,039	193	120	193	226
Basement / Floor– other refurbishment 3	9,735	21,663	2,039	190	119	190	222
Window – usual refurbishment	9,081	20,208	2,039	178	111	178	207
Window – advanced refurbishment	8,927	19,865	2,039	175	110	175	204
Door – usual refurbishment	10,485	23,332	2,039	203	127	204	239
Door – advanced refurbishment	10,455	23,266	2,039	202	127	203	239
ACTUAL STATE	10,665	23,733	2,039	206	129	207	243
USUAL REFURBISHMENT	6,551	14,578	2,039	133	83	132	150
ADVANCED REFURBISHMENT	5,861	13,042	2,039	121	75	119	134

To make the table easily understandable, energy need and net primary energy values are listed per m². The interim values are not relevant for the final results and therefore not listed in the table above. The domestic hot water demand is independent from various insulation measures, therefore it is constant in the table (2039 kWh/a).

The current energy performance values, which show the reference building without any insulation measure, are displayed in the line “ACTUAL STATE” above.

Some facts should be pointed out:

- The most profitable single insulation measure is “Wall – other refurbishment 3”. Here, 20 cm of thermal insulation is added to the building façade, which decreases the energy need per m² from 206 [kWh/m²a] to 164 [kWh/m²a].

- Taking into account the combination of several insulation measures (e.g. advanced refurbishment package), the energy need can be decreased to 121 [kWh/m²a] at its best.
- The lowest net primary energy demand per m² can be found for the variant with insulation measure on the wall (Wall – other refurbishment 3). The lowest value is reached for the variant of refurbishment on the wall in combination with heat pump.
- Due to the geographical location of the reference building, it should be noted that the use of a solar thermal system for heat supply is not the most optimal solution. The solar thermal system could only be used for the domestic hot water, but it is not sufficient for space heating and the portion supplied by the conventional heating system is still too big.

4.1.1.3 Calculation of global costs

The calculation of global costs is crucial for the economic analysis. The importance of energy costs for buildings and how building components can improve a building's energy performance (in other words reduce its energy needs) is clear. Obviously, in most cases, the initial investment grows by improving energy performances.

In this chapter, the calculation of global costs over a period of 30 years, all discounted to year zero (year 2014) is displayed. All calculated global costs are listed in the table below. These costs include envelope costs, which are related to the installation measures for building components, and costs related to heating systems. This separation of the costs shows the initial investments for each refurbishment and their influences on the global costs after 30 years. For a better understanding, global costs are listed per floor area per year. Based on this list, the connection of these values to their primary energies is shown in the following steps.

Table 4-9 Global costs of the single-family house in Sweden for each insulation measure and used heating system (discount rate = 2%, service factor = 1)

Refurbishment measures	**Envelope costs per floor area [€/m²]**	**Heat pumps – global costs after 30 years per floor area per year [€/m²a]**	**Solar thermal – global costs after 30 years per floor area per year [€/m²a]**	**Conventional gas – global costs after 30 years per floor area per year [€/m²a]**
Roof – usual refurbishment	109	439	729	709
Roof – advanced refurbishment	139	432	721	699
Roof – other refurbishment 1	93	441	732	712

Refurbishment measures	Envelope costs per floor area [€/m²]	Heat pumps – global costs after 30 years per floor area per year [€/m²a]	Solar thermal – global costs after 30 years per floor area per year [€/m²a]	Conventional gas – global costs after 30 years per floor area per year [€/m²a]
Roof – other refurbishment 2	125	436	726	704
Wall – usual refurbishment	77	406	689	662
Wall – advanced refurbishment	81	392	671	641
Wall – other refurbishment 1	77	402	684	657
Wall – other refurbishment 2	81	382	657	625
Wall – other refurbishment 3	101	367	636	601
Basement / Floor – usual refurbishment	50	444	736	716
Basement / Floor – advanced refurbishment	50	444	736	716
Basement / Floor – other refurbishment 1	53	443	734	714
Basement / Floor – other refurbishment 2	77	431	719	697
Basement / Floor – other refurbishment 3	101	423	710	687
Window – usual refurbishment	77	397	677	648
Window – advanced refurbishment	85	391	669	639
Door – usual refurbishment	5	456	749	732
Door – advanced refurbishment	6	455	748	730
ACTUAL STATE	0	465	759	742
USUAL REFURBISHMENT	318	313	543	497
ADVANCED REFURBISHMENT	361	294	506	456

Global costs for the individual heating systems are listed in Euros per m² per year. The table above shows the costs for a discount rate of 2%. The impact of the service factor is not considered. The impact of the discount rate and service factor will be discussed in the chapter "*Sensitivity analysis*".

Envelope costs and costs related to the heating systems are shown separately. Envelope costs are paid only in year zero. Global costs of the heating systems include investment costs and running costs, which need to be paid on an annual (rather than a monthly) basis. Therefore, for the calculation of the global costs, envelope costs should be added to the global costs of each heating system.

The following lists additional facts which cannot be deduced directly from the table (Table 4-9) above:

- The lowest running costs (maintenance and energy costs) apply to the variant with heat pumps, followed by the solar thermal system. In case of operation with a conventional heating system, the running costs are most expensive.
- As expected, a solar thermal system is not really profitable due to the geographical location of the house. The running costs are lower than the conventional heating system, but because of the high investment cost for the renewal of the heating system, it doesn’t make too much profit in the end.
- Only renewal of the heating system (without refurbishment of the building envelope) can save costs as a long-term investment. The global costs for a conventional heating system are €742/m²a, and for heat pumps they are €465/m²a for a period of 30 years. This means that, annually, €277/m² can be saved for this period.

4.1.1.4 Sensitivity analysis

A sensitivity analysis is carried out on the discount rates and service factors. The description and relevance of service factors and discount rates are discussed in chapters 3.7 and 3.8.

Please note that:

- The variation of the discount rate only influences the running costs and not the investment costs.
- The variation of service factor has an impact on the energy performance and therefore influences the investment and running costs.
- For the reference building, corresponding values of net primary energy include only space heating and domestic hot water.

In the figures below, the variation of three different service factors (fs =1, 0.85 and 0.55) is performed. This means that the discount rate has been varied by 1%, 2%, 3%, 7% and 10% for each service factor.

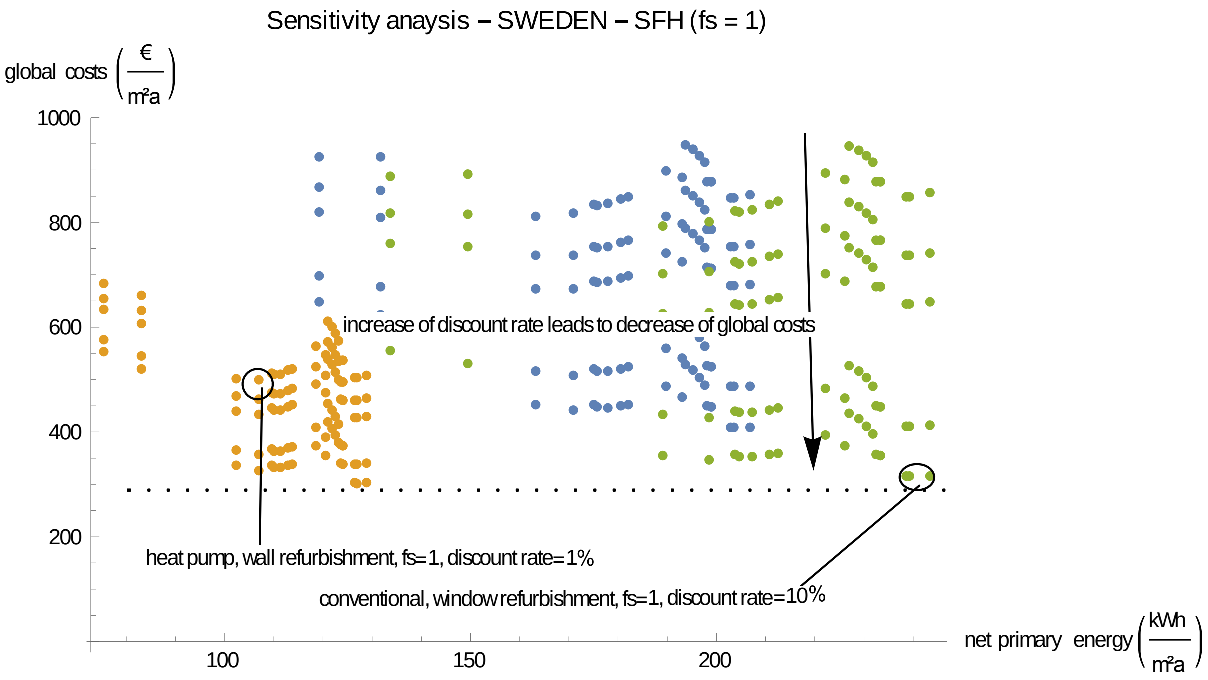

Figure 4-3 Sensitivity analysis of a single-family house in Sweden without the impact of service factor; orange points represent the use of heat pumps, blue points stand for solar thermal systems and green points illustrate conventional heating systems

If the service factor is neglected, the cost-optimal level is a combination of heat pump and refurbishment on the wall (adding 20 cm thermal insulation to the building façade). By increasing the discount rate, it becomes evident that any measures on the building envelope and on the heating system become unnecessary. In this case, all curves are very flat which means that any refurbishment measures are not profitable.

The cost-optimal point for the discount rate of 10% is applicable for the following combination:

- no renewal of the heating system and
- no refurbishment measure on any building component (or optional window refurbishment).

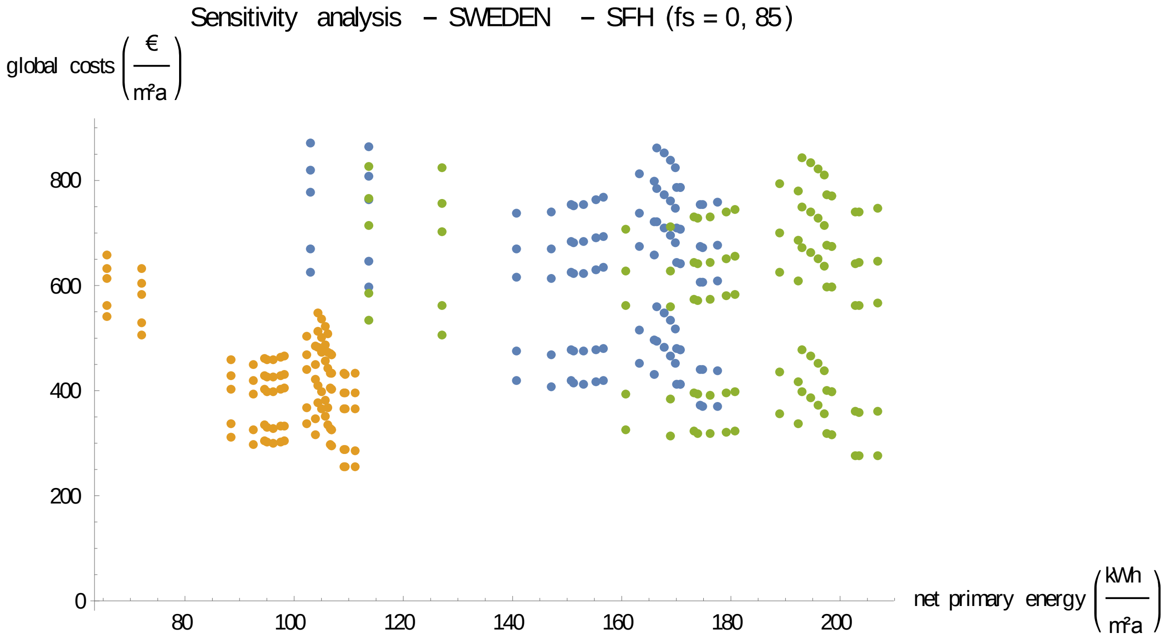

Figure 4-4 Sensitivity analysis of a single-family house in Sweden with service factor = 0.85; orange points represent the use of heat pumps, blue points stand for solar thermal systems and green points illustrate conventional heating systems

A decrease of the service factor leads to less influence of any refurbishment on the building envelope. Only a renewal of the heating system would be sufficient.

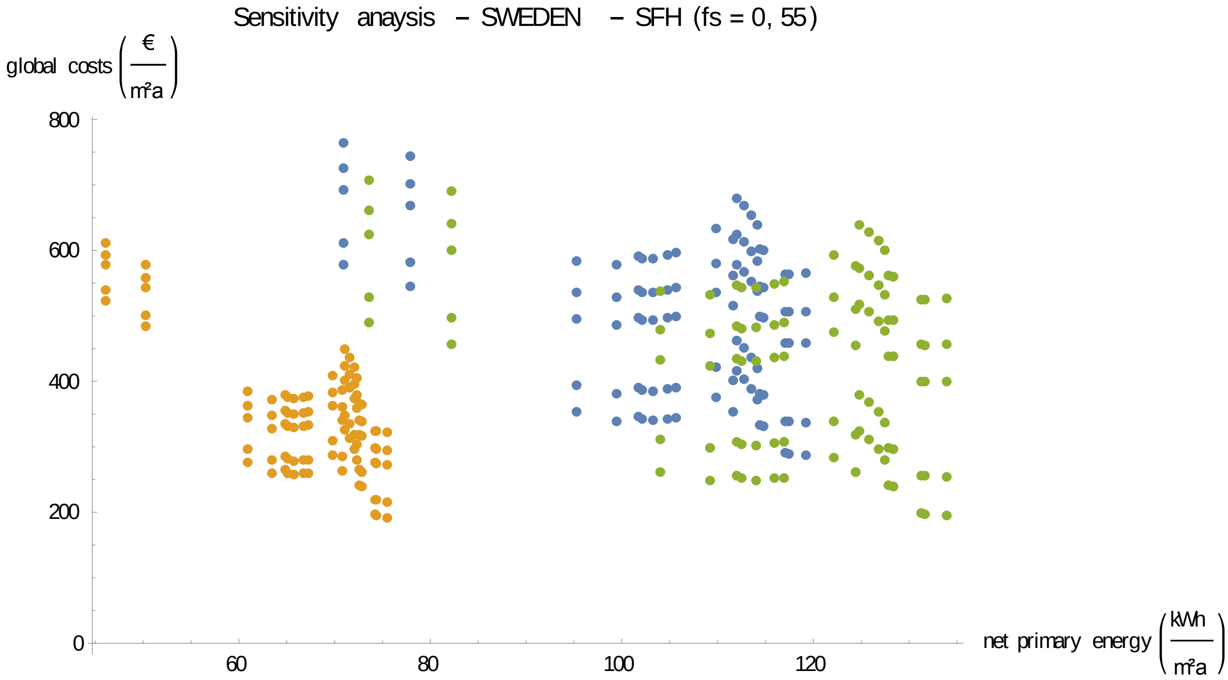

Figure 4-5 Sensitivity analysis of a single-family house in Sweden with service factor = 0.55; orange points represent the use of heat pumps, blue points stand for solar thermal systems and green points illustrate conventional heating systems

The following conclusions could be reached after thorough analysis of the figures:

- By decreasing the service factor, the net primary energy area is narrowing and the curves slope steeply. This is especially remarkable for the use of heat pumps.
- The influence of the discount rate is more noticeable for higher service factors and higher net primary energies. The impact on variants with heat pump is less than on the variants with conventional heating systems.
- By increasing the discount rate, the cost-optimal level moves from left to right, meaning from a lower net primary energy to a higher one.
- In general, heat pump heating systems perform better. These heating systems are also more independent from energy prices than conventional heating systems. By neglecting service factor, the refurbishment on the building façade should be taken into consideration.

All mentioned variations are shown in Figure 4-6 below. The cost-optimal levels apply to variants with lower service factors and higher discount rates.

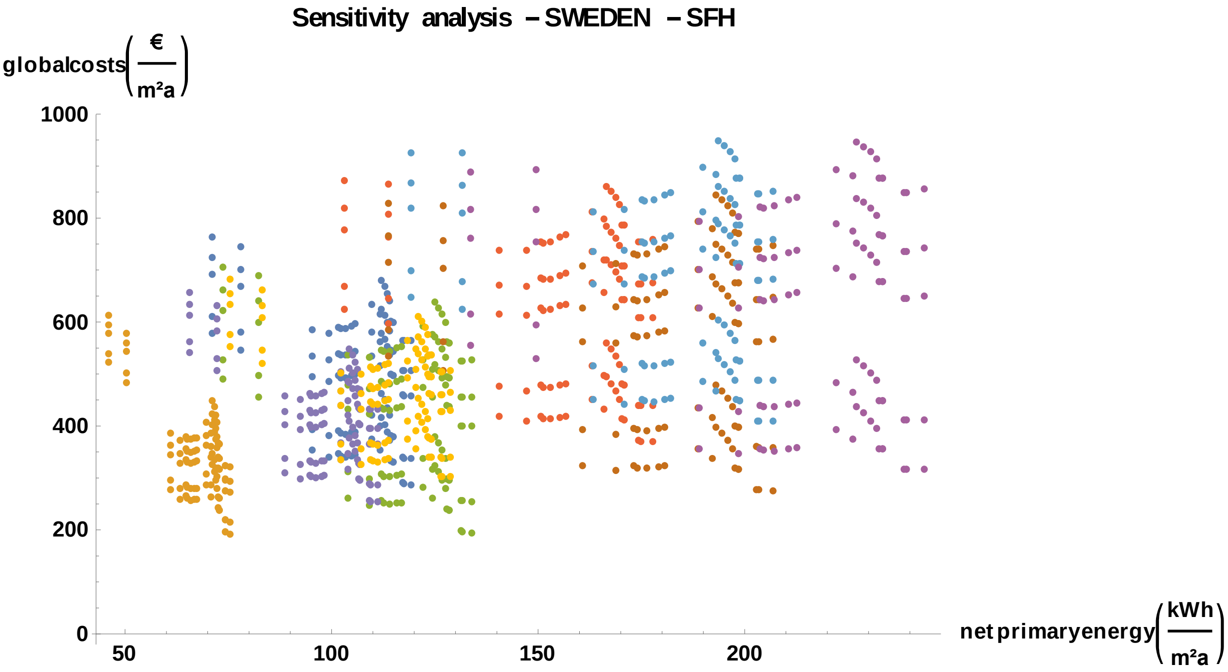

Figure 4-6 Sensitivity analysis of a single-family house in Sweden considering all variants (Combination of Figure 4-3, Figure 4-4 and Figure 4-5)

4.1.2 Slovenia

This chapter focuses on the case study for the single-family house in Slovenia for the illustration of cost-optimal level calculation. Below (Figure 4-7) is a photo of the single-family house.

Figure 4-7 Photo of the single-family house in Slovenia which is used as a reference building in this case study

The location of Ljubljana has been chosen for the calculation to represent the average Slovenian climate.

Basic information of the building is as follows:

- Location: Ljubljana
- Construction year(s): 1971 … 1980
- Conditioned floor area: 181 m²
- Lifetime of buildings components: 30 years
- Calculation period: 30 years
- Number of residents: 3

In addition to the general information listed above, the following input data is specified:

Table 4-10 List of input data for the single-family house in Slovenia

Input data	Temperature [°C]
Standard external temperature t_{an}	-16 °C
Average internal room temperature t_{im} (conditioned)	+20 °C
Average internal room temperature t_{im} (unconditioned e.g. roof)	-5 °C
Set-point (of the internal) temperature	+12 °C

Based on the general information and input data for the single-family house, heat degree days (HDD) are calculated. Therefore, *HDD* is *3675* [Kd].

Table 4-11 summarises the characteristics for the main building components of the single-family house in Slovenia, which is used as reference building for the calculations. The building data of current state, usual and advanced refurbishment are taken from TABULA WebTool. (TABULA, 2012). In this context, some adaptations on the building data and refurbishment packages have been elaborated to determine the cost-optimal levels. All refurbishment packages are defined in chapter 4.1.1.1.

Table 4-11 Characteristics of the (existing) single-family house in Slovenia

	Building components	Current state	U-value	[m²]
Single-family house in Slovenia	Roof	concrete ceiling with thin insulation (2 cm)	0.77	91.7
	Wall	honeycomb brick wall with thin insulation (3 cm)	0.7	149
	Basement / Floor	floor on ground with thin insulation (3 cm)	0.75	89.2
	Window	wooden window 2P	2.8	22.8
	Door	standard door, no insulation	2.2	7.7

As in further procedures, the usage and influence of solar thermal heating systems will be shown; here, I would like to create an overview of the global horizontal irradiation of Ljubljana. (Solar, 2015).

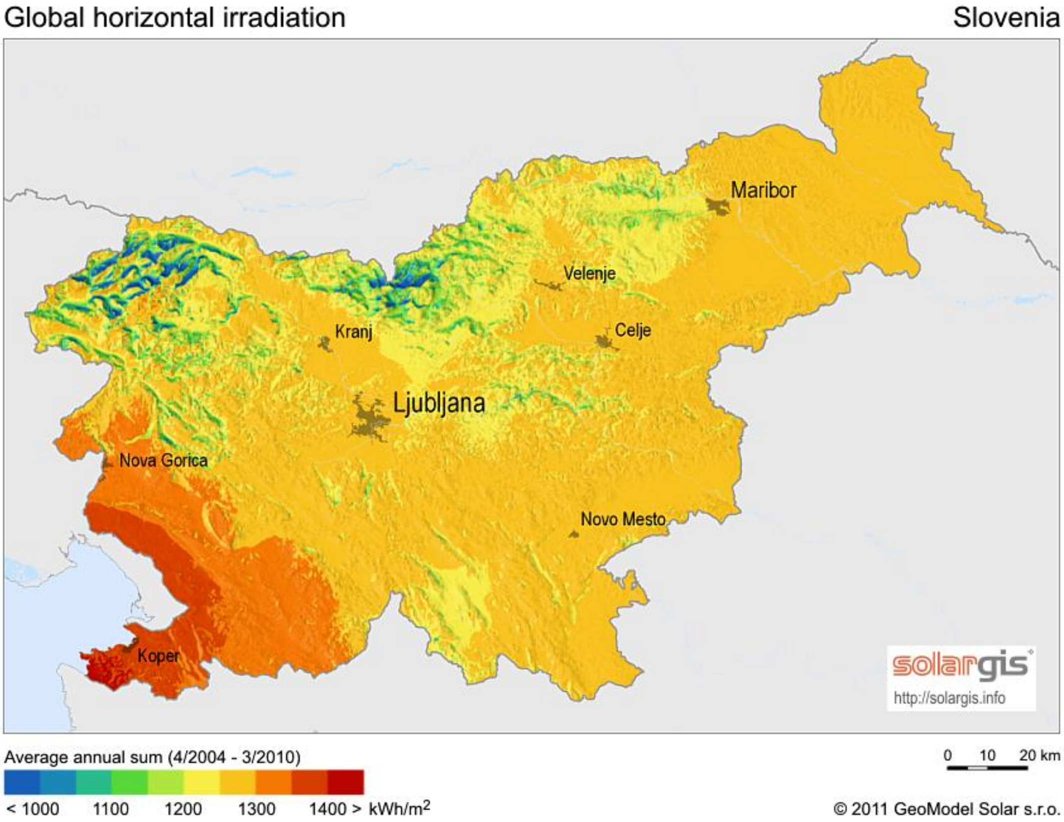

Figure 4-8 Global horizontal irradiation – Slovenia[17]

The figure shows the global horizontal irradiation of Ljubljana as $H\,(Ljubljana) = 1250$ (Solar, 2015). This value (H) was taken from the solargis website.

For the calculation of the reference building's energy performance, annual global horizontal irradiation needs to be considered. According to (Nielsen, 2011), the annual global horizontal solar irradiation in Ljubljana at collector output is $490\ [\frac{kWh}{m^2}]$.

4.1.2.1 Definition of refurbishment measures

The different thermal installation measures are defined in this chapter. In total, five different refurbishment packages are created. Usual and advanced refurbishment packages reflect the values from TABULA WebTool[18]. Other installation measures, named "*other refurbishment packages*" were derived from available data on TABULA WebTool and

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[17] http://solargis.info/imaps/#loc=46.056422,14.492477&c=45.777636,15.20084&z=9 (last accessed on 28th December 2015)

[18] http://webtool.building-typology.eu/ (last accessed on 23rd December 2015)

calculated. Each package includes various installation measures like installation of roof, walls, cellar ceiling and thermally improved windows/doors. In addition to the defined refurbishment packages, the renewal of heat supply systems was taken into consideration. For the determination of cost-optimal levels, each installation measure is taken into account separately.

The tables listed below give an overview about the protection standards of the building components and improved U-values after refurbishment.

Table 4-12 SI-SFH Variant 1 – Usual refurbishment with respective insulation measures and U-values[19]

Building component	U-value	Insulation measure
Roof	0.3	add 8 cm of insulation (external insulated render system)
Wall	0.19	add 15 cm of insulation (external insulated render system)
Basement / Floor	0.35	add 6 cm of insulation below / alternatively: on top of ceiling (in case of floor renovation)
Window	1.4	mount new windows, double glazed, argon filled, low E
Door	2.2	no refurbishment

Table 4-13 SI-SFH Variant 2 – Advanced refurbishment with respective insulation measures and U-values[20]

Building component	U-value	Insulation measure
Roof	0.16	add 20 cm of insulation (external insulated render system)
Wall	0.16	add 20 cm of insulation (external insulated render system)
Basement / Floor	0.23	add 12 cm of insulation below (in case of sufficient cellar height) / alternatively: on top of ceiling (in case of floor renovation) or combination of both
Window	1.1	mount new windows, triple glazed, argon filled, low E
Door	0.95	replacement of doors

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[19] Source: http://webtool.building-typology.eu/ (last accessed on 23rd December 2015)
[20] Source: http://webtool.building-typology.eu/ (last accessed on 23rd December 2015)

U-values for Variants 3-5 were calculated according the correlation of U-values with insulation thickness. For calculation details, please refer to chapter 3.6.

Table 4-14 SI-SFH Variant 3 – Other refurbishment with respective insulation measures and U-values

Building component	U-value	Insulation measure
Roof	0.13	25 cm of thermal insulation
Wall	0.23	10 cm of thermal insulation
Basement / Floor	0.38	5 cm of thermal insulation

Table 4-15 SI-SFH Variant 4 – Other refurbishment with respective insulation measures and U-values

Building component	U-value	Insulation measure
Roof	0.12	30 cm of thermal insulation
Wall	0.14	25 cm of thermal insulation
Basement / Floor	0.25	10 cm of thermal insulation

Table 4-16 SI-SFH Variant 5 – Other refurbishment with respective insulation measures and U-values

Building component	U-value	Insulation measure
Wall	0.12	30 cm of thermal insulation
Basement / Floor	0.19	15 cm of thermal insulation

Furthermore, the impact of different heating systems in combination with each insulation measure has been assessed. The considered heating systems are listed below:

- Conventional heat supply systems – condensing boiler (gas) – currently in use
- Heat pump (ground source heat pump)
- Solar thermal heating system

Due to the fact that a solar thermal system alone is not sufficient to comply with the energy need of the whole reference building (a solar coverage ratio of 20% has been estimated), this system is combined with a conventional heating system, meaning that this system needs to be considered divalent. The other two heating systems are rated as monovalent in the calculation.

4.1.2.2 Calculation of energy performance

Based on the general information, input data, refurbishment packages and chosen heating system, the following values for the net primary energy demand are calculated.

Table 4-17 Energy performance of the single-family house in Slovenia

Refurbishment measures	**Heat transfer [W]**	**Energy need – space heating [kWh/a]**	**Energy need – domestic hot water [kWh/a]**	**Total energy need [kWh/m^2a]**	**Net primary energy per m^2 – heat pump [kWh/m^2a]**	**Net Primary energy per m^2 – solar thermal [kWh/m^2a]**	**Net primary energy per m^2 – conventional gas [kWh/m^2a]**
Roof – usual refurbishment	11,985	29,363	2,039	173	108	175	208
Roof – advanced refurbishment	11,664	28,576	2,039	169	106	170	202
Roof – other refurbishment 1	11,604	28,430	2,039	168	105	169	201
Roof – other refurbishment 2	11,561	28,325	2,039	168	105	169	201
Wall – usual refurbishment	10,327	25,300	2,039	151	94	152	179
Wall – advanced refurbishment	10,166	24,906	2,039	149	93	149	176
Wall – other refurbishment 1	10,562	25,877	2,039	154	96	155	183
Wall – other refurbishment 2	10,049	24,619	2,039	147	92	148	174
Wall – other refurbishment 3	9,960	24,401	2,039	146	91	147	173

Refurbishment measures	Heat transfer [W]	Energy need – space heating [kWh/a]	Energy need – domestic hot water [kWh/a]	Total energy need [kWh/m^2a]	Net primary energy per m^2 – heat pump [kWh/m^2a]	Net Primary energy per m^2 – solar thermal [kWh/m^2a]	Net primary energy per m^2 – conventional gas [kWh/m^2a]
Basement / Floor– usual refurbishment	11,778	28,856	2,039	171	107	172	204
Basement / Floor– advanced refurbishment	11,392	27,912	2,039	165	103	167	198
Basement / Floor– other refurbishment 1	11,866	29,072	2,039	172	107	173	206
Basement / Floor– other refurbishment 2	11,464	28,086	2,039	166	104	168	199
Basement / Floor– other refurbishment 3	11,262	27,592	2,039	164	102	165	195
Window – usual refurbishment	11,913	29,187	2,039	173	108	174	207
Window – advanced refurbishment	11,667	28,584	2,039	169	106	170	202
Door – usual refurbishment	13,062	32,003	2,039	188	118	190	227
Door – advanced refurbishment	12,716	31,154	2,039	183	115	185	221
ACTUAL STATE	13,062	32,003	2,039	188	118	190	227
USUAL REFURBISHMENT	6,816	16,698	2,039	104	65	103	118
ADVANCED REFURBISHMENT	5,356	13,121	2,039	84	52	83	93

To make the table easily understandable, energy need and net primary energy values are listed per m^2. The interim values are not relevant for the final results and therefore not listed in the table above. The domestic hot water demand is independent from various insulation measures, therefore it is constant in the table (2039 kWh/a).

The current energy performance values, which show the reference building without any insulation measure, are displayed in the line “ACTUAL STATE” above.

Some facts should be pointed out:

- In addition to the combined insulation measure packages (e.g. usual and advanced refurbishment), more profitable single insulation measures are those which are done on the walls. The best case is “Wall – other refurbishment 3”. Here, 30 cm of thermal insulation is added to the building façade, which decreases the energy need per m² from 188 [kWh/m²a] to 146 [kWh/m²a].
- Taking into account the combination of several insulation measures (e.g. advanced refurbishment package), the energy need can be decreased to 84 [kWh/m²a] at its best.
- The lowest net primary energy demand per m² can be found for the variant with insulation measure on the wall (Wall – other refurbishment 3). The lowest value is reached for the variant of refurbishment on the wall in combination with heat pump.
-

4.1.2.3 Calculation of global costs

All calculated global costs are listed in the table below. These costs include envelope costs, which are related to the installation measures for building components, and costs related to heating systems.

Table 4-18 Global costs of the single-family house in Slovenia for each insulation measure and used heating system (discount rate = 1%, service factor = 1)

Refurbishment measures	Envelope costs per floor area [€/m²]	Heat pumps – global costs after 30 years per floor area per year [€/m²a]	Solar thermal – global costs after 30 years per floor area per year [€/m²a]	Conventional gas – global costs after 30 years per floor area per year
Roof – usual refurbishment	43	445	538	521
Roof – advanced refurbishment	55	442	541	522
Roof – other refurbishment 1	59	443	543	525
Roof – other refurbishment 2	64	445	546	527
Wall – usual refurbishment	93	423	538	515
Wall – advanced refurbishment	103	427	544	520
Wall – other refurbishment 1	83	421	535	513
Wall – other refurbishment 2	109	427	546	521

Refurbishment measures	Envelope costs per floor area [€/m²]	Heat pumps – global costs after 30 years per floor area per year [€/m²a]	Solar thermal – global costs after 30 years per floor area per year [€/m²a]	Conventional gas – global costs after 30 years per floor area per year
Wall – other refurbishment 3	111	427	546	520
Basement / Floor – usual refurbishment	16	408	505	487
Basement / Floor – advanced refurbishment	24	398	501	482
Basement / Floor – other refurbishment 1	15	411	507	490
Basement / Floor – other refurbishment 2	20	397	499	480
Basement / Floor – other refurbishment 3	28	396	501	481
Window – usual refurbishment	50	448	543	526
Window – advanced refurbishment	55	442	540	522
Door – usual refurbishment	0	459	527	515
Door – advanced refurbishment	17	457	534	520
ACTUAL STATE	0	459	527	515
USUAL REFURBISHMENT	202	427	540	504
ADVANCED REFURBISHMENT	254	449	547	507

Global costs for the individual heating systems are listed in Euros per m² per year. The table above shows the costs for a discount rate of 1%. The impact of the service factor is not considered. The impact of changing the discount rate and service factor will be discussed in the chapter “*Sensitivity analysis*”.

Envelope costs and costs related to the heating systems are shown separately. Envelope costs are paid only in year zero. Global costs of the heating systems include investment costs and running costs, which need to be paid on an annual (rather than a monthly) basis. Therefore, for the calculation of the global costs, envelope costs should be added to the global costs of each heating system.

The following lists additional facts which cannot be deduced directly from the table (Table 4-18) above.

- The lowest running costs (maintenance and energy costs) apply to the variant with heat pumps, followed by the solar thermal system. The highest costs are incurred with the conventional heating system. As an example, the annual costs in consideration of refurbishment on the wall (Wall – other refurbishment 3) for the use

of a heat pump are €1,192, for the solar thermal system they are €1,871 and for the conventional heating system they are €2,271.
- Due to the geographical location of the house, a solar thermal system is more profitable than in Sweden but still not sufficient for the purpose. The running costs for a solar thermal system are lower than for the conventional heating system but considering the high investment costs for the renewal of the heating system, it doesn't make too much profit in the end.
- Only a renewal of the heating system (without refurbishment on the building envelope) can save costs as a long-term investment. The global costs for a conventional heating system are €515/m²a, and for heat pumps they are €459/m²a for a period of 30 years.

4.1.2.4 Sensitivity analysis

A sensitivity analysis is carried out on the discount rates and service factors. The description and meaning of service factors and discount rates are described in chapter 3.7 and 3.8.

Please note that:

- The variation of the discount rate only influences the running costs and not the investment costs.
- The variation of service factor has an impact on the energy performance and therefore influences the investment and running costs.
- For the reference building, corresponding values of net primary energy include only space heating and domestic hot water.

In the figures below, the variation of three different service factors (fs =1, 0.85 and 0.55) is performed. This means that the discount rate has been varied by 1%, 2%, 3%, 7% and 10% for each service factor.

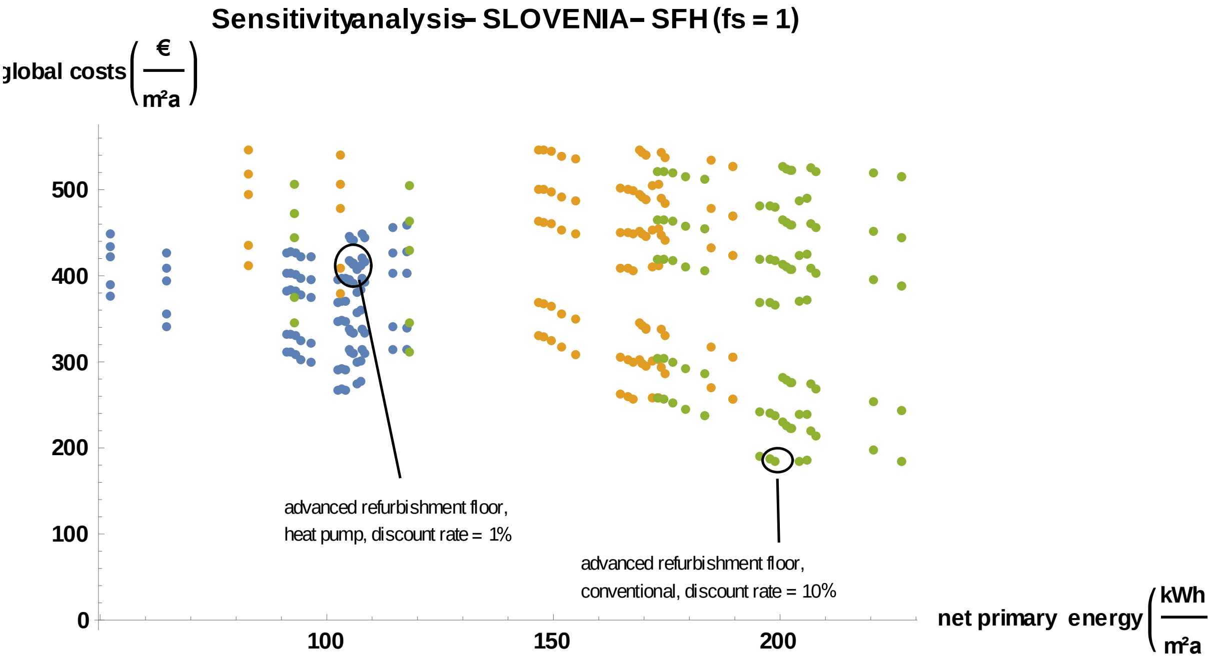

Figure 4-9 Sensitivity analysis of a single-family house in Slovenia without the impact of service factor; blue points represent the use of heat pumps, orange points stand for solar thermal systems and green points illustrate conventional heating systems

If the service factor is neglected, the cost-optimal level is a combination of heat pump and and advanced refurbishment on the basement/floor (add 12 cm of insulation below (in case of sufficient cellar height) / alternatively: on top of ceiling (in case of floor renovation) or a combination of both). By increasing the discount rate, it becomes evident that any measures on the heating system become unnecessary, because all curves are almost at the same level. The cost-optimal point is still reached with the same insulation measure (i.e. floor renovation) but the heating system switches from heat pumps to conventional heating systems. Cost-optimal points for the discount rate at 1% and 10% are shown in the figure (Figure 4-9) above.

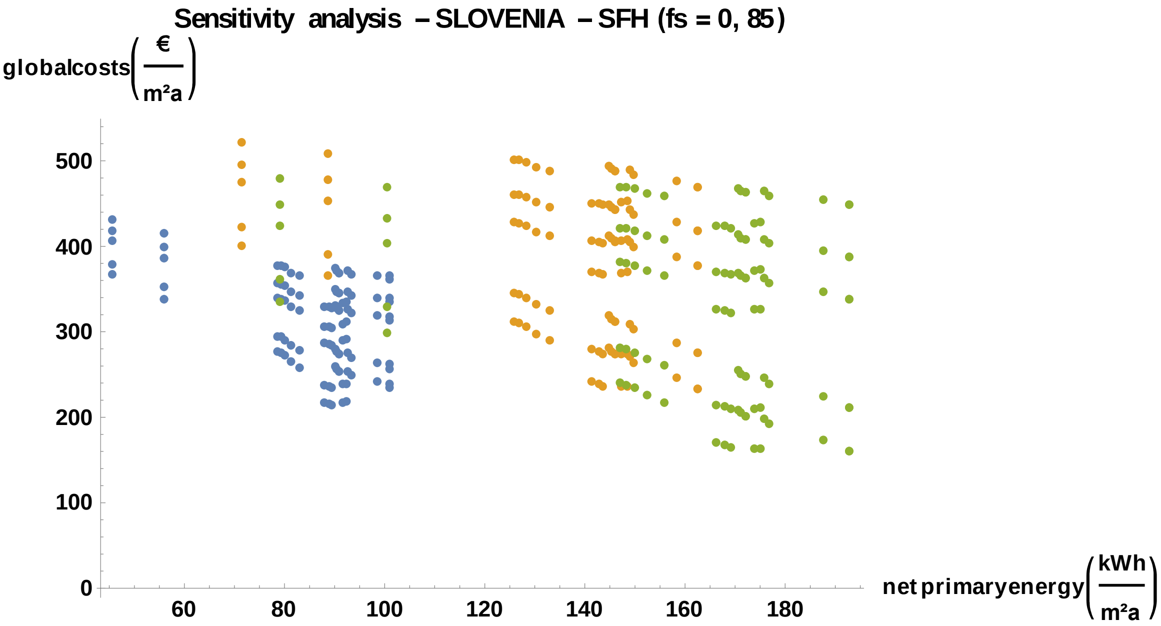

Figure 4-10 Sensitivity analysis for a single-family house in Slovenia with service factor = 0.85; blue points represent the use of heat pumps, orange points stand for solar thermal systems and green points illustrate conventional heating systems

A decrease of the service factor leads to less influence of any refurbishment on the building envelope. Although the net primary energy is decreasing, the global costs are increasing.

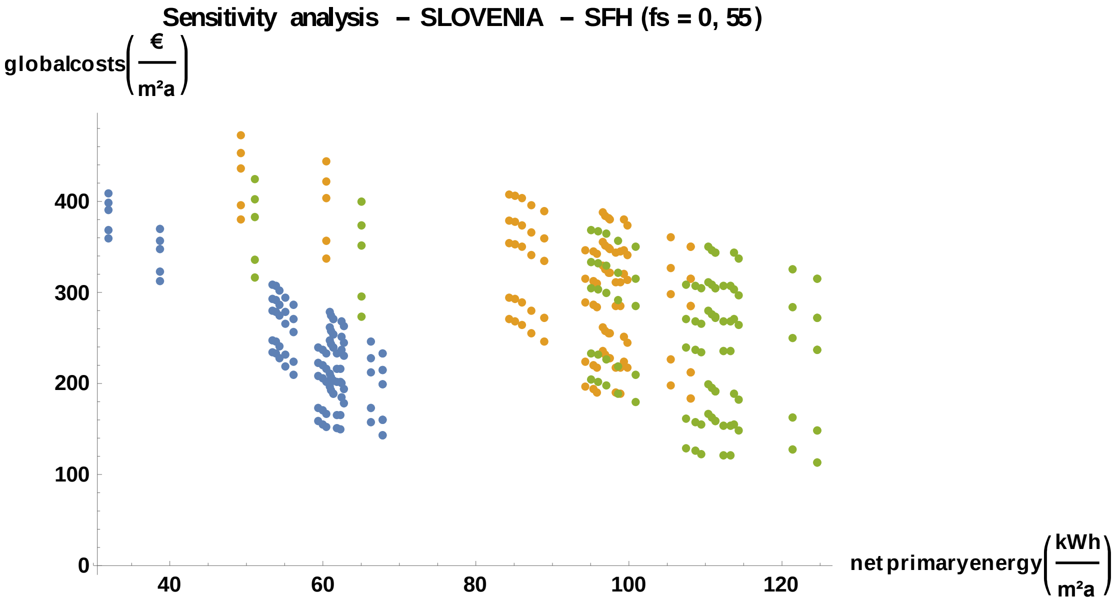

Figure 4-11 Sensitivity analysis for a single-family house in Slovenia with service factor = 0.55; blue points represent the use of heat pumps, orange points stand for solar thermal systems and green points illustrate conventional heating systems

The following conclusions could be reached after thorough analysis of the figures:

- By decreasing the service factor, the net primary energy area is narrowing and the curves slope steeply. E.g. if the service factor is neglected, net primary energies are between 52 [kWh/m²a] and 118 [kWh/m²a]. For service factor = 0.55, this value is between 32 [kWh/m²a] and 68 [kWh/m²a].
- The influence of the discount rate is more noticeable for higher service factors and higher net primary energies.
- By increasing the discount rate, the cost-optimal level moves from left to right, meaning from a lower net primary energy to a higher one. On the other hand, the global cost difference between heat pumps and conventional heating systems is getting smaller.
- In general, heat pump heating systems perform better. By neglecting the service factor, the refurbishment on the floor/basement should be taken into consideration.

All mentioned variations are shown in Figure 4-12. The overall cost-optimality point applies to variants with lower service factor (0.55) and use of a conventional heating system.

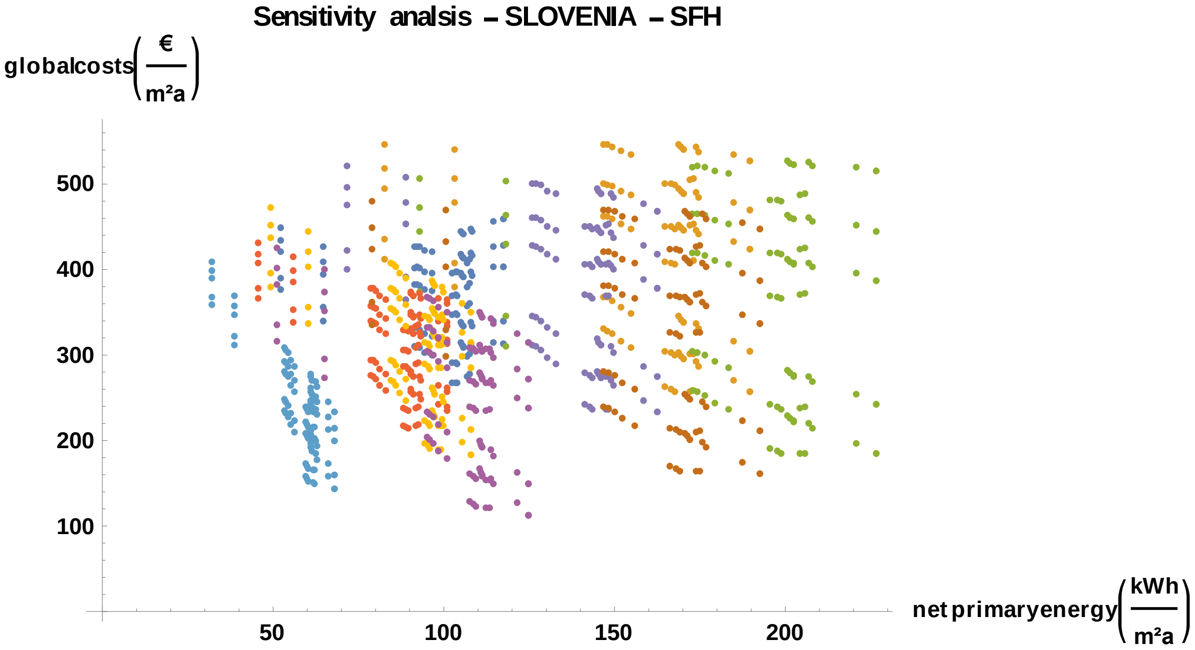

Figure 4-12 Sensitivity analysis of a single-family house in Slovenia considering all variants (Combination of Figure 4-9, Figure 4-10 and Figure 4-11)

4.2 Multi-family houses

4.2.1 Sweden

This chapter illustrates the calculation of cost-optimal levels based on a case study for a multi-family house in Sweden. A photo (Figure 4-13) of the multi-family house is displayed below.

Figure 4-13 Photo of the multi-family house in Sweden which is used as a reference building in the case study

The location of Stockholm has been chosen for the calculation to represent a Swedish climate average.

Basic information of the reference building is as follows:

Location:	Stockholm
Construction year(s):	1960
Conditioned floor area:	700 m²
Number of apartments:	7
Residents per apartment:	3 persons (total: 30 persons)
Lifetime of buildings components:	30 years
Calculation period:	30 years

In addition to the general information listed above, the following input data is specified:

Table 4-19 List of input data for the multi-family house in Sweden

Input data	Temperature [°C]
Standard external temperature t_{an}	-30 °C
Average internal room temperature t_{im} (conditioned)	+20 °C
Average internal room temperature t_{im} (unconditioned e.g. roof)	-5 °C
Set-point (of the internal) temperature	+12 °C

Based on the general information and input data for the multi-family house, heat degree days (HDD) are calculated. Therefore, *HDD* is *4636* [Kd].

Table 4-20 summarises the characteristics for the main building components of the multi-family house in Sweden, which is used as reference building for the calculations. The building data of the current state, usual and advanced refurbishment are taken from TABULA WebTool. (TABULA, 2012). In this context, some adaptations on the building data and refurbishment packages have been elaborated to determine the cost-optimal levels. All refurbishment packages are defined in chapter 4.2.1.1.

Table 4-20 Characteristics of the (existing) multi-family house in Sweden

	Building components	Current state	U-value	[m²]
Multi-family house in Sweden	Roof	horizontal wind	0.36	235
	Wall 1	no data available wall multi-family house ...1960	0.58	280
	Wall 2 (basement wall)	no data available Basement wall	0.7	120
	Floor	concrete slab	0.32	235
	Window	Window	2.22	90
	Door	Door	3	5

For data of the global horizontal irradiation of Stockholm, please refer to chapter (4.1.1) where the cost-optimal levels of a single-family house in Sweden were calculated in a case study. (Solar, 2015)

4.2.1.1 Definition of refurbishment measures

The different thermal installation measures are defined in this chapter. In total, five different refurbishment packages are created. Usual and advanced refurbishment packages reflect the values from TABULA WebTool[21]. Other installation measures named “*other refurbishment packages*” were derived from available data on TABULA WebTool and calculated. Each package includes various installation measures like installation of roof, walls, cellar ceiling, and thermally improved windows/doors. In addition to the defined refurbishment packages, the renewal of heat supply systems was taken into consideration. For the determination of cost-optimal levels, each installation measure is taken into account separately.

The tables listed below give an overview about the protection standards of the building components and improved U-values after refurbishment.

Table 4-21 SE-MFH Variant 1 – Usual refurbishment with respective insulation measures and U-values[22]

Building component	U-value	Insulation measure
Roof	0.12	add 200 mm of insulation, loose wool
Wall 1	0.29	add 50 mm of insulation / brick
Wall 2 (basement wall)	0.7	no insulation measure
Floor	0.24	add 40 mm of insulation
Window	0.9	new window, 3 glazed
Door	1.2	new door

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[21] http://webtool.building-typology.eu/ (last accessed on 23rd December 2015)
[22] Source: http://webtool.building-typology.eu/ (last accessed on 23rd December 2015)

Table 4-22 SE-MFH Variant 2 – Advanced refurbishment with respective insulation measures and U-values[23]

Building component	U-value	Insulation measure
Roof	0.06	add 500 mm of insulation, loose wool
Wall 1	0.09	add 300 mm of insulation / brick
Wall 2 (basement wall)	0.39	add 40 mm of insulation
Floor	0.23	add 45 mm of insulation
Window	0.76	new window, 2 + 2 glazed
Door	0.9	new door

U-values for variants 3-5 were calculated according to the correlation of U-values with insulation thickness. For calculation details, please refer to chapter 3.6.

Table 4-23 SE-MFH Variant 3 – Other refurbishment with respective insulation measures and U-values

Building component	U-value	Insulation measure
Roof	0.19	add 100 mm of insulation, loose wool
Wall 1	0.42	15 cm of thermal insulation
Floor	0.22	5 cm of thermal insulation

Table 4-24 SE-MFH Variant 4 – other refurbishment with respective insulation measures and U-values

Building component	U-value	Insulation measure
Roof	0.10	add 300 mm of insulation, loose wool
Wall 1	0.12	20 cm of thermal insulation
Floor	0.16	10 cm of thermal insulation

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[23] Source: http://webtool.building-typology.eu/ (last accessed on 23rd December 2015)

Table 4-25 SE-MFH Variant 5 – Other refurbishment with respective insulation measures and U-values

Building component	U-value	Insulation measure
Wall 1	0.10	25 cm of thermal insulation
Floor	0.12	15 cm of thermal insulation

Furthermore, the impact of different heating systems in combination with each insulation measure has been assessed. The considered heating systems are listed below:

- Conventional heat supply systems – condensing boiler (gas) – currently in use
- Heat pump (ground source heat pump)
- Solar thermal heating system

Due to the size of the building and its high energy need, a solar thermal system is not sufficient for space heating. The solar thermal system is only used for the supply of domestic hot water; therefore, it is combined with a conventional heating system, which means that this system is divalent. The other two heating systems are rated as monovalent in the calculation.

4.2.1.2 Calculation of energy performance

Based on the general information, input data, refurbishment packages and chosen heating system, the following values for the net primary energy demand are calculated.

Table 4-26 Energy performance of the multi-family house in Sweden

Refurbishment measures	Heat transfer [W]	Energy need – space heating [kWh/a]	Energy need – domestic hot water [kWh/a]	Total energy need [kWh/m^2a]	Net primary energy per m^2 – heat pump [kWh/m^2a]	Net primary energy per m^2 – solar thermal [kWh/m^2a]	Net primary energy per m^2 – conventional gas [kWh/m^2a]
Roof – usual refurbishment	39,481	87,855	14,274	146	91	139	161
Roof – advanced refurbishment	39,128	87,071	14,274	145	90	138	159
Roof – other refurbishment 1	39,883	88,752	14,274	147	92	140	163
Roof – other refurbishment 2	39,343	87,549	14,274	145	91	138	160
Wall 1 – usual refurbishment	36,831	81,958	14,274	137	86	130	150
Wall 1 – advanced refurbishment	34,031	75,728	14,274	129	80	121	139
Wall 2 (basement wall) – advanced refurbishment	39,031	86,854	14,274	144	90	137	159
Wall 1 – other refurbishment 1	38,664	86,039	14,274	143	90	136	158
Wall 1 – other refurbishment 2	34,511	76,796	14,274	130	81	122	141
Wall 1 – other refurbishment 3	34,232	76,176	14,274	129	81	122	140
Floor – usual refurbishment	39,951	88,901	14,274	147	92	140	163
Floor– advanced refurbishment	39,833	88,640	14,274	147	92	140	162
Floor– other refurbishment 1	39,725	88,399	14,274	147	92	139	162
Floor– other refurbishment 2	38,984	86,750	14,274	144	90	137	159
Floor– other refurbishment 3	38,572	85,833	14,274	143	89	136	157
Window – usual refurbishment	34,951	77,775	14,274	131	82	124	142
Window – advanced refurbishment	34,321	76,373	14,274	129	81	122	140
Door – usual refurbishment	40,441	89,992	14,274	149	93	142	165
Door – advanced refurbishment	40,366	89,825	14,274	149	93	142	165
ACTUAL STATE	40,891	90,993	14,274	150	94	143	167
USUAL REFURBISHMENT	28,091	62,509	14,274	110	69	102	114
ADVANCED REFURBISHMENT	22,256	49,525	14,274	91	57	83	91

To make the table easily understandable, energy need and net primary energy values are listed per m². The interim values are not relevant for the final results and therefore not listed in the table above.

The domestic hot water calculation was based on seven apartments and three residents per apartment. As domestic hot water demand is independent from insulation measures, it remains constant in the table (14,274 kWh/a).

Please note that a total collector surface of 50 m² is stipulated for the use of a solar thermal system for the supply of domestic hot water. Considering to the geographical location of the building, a total usable energy of 14,348 kWh/a can be obtained by adding electrical support energy of 2,792 kWh/a.

The current energy performance values, which show the reference building without any insulation measure, are displayed in the line "ACTUAL STATE" above.

Some facts should be pointed out:

- In addition to the combined insulation measure packages (e.g. usual and advanced refurbishment), the single more profitable insulation measures are refurbishments on the walls and windows. These measures can decrease the energy need per m² from 150 [kWh/m²a] to 129 [kWh/m²a].
- Taking into account the combination of several insulation measures (e.g. advanced refurbishment package), the energy need can be decreased to 57 [kWh/m²a] at best.
- The lowest net primary energy demand per m² for a single insulation measure can be found for the variant on the building wall (Wall – advanced refurbishment) in combination with a heat pump as the heating system. The net primary energy for this variant is 80 [kWh/m²a].

4.2.1.3 Calculation of global costs

All calculated global costs are listed in the table below. These costs include envelope costs, which are related to the installation measures for building components, and costs related to heating systems.

Table 4-27 Global costs of the multi-family house in Sweden for each insulation measure and used heating system (discount rate = 1%, service factor = 1)

Refurbishment measures	Envelope costs per floor area [€/m²]	Heat pumps – global costs after 30 years per floor area per year [€/m²a]	Solar thermal – global costs after 30 years per floor area per year [€/m²a]	Conventional gas – global costs after 30 years per floor area per year
Roof - usual refurbishment	37	375	571	579
Roof – advanced refurbishment	47	373	567	575
Roof – other refurbishment 1	28	378	576	584
Roof – other refurbishment 2	42	374	569	577
Wall 1 – usual refurbishment	39	356	539	547
Wall 1 – advanced refurbishment	54	337	504	512
Wall 2 (basement wall) – advanced refurbishment	17	370	561	569
Wall 1 – other refurbishment 1	45	369	561	569
Wall 1 – other refurbishment 2	50	340	510	518
Wall 1 – other refurbishment 3	53	338	507	515
Floor – usual refurbishment	17	378	577	585
Floor – advanced refurbishment	17	378	575	583
Floor – other refurbishment 1	11	377	574	582
Floor – other refurbishment 2	14	372	565	573
Floor – other refurbishment 3	19	369	560	568
Window – usual refurbishment	56	343	516	524
Window – advanced refurbishment	62	339	508	516
Door – usual refurbishment	2	382	583	591
Door – advanced refurbishment	3	381	582	590
ACTUAL STATE	0	385	588	596
USUAL REFURBISHMENT	150	295	431	439
ADVANCED REFURBISHMENT	199	253	360	368

Global costs for the individual heating systems are listed in Euros per m² per year. The table above shows the costs for a discount rate of 1%. The impact of the service factor is not considered. The impact changing the discount rate and service factor will be discussed in the chapter “*Sensitivity analysis*”.

Envelope costs and costs related to the heating systems are shown separately. Envelope costs are paid only in year zero. Global costs of the heating systems include investment costs and running costs, which need to be paid on an annual (rather than a monthly) basis. Therefore, for the calculation of the global costs, envelope costs should be added to the global costs of each heating system.

The following lists additional facts which cannot be deduced directly from the table (Table 4-27) above.

- The lowest running costs (maintenance and energy costs) apply to the variant with heat pumps. These costs are almost half compared to other heating systems.
- The difference of annual costs between solar thermal and conventional heating systems is not considerable.
- The highest running costs are reached when a conventional heating system is used. E.g. for the refurbishment on the wall (Wall – advanced refurbishment), the annual costs are €5,397 for heat pumps, €10,395 for solar thermal systems and €11,903 for conventional heating systems.
- Due to the geographical location of the house, a solar thermal system is not really profitable, which was expected. Even the running costs are not considerably lower than for the conventional heating system. Additionally, a high investment cost for the renewal of the heating system needs to be considered so that it does not seem very profitable.
- Only the renewal of the heating system (without refurbishment on the building envelope) can save costs as a long-term solution. The global costs for a conventional heating system are €596m²a and €385/m²a for heat pumps for a period of 30 years.

4.2.1.4 Sensitivity analysis

A sensitivity analysis is carried out on the discount rates and service factors. The description and meaning of service factors and discount rates are described in chapter 3.7 and 3.8.

Please note that:

- The variation of the discount rate only influences the running costs and not the investment costs.
- The variation of service factor has an impact on the energy performance and therefore influences the investment and running costs.
- For the reference building, corresponding values of net primary energy include only space heating and domestic hot water.

In the figures below, the variation of three different service factors (fs =1, 0.85 and 0.55) is performed. This means that the discount rate has been varied by 1%, 2%, 3%, 7% and 10% for each service factor.

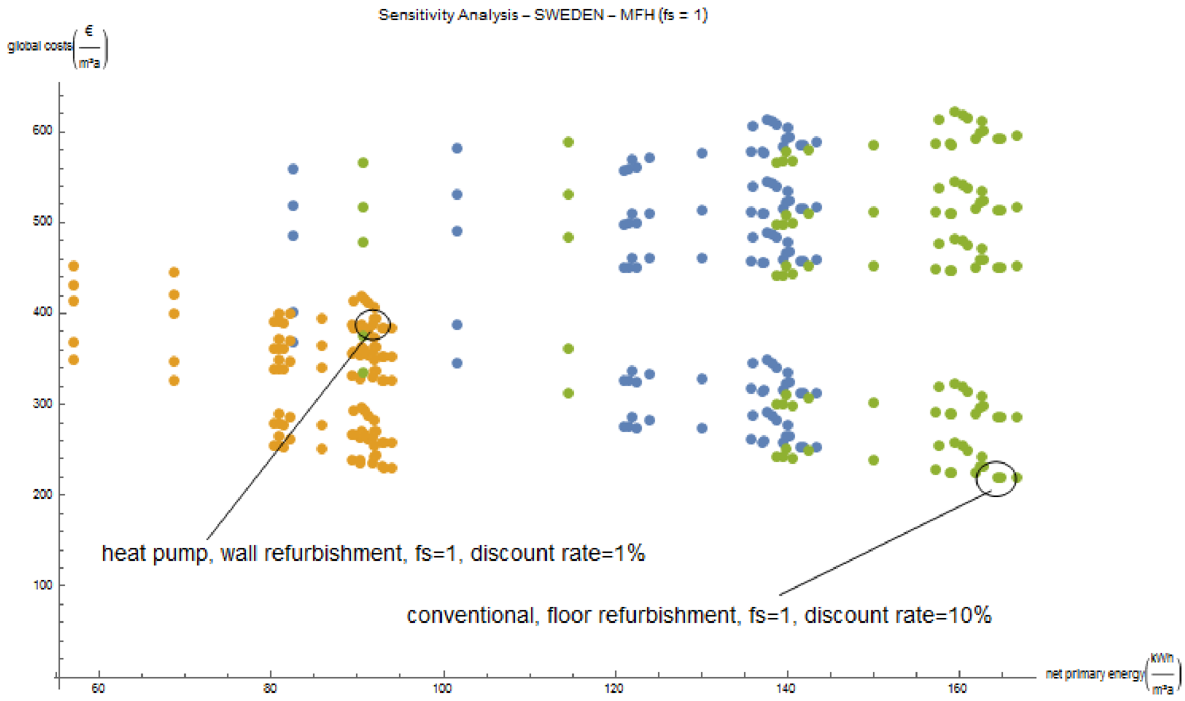

Figure 4-14 Sensitivity analysis of a multi-family house in Sweden without the impact of service factor; orange points represent heat pumps, blue points stand for solar thermal systems and green points illustrate conventional heating systems

If the service factor is neglected, the cost-optimal level is a combination of heat pump and refurbishment on the wall (25 cm of thermal insulation added to the building façade). By increasing the discount rate, it becomes evident that any measures on the heating system become unnecessary because all curves are converging at almost the same level. The cost-optimal levels, however, move to insulation measures with refurbishment on the floor in combination with a conventional heating system. Additionally, the option with a window refurbishment comes very close to cost-optimal levels.

Cost-optimal points for the discount rate at 1% and 10% are shown in the figure (Figure 4-14) above.

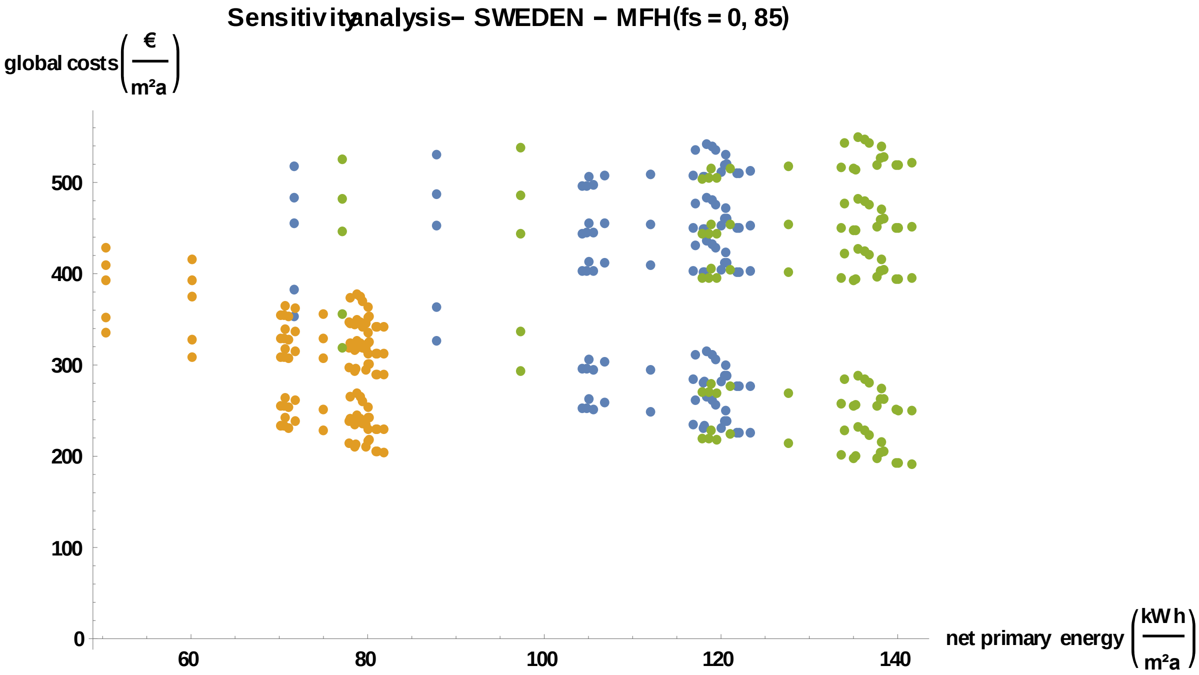

Figure 4-15 Sensitivity analysis for a multi-family house in Sweden with service factor = 0.85; orange points represent heat pumps, blue points stand for solar thermal systems and green points illustrate conventional heating systems

A decrease of the service factor leads to less influence of any refurbishment on the building envelope. The difference of global costs between various refurbishment measures decreases as well. Furthermore, the global cost differences between refurbishment measures shrink even more when heat pumps are used.

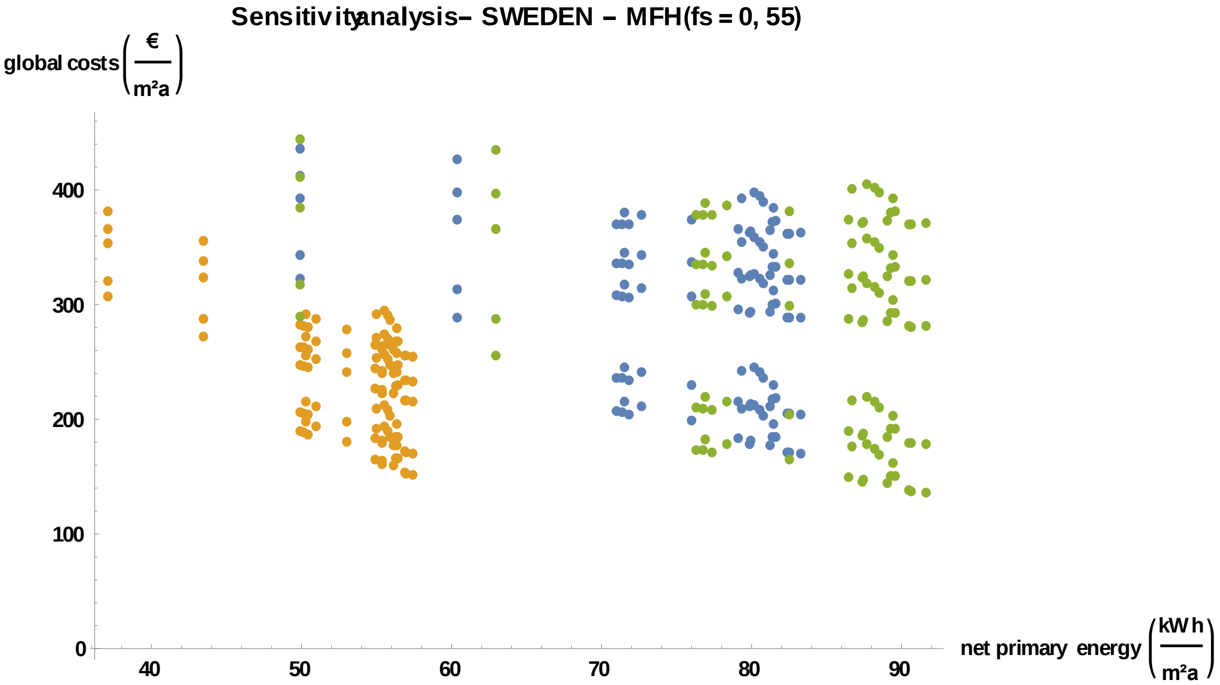

Figure 4-16 Sensitivity analysis for a multi-family house in Sweden with service factor = 0.55; orange points represent heat pumps, blue points stand for solar thermal systems and green points illustrate conventional heating systems

The following conclusions could be reached after thorough analysis of the figures:

- By decreasing the service factor, the net primary energy area is narrowing and the curves slope steeply. E.g. if the service factor is neglected, net primary energies (for the use of a heat pump) are between 56 [kWh/m²a] and 94 [kWh/m²a]. For service factor = 0.55, this value is between 37 [kWh/m²a] and 57 [kWh/m²a].
- The influence of the discount rate is more noticeable for higher service factors and higher net primary energies. Since the percentage of bought energy is higher if a conventional heating system is used, the discount rate has a higher influence on this kind of heating system.
- By increasing the discount rate, the cost-optimal level moves from left to right, meaning from a lower net primary energy to a higher one. On the other hand, the global cost difference between heat pumps and conventional heating systems is getting smaller.
- In general, heat pump heating systems are performing better. By neglecting service factor, the refurbishment on the floor/basement should be taken into consideration.

All mentioned variations are shown in Figure 4-17 below. The overall cost-optimality point is reached where a service factor of 0.55 and the use of a conventional heating system in combination with refurbishment measure “basement/floor – other refurbishment 3” converge.

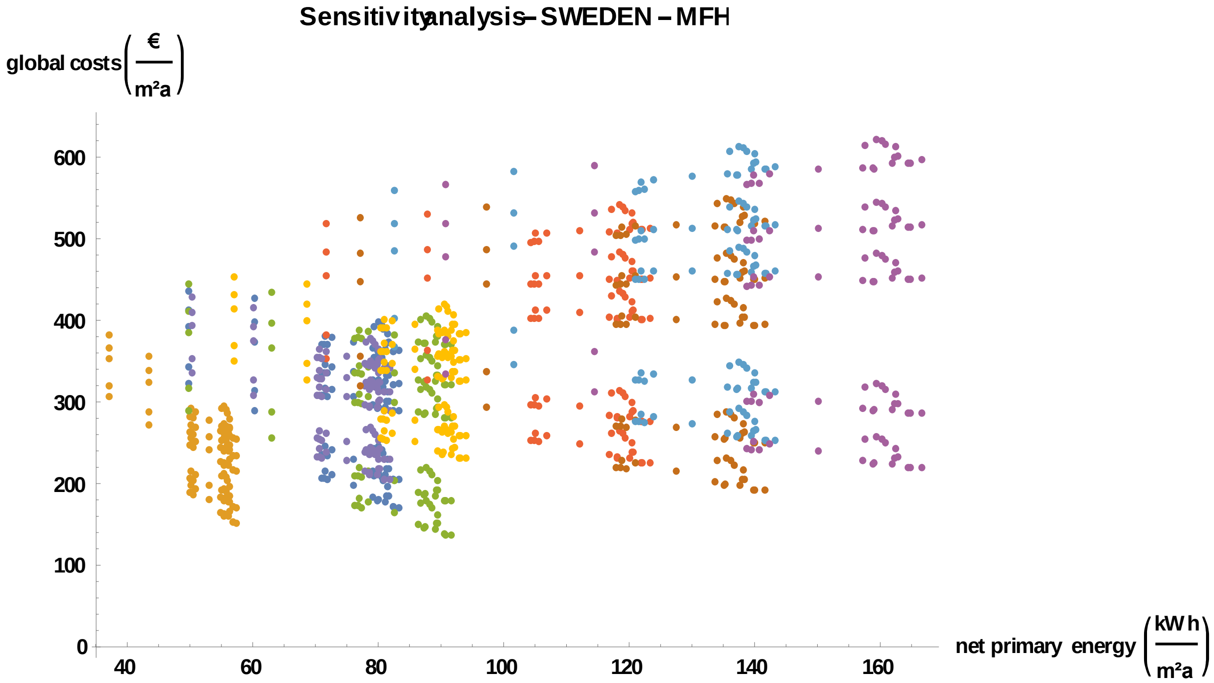

Figure 4-17 Sensitivity analysis of a multi-family house in Sweden considering all variants (Combination of Figure 4-14, Figure 4-15 and Figure 4-16)

4.2.2 Slovenia

This chapter illustrates the calculation of cost-optimal levels based on a case study for a multi-family house in Slovenia. A photo (Figure 4-18) of the multi-family house is displayed below.

Figure 4-18 Photo of the multi-family house in Slovenia which is used as a reference building in the case study

The location of Ljubljana has been chosen for the calculation to represent the average Slovenian climate.

Basic information of the building is as follows:

- Location: Ljubljana
- Construction year(s): 1971...1980
- Conditioned floor area: 632 m²
- Number of apartments: 10
- Residents per apartment: 3 persons (total: 30 persons)
- Lifetime of buildings components: 30 years
- Calculation period: 30 years

In addition to the general information listed above, the following input data is specified:

Table 4-28 List of input data for the multi-family house in Slovenia

Input data	Temperature [°C]
Standard external temperature t_{an}	-16 °C
Average internal room temperature t_{im} (conditioned)	+20 °C
Average internal room temperature t_{im} (unconditioned e.g. roof)	-5 °C
Set-point (of the internal) temperature	+12 °C

Based on the general information and input data for the multi-family house, heat degree days (HDD) are calculated. Therefore, *HDD* is *3675* [Kd].

Table 4-29 the characteristics for the main building components of the multi-family house in Slovenia, which is used as reference building for the calculations. The building data of the current state, usual and advanced refurbishment are taken from TABULA WebTool. (TABULA, 2012). In this context, some adaptations on the building data and refurbishment packages have been elaborated to determine the cost-optimal levels. All refurbishment packages are defined in chapter 4.1.1.1. Due to the size of the whole building and available data for the refurbishment packages, only one quarter of the building is considered for the calculations. The referenced building in the TABULA WebTool is bigger than the used one used for this thesis.

Table 4-29 Characteristics of the multi-family house in Slovenia

	Building components	Current state	U-value	[m²]
Multi-family house in Slovenia	Roof	concrete ceiling, no insulation	1.17	127
	Wall	concrete brick wall	1.80	311
	Basement / Floor	floor on ground with thin insulation (3 cm)	0.75	127
	Window	wooden window 2P	2.8	67
	Door	standard door, no insulation	Not applicable	Not applicable

For data of the global horizontal irradiation of Ljubljana, please refer to the chapter (4.1.2), where the cost-optimal levels of a single-family house in Slovenia were calculated in a case study. (Solar, 2015)

4.2.2.1 Definition of refurbishment measures

The different thermal installation measures are defined in this chapter. In total, five different refurbishment packages are created. As mentioned above, due to the size of the building and available data, the data taken from TABULA WebTool was adapted. Only U-values for usual and advanced refurbishment packages reflect the values from TABULA WebTool[24]; other refurbishment packages were derived from available data. Each package includes various measures like installation of roof, walls, cellar ceiling, thermally improved windows/doors and/or renewal of heat supply systems. For the determination of cost-optimal levels, each installation measure is taken into account separately.

The tables listed below give an overview about the protection standards of the building components and improved U-values after refurbishment.

Table 4-30 SI-MFH Variant 1 – Usual refurbishment with respective insulation measures and U-values[25]

Building component	U-value	Insulation measure
Roof	0.35	add 8 cm of insulation (external insulated render system)
Wall	0.23	add 15 cm of insulation (external insulated render system)
Basement / Floor	0.35	add 6 cm of insulation below / alternatively: on top of ceiling (in case of floor renovation)
Window	1.4	mount new windows, double glazed, argon filled, low E

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[24] Source: http://webtool.building-typology.eu/ (last accessed on 23rd December 2015)
[25] Source: http://webtool.building-typology.eu/ (last accessed on 23rd December 2015)

Table 4-31 SI-MFH Variant 2 – Advanced refurbishment with respective insulation measures and U-values[26]

Building component	U-value	Insulation measure
Roof	0.17	add 20 cm of insulation (external insulated render system)
Wall	0.18	add 20 cm of insulation (external insulated render system)
Basement / Floor	0.23	add 12 cm of insulation below (in case of sufficient cellar height) / alternatively: on top of ceiling (in case of floor renovation) or a combination of both
Window	1.1	mount new windows, triple glazed, argon filled, low E

U-values for variants 3-5 were calculated according to the correlation of U-values with insulation thickness. For calculation details, please refer to chapter 3.6.

Table 4-32 SI-MFH Variant 3 – Other refurbishment with respective insulation measures and U-values

Building component	U-value	Insulation measure
Roof	0.13	add 25 cm of thermal insulation
Wall	0.23	add 10 cm of thermal insulation
Basement / Floor	0.38	add 5 cm of thermal insulation

Table 4-33 SI-MFH Variant 4 – Other refurbishment with respective insulation measures and U-values

Building component	U-value	Insulation measure
Roof	0.12	add 30 cm of thermal insulation
Wall	0.14	add 25 cm of thermal insulation
Basement / Floor	0.25	add 10 cm of thermal insulation

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[26] Source: http://webtool.building-typology.eu/ (last accessed on 23rd December 2015)

Table 4-34 SI-MFH Variant 5 – Other refurbishment with respective insulation measures and U-values

Building component	U-value	Insulation measure
Wall	0.12	add 30 cm of thermal insulation
Basement / Floor	0.19	add 15 cm of thermal insulation

Furthermore, the impact of different heating systems in combination with each insulation measure has been assessed. The considered heating systems are listed below:

- Conventional heat supply systems – condensing boiler (gas) – currently in use
- Heat pump (ground source heat pump)
- Solar thermal heating system

Due to the size of the building and its high energy need, a solar thermal system is not sufficient for space heating. The solar thermal system is only used for the supply of domestic hot water; therefore, it is combined with a conventional heating system, which means that this system is divalent. The other two heating systems are rated as monovalent in the calculation.

4.2.2.2 Calculation of energy performance

Based on the general information, input data, refurbishment packages and chosen heating system, the following values for the net primary energy demand are calculated.

Table 4-35 Energy performance of the multi-family house in Slovenia

Refurbishment measures	Heat transfer [W]	Energy need – space heating [kWh/a]	Energy need – domestic hot water [kWh/a]	Total energy need [kWh/m^{2}a]	Net primary energy per m^2 – heat pump [kWh/m^{2}a]	Net primary energy per m^2 – solar thermal [kWh/m^{2}a]	Net primary energy per m^2 – conventional gas [kWh/m^{2}a]
Roof – usual refurbishment	39,185	96,003	20,391	184	115	169	195
Roof – advanced refurbishment	38,615	94,607	20,391	182	114	167	192
Roof – other refurbishment 1	38,501	94,327	20,391	182	113	166	191
Roof – other refurbishment 2	38,441	94,182	20,391	181	113	166	191
Wall – usual refurbishment	24,218	59,335	20,391	126	79	110	120
Wall – advanced refurbishment	23,659	57,965	20,391	124	77	107	118
Wall – other refurbishment 1	24,261	59,440	20,391	126	79	110	121
Wall – other refurbishment 2	23,191	56,819	20,391	122	76	105	115
Wall – other refurbishment 3	23,006	56,364	20,391	121	76	105	114
Basement/Floor – usual refurbishment	39,957	97,895	20,391	187	117	172	199
Basement/Floor – advanced refurbishment	39,410	96,555	20,391	185	116	170	196
Basement/Floor – other refurbishment 1	40,082	98,202	20,391	188	117	173	199
Basement/Floor – other refurbishment 2	39,511	96,803	20,391	185	116	170	196
Basement/Floor – other refurbishment 3	39,225	96,101	20,391	184	115	169	195
Window – usual refurbishment	38,405	94,092	20,391	181	113	166	191
Window – advanced refurbishment	37,682	92,320	20,391	178	111	163	187
ACTUAL STATE	41,781	102,362	20,391	194	121	179	208
USUAL REFURBISHMENT	16,424	40,238	20,391	96	60	79	82
ADVANCED REFURBISHMENT	14,024	34,359	20,391	87	54	69	70

To make the table easily understandable, energy need and net primary energy values are listed per m². The interim values are not relevant for the final results and therefore not listed in the table above.

The domestic hot water calculation was based on ten apartments and three residents per apartment. As domestic hot water demand is independent from insulation measures, it remains constant in the table.

Please note that a total collector surface of 60 m² is stipulated for the use of a solar thermal system for the supply of domestic hot water. Considering the geographical location of the building, a total usable energy of 20,497 kWh/a can be obtained by adding electrical support energy of 3,350 kWh/a.

The current energy performance values, which show the reference building without any insulation measure, are displayed in the line “ACTUAL STATE” above.

Some facts should be pointed out:

- In addition to the combined insulation measure packages (e.g. usual and advanced refurbishment), the single more profitable insulation measures are refurbishments on the walls. These measures can decrease the energy need per m² from 194 [kWh/m²a] up to 121 [kWh/m²a].
- Taking into account the combination of several insulation measures (e.g. advanced refurbishment package), the energy need can be decreased to 87 [kWh/m²a] at best.
- The lowest net primary energy demand per m² for a single insulation measure can be found for the variant on the building wall (Wall – other refurbishment 3), where a heat pump is used as the heating system. The net primary energy for this variant is 105 [kWh/m²a].

4.2.2.3 Calculation of global costs

All calculated global costs are listed in the table below. These costs include envelope costs, which are related to the installation measures for building components, and costs related to heating systems.

Table 4-36 Global costs of the multi-family house in Slovenia for each insulation measure and used heating system (discount rate = 1%, service factor = 1)

Refurbishment measures	Envelope costs per floor area [€/m²]	Heat pumps – global costs after 30 years per floor area per year [€/m²a]	Solar thermal – global costs after 30 years per floor area per year [€/m²a]	Conventional gas – global costs after 30 years per floor area per year [€/m²a]
Roof – usual refurbishment	17	419	490	475
Roof – advanced refurbishment	22	414	484	470
Roof – other refurbishment 1	23	413	483	468
Roof – other refurbishment 2	25	413	482	468
Wall – usual refurbishment	56	306	344	329
Wall – advanced refurbishment	62	302	338	324
Wall – other refurbishment 1	49	306	344	330
Wall – other refurbishment 2	65	298	334	319
Wall – other refurbishment 3	66	297	332	317
Basement/Floor– usual refurbishment	7	424	497	483
Basement/Floor – advanced refurbishment	10	420	492	477
Basement/Floor – other refurbishment 1	6	425	498	484
Basement/Floor – other refurbishment 2	8	421	493	478
Basement/Floor – other refurbishment 3	11	419	490	475
Window – usual refurbishment	42	413	482	467
Window – advanced refurbishment	46	407	475	460
ACTUAL STATE	0	438	515	500
USUAL REFURBISHMENT	121	248	268	253
ADVANCED REFURBISHMENT	140	230	244	230

Global costs for the individual heating systems are listed in Euros per m² per year. The table above shows the costs for a discount rate of 1%. The impact of the service factor is not considered. The impact changing the discount rate and service factor will be discussed in the chapter "*Sensitivity analysis*".

Envelope costs and costs related to the heating systems are shown separately. Envelope costs are paid only in year zero. Global costs of the heating systems include investment costs and running costs, which need to be paid on an annual (rather than a monthly) basis.

Therefore, for the calculation of the global costs, envelope costs should be added to the global costs of each heating system.

The following lists additional facts which cannot be deduced directly from the table (Table 4-27) above.

- The lowest running costs (maintenance and energy costs) apply to the variant with heat pumps.
- The difference of running costs between heat pump and conventional heating systems is considerable. The difference increases with higher energy need.
- The highest running costs are reached when a conventional heating system is used. E.g. for the refurbishment on the wall (Wall – advanced refurbishment), the annual costs for heat pumps are €4,134, €5,068 for solar thermal systems and €6,174 for conventional heating systems.
- Due to the geographical location of the house, a solar thermal system is not really profitable, which was expected. Even the running costs are not considerably lower than for the conventional heating system. Additionally, a high investment cost for the renewal of the heating system needs to be considered so that it does not seem very profitable.
- Only the renewal of the heating system (without refurbishment on the building envelope) can save costs as a long-term solution. The global costs for a conventional heating system are €500/m²a and €438/m²a for heat pumps for a period of 30 years. This is only applicable for heat pumps and not for the solar thermal heating systems. The global costs for solar thermal systems are €515/m²a, which means they are even higher than for the conventional heating system.

4.2.2.4 Sensitivity analysis

A sensitivity analysis is carried out on the discount rates and service factors. The description and meaning of service factors and discount rates are described in chapter 3.7 and 3.8.

Please note that:

- The variation of the discount rate only influences the running costs and not the investment costs.
- The variation of service factor has an impact on the energy performance and therefore influences the investment and running costs.
- For the reference building, corresponding values of net primary energy include only space heating and domestic hot water.

In the figures below, the variation of three different service factors (fs =1, 0.85 and 0.55) is performed. This means that the discount rate has been varied by 1%, 2%, 3%, 7% and 10% for each service factor.

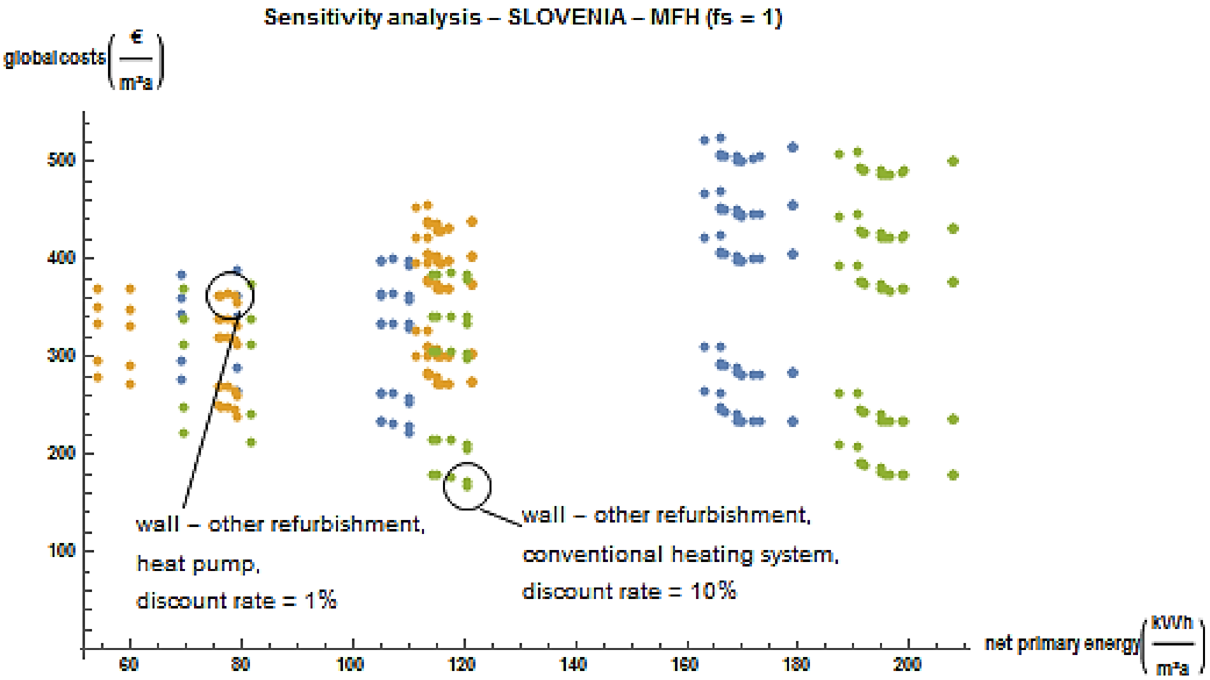

Figure 4-19 Sensitivity analysis of a multi-family house in Slovenia without the impact of service factor; orange points represent heat pumps, blue points stand for solar thermal systems and green points illustrate conventional heating systems

If the service factor is neglected, the cost-optimal level is a combination of heat pump and refurbishment on the wall (10 cm of thermal insulation added to the building façade). By increasing the discount rate, it becomes evident that any measures on the heating system become unnecessary, which means that the importance of conventional heating systems is increasing.

The cost-optimal point is reached with the same insulation measure, but the heating system changes, i.e. in this case a conventional heating system is used. At a discount rate of 10%, the implementation of solar thermal systems performs better than heat pumps.

Cost-optimal points for the discount rate at 1% and 10% are shown in the figure (Figure 4-14) above.

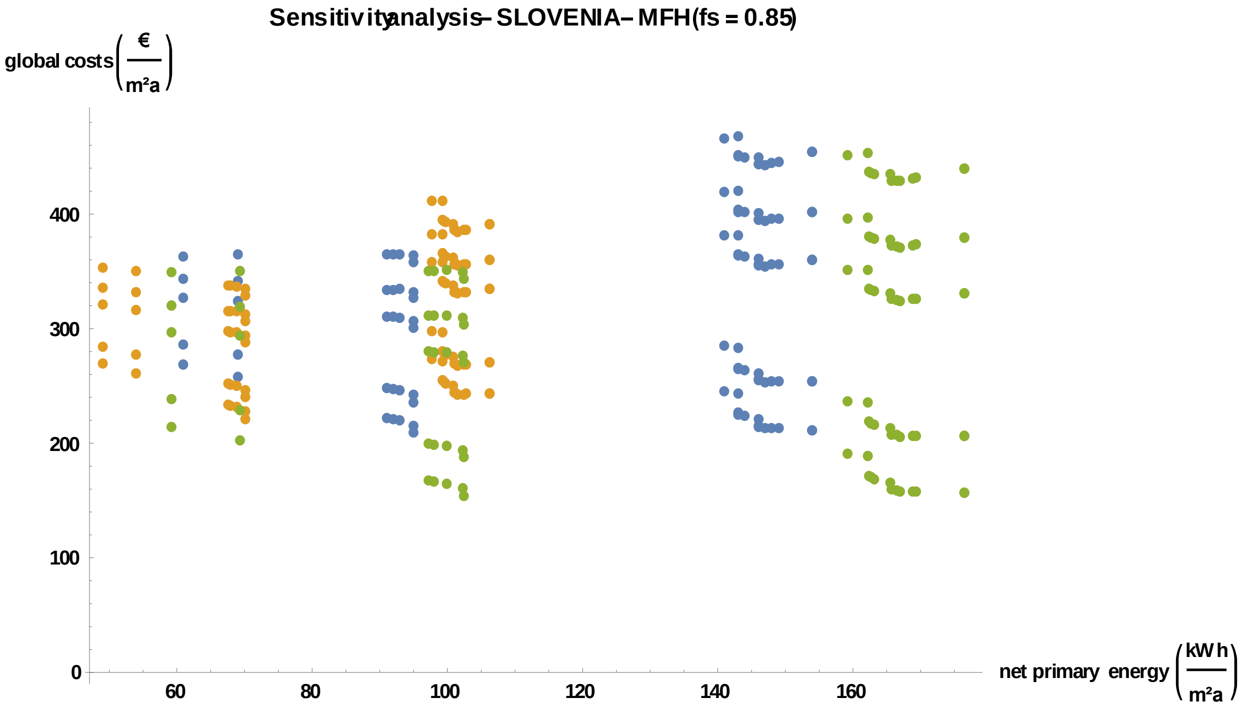

Figure 4-20 Sensitivity analysis of a multi-family house in Slovenia with service factor = 0.85; orange points represent heat pumps, blue points stand for solar thermal systems and green points illustrate conventional heating systems

A decrease of the service factor leads to less influence of any refurbishment on the building envelope. The difference of global costs between various refurbishment measures decreases as well. Furthermore, the global cost differences between refurbishment measures shrink even more when heat pumps are used.

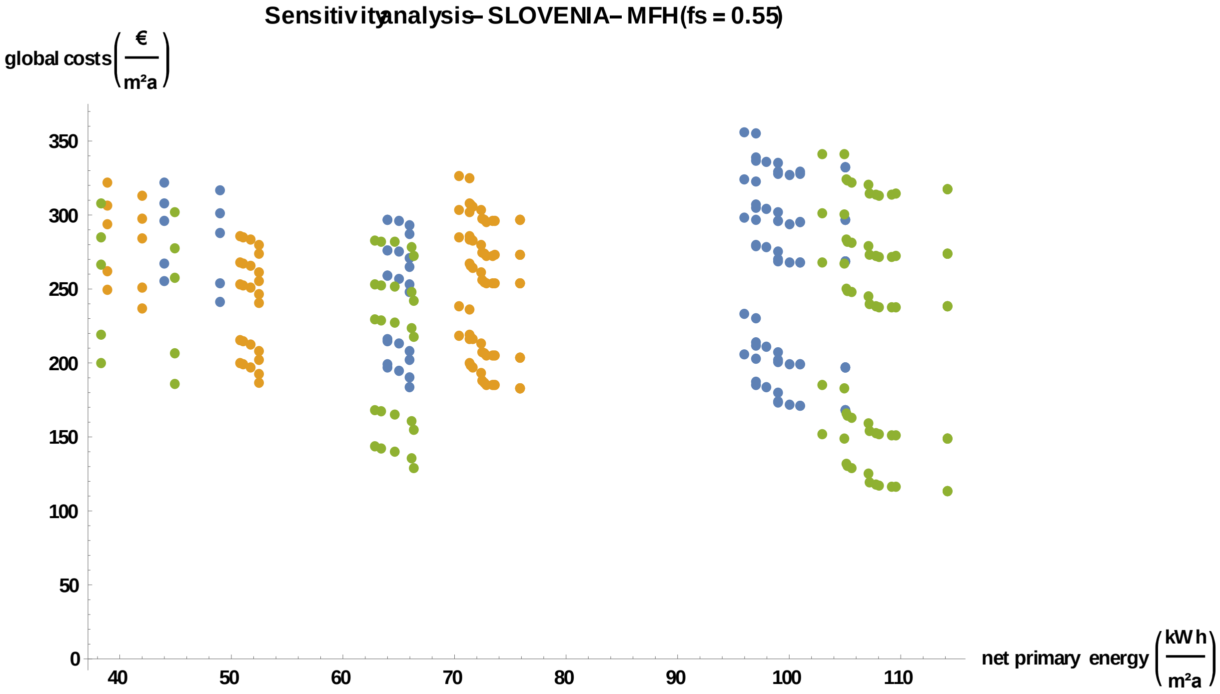

Figure 4-21 Sensitivity analysis of a multi-family house in Slovenia with service factor = 0.55; orange points represent heat pumps, blue points stand for solar thermal systems and green points illustrate conventional heating systems

The following conclusions could be reached after thorough analysis of the figures:

- By decreasing the service factor, the net primary energy area is narrowing and the curves slope steeply. E.g. if the service factor is neglected, net primary energies (heat pump) are between 54 [kWh/m²a] and 122 [kWh/m²a]. For a service factor of 0.55, this value is between 38 [kWh/m²a] and 77 [kWh/m²a].
- The influence of the discount rate is more noticeable for higher service factors and higher net primary energies.
- By increasing the discount rate, the cost-optimal level moves from left to right, meaning from a lower net primary energy to a higher one. On the other hand, the global cost difference between heat pumps and conventional heating systems is getting smaller.
- In general, heat pump heating systems are performing better. By neglecting service factor, the refurbishment on the wall should be taken into consideration.

All mentioned variations are shown in Figure 4-22 below. The overall cost-optimality point is reached where a service factor of 0.55 and the use of conventional heating system converge.

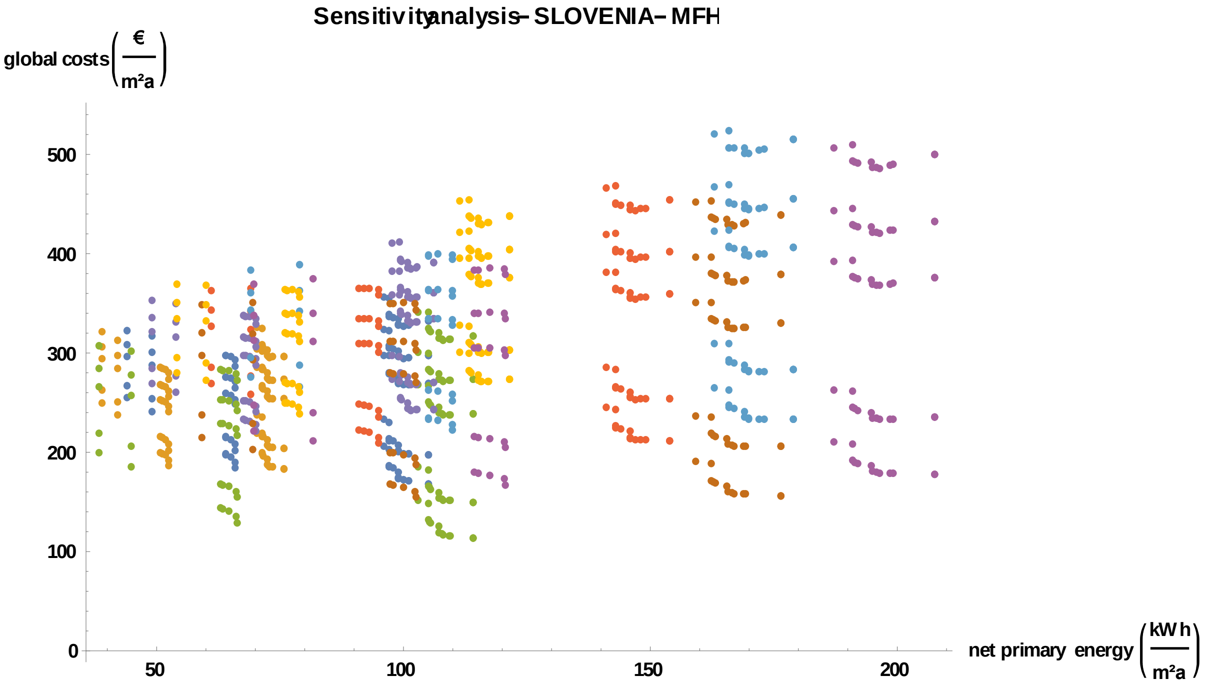

Figure 4-22 Sensitivity analysis of a multi-family house in Slovenia considering all variants (Combination of Figure 4-19, Figure 4-20 and Figure 4-21)

5 Conclusion – Discussion of the results

Before any decisions are made, it should be considered, which result yields the best benefits. An installation measure or refurbishment package in combination with the renewal of a heating system only makes sense if the implementation cost is lower than the resulting benefits. Both are based on comparing the costs and savings of a potential action. The cost-optimal methodology is used to find the **optimal balance between investment and benefit**. In order to realise the goals of decreasing the energy need and increasing the renewable energy supply, a building's energy savings should be maximised while still being cost-efficient. In addition, future energy price changes and interest rates have to be taken into account.

A measure's energy savings depend on the current energy characteristics of a building. It is **not easy to define reference buildings** for existing buildings, which can be used for setting the cost-optimal levels for the whole country. A measure's energy savings depend on the energy **characteristics of a building**, which means that there can be no general statement for a large number of buildings. Although the results show that refurbishments on the building façade seem to be preferable in many cases, all options need to be studied and considered in detail to find the cost-optimal level.

While comparing the results of the case studies with the reports from available sources like ENTRANZE Project (Marco Pietrobon, 2013), (BPIE, 2010), (Thomas Boermans, 2011) etc., it is remarkable that the results of the **Slovenian multi-family house** look quite similar. This means that the cost-optimal range corresponds to the results found in relevant literature. However, this is not the case for the other case studies (single- and multi-family houses), where the available literature uses a different form. One of the reasons is the **non-consideration of external costs**, which are related to environmental or health damages from CO_2. All construction costs which are not directly related to energy (e.g. polluting emissions and external costs) are not part of this work. Furthermore, costs of land, property taxes, subsidies etc. are also not included. Another reason may be the parameters used for the **sensitivity analysis**. In the thesis, changes of the discount rate and service factors were taken into account. This exact combination cannot be found in the available literature, where changes of energy prices and discount rates are considered for the sensitivity analysis.

All internal and external influences such as user behaviour, individual ventilation habits, solar radiation gains and internal heat sources are consolidated into a so-called **service factor**. As (Biermayr, 1998) showed, the influence of energy prices does not have a permanent impact on the energy need. Users (residents) will not change their behaviour as long as a specific price barrier is not crossed. A similar influence can be assumed for thermal building renovations, which lead to increased **comfort**. The influence of this variable is not considered in this work.

Only the renewal of the heating system (without refurbishment on the building envelope) might be considered as a viable option. This may save costs and can be considered a long-term investment. The case studies show that the renewal of the heating system is more profitable for the SFH in Slovenia than for the SFH in Sweden. This conclusion can be explained by the building characteristics. However, it has to be taken into account that it might not be feasible to achieve certain overall greenhouse gas emission targets only by renewable heating systems and without thermal improvement of the building envelope.

As a result of each case study, it becomes apparent that the most effective heating systems are **heat pumps**, since they **provide the highest primary energy savings**. The following table shows the primary energy savings (without any refurbishment on the building envelope) for reference buildings used in the case studies:

Reference building	**Net primary energy per m²** ***conventional gas*** **[kWh/m²a]**	**Net primary energy per m²** ***heat pump*** **[kWh/m²a]**
SFH – Sweden	243	129
SFH – Slovenia	227	118
MFH – Sweden	167	94
MFH – Slovenia	208	121

In percentages, the highest energy savings of about 58% can be applied to the multi-family house in Slovenia. It is important to note that primary energy savings of heat pumps depend on the **coefficient of performance** (which cannot be achieved in any building due to high uncertainties regarding practically achieved COP-values).

If discount rates are small, there is a clear difference between different heating systems. With **higher discount rates** (interest rates), the **global costs** for buildings with the use of heat pumps and conventional heating systems **align**. E.g. for the Swedish single-family house, if service factor is neglected, the cost-optimal level for the discount rate of 1% can be found with the combination of heat pump and refurbishment on the wall (€499/m²a at 107 kWh/m²a of net primary energy). For the same refurbishment measure, but in combination with a conventional heating system, the global costs are €802/m²a at 199 kWh/m²a of net primary energy. By increasing the discount rate to 10%, the cost-optimal level is set to the combination of a heat pump with refurbishment on windows (€306/m²a at 239 kWh/m²a of net primary energy). For the same discount rate of 10% but with a conventional heating system and refurbishment on windows, the global costs are €316/m²a at 239 kWh/m²a of net primary energy. For a discount rate of 1%, the same refurbishment measure leads to different global costs with different heating systems, namely the global costs vary by €303 per floor area per year. For a discount rate of 10%, the cost differences are only €10 per floor area per year. Furthermore, the cost-optimal level moves from 107 kWh/m²a to a higher net primary energy of 239 kWh/m²a. This means that the cost-optimal level becomes increasingly dependent on energy prices.

After all, the development of the energy market in the EU over the last 20 years shows that Europe is becoming more and more dependent on energy imports. Nevertheless, improving existing building components is essential for achieving **climate targets,** and buildings are **more independent from energy prices** if they use heat pumps

For the use of **solar thermal systems**, the geographical location is very important. To find out if a solar thermal system is really profitable, a southern country like Spain or Portugal should be considered for cost-optimality calculations. According to the results, even Slovenia is not “southern” enough to assess the benefit of solar thermal heating systems.

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Annexes

Annex 1 – Calculation of U-value for the wall (50mm of insulation) based on „U-Wert Rechner”

Annex 2 – Calculation of U-value for the wall (100mm of insulation) based on „U-Wert Rechner”

Annex 3 – Calculation of U-value for the wall (200mm of insulation) based on „U-Wert Rechner”

Annex 4 – ENTRANZE cost database

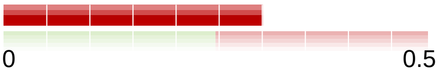
Annex 1

Calculation of U-value for the wall (50mm of insulation) based on „U-Wert Rechner”

Außenwand

Außenwand, U=0,301 W/m²K
erstellt am 1.3.2015 13:40

U = 0,301 W/m²K
(Wärmedämmung)

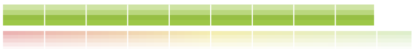


EnEV Bestand*: U<0,24 W/m²K

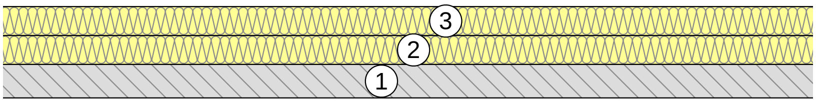
Kein Tauwasser
(Feuchteschutz)

Kein Tauwasser

TA-Dämpfung: 23,8
(Hitzeschutz)

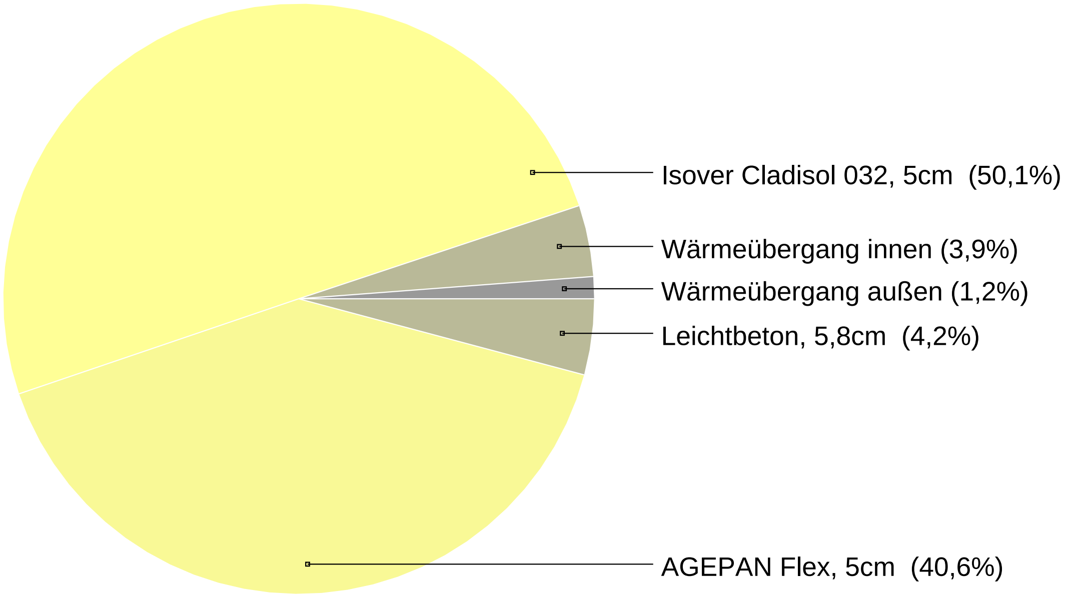


Temperaturamplitudendämpfung: 23.8
Phasenverschiebung: 7.0h



① Leichtbeton (58 mm)
② AGEPAN Flex (50 mm)
③ Isover Cladisol 032 (50 mm)

Beitrag einzelner Schichten zur Wärmedämmung



Raumluft:	20°C / 50%	Tauwasser:	0,000 kg/m²	Wärmekapazität:	110 kJ/m²K
Außenluft:	-5°C / 80%	Trocknungsdauer:	0 Tage	Wärmekapazität innen:	98 kJ/m²K
Oberflächentemp.:	18,2 °C	sd-Wert:	4,3 m	Gewicht:	107 kg/m²
Dicke:	15,8 cm				

---

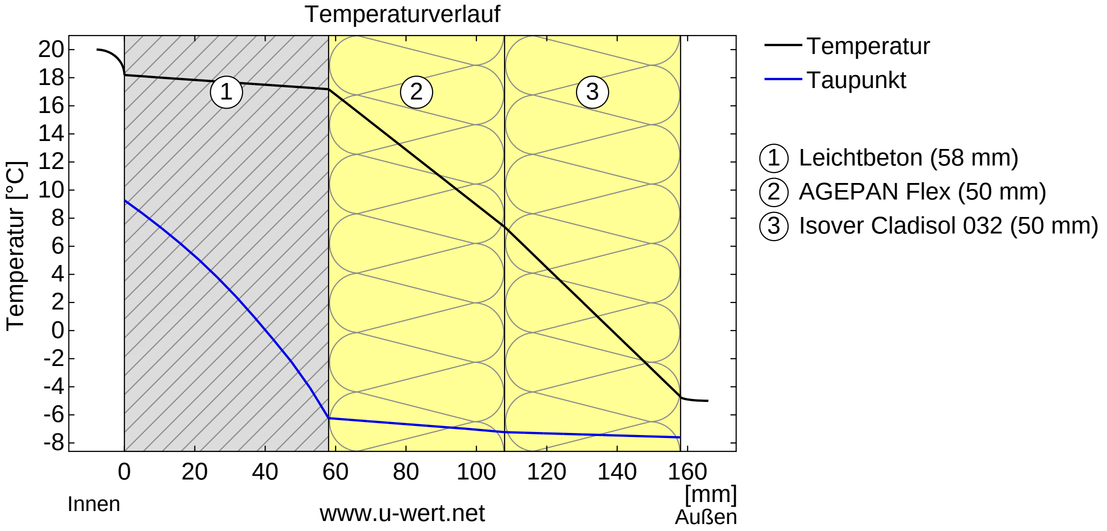
*Vergleich mit dem Höchstwert gemäß EnEV 2014 für erstmaligen Einbau, Ersatz oder Erneuerung von Außenwänden (Anlage 3, Tabelle 1, Zeile 1).

Hier klicken, um das Bauteil auf www.u-wert.net zu bearbeiten.

Außenwand

Außenwand, U=0,301 W/m²K
erstellt am 1.3.2015 13:40

Temperaturverlauf / Tauwasserzone



Verlauf von Temperatur und Taupunkt innerhalb des Bauteils. Der Taupunkt kennzeichnet die Temperatur, bei der Wasserdampf kondensieren und Tauwasser entstehen würde. Solange die Temperatur des Bauteils an jeder Stelle über der Taupunkttemperatur liegt, entsteht kein Tauwasser. Falls sich die beiden Kurven berühren, fällt an den Berührungspunkten Tauwasser aus.

Schichten (von innen nach außen)

Folgende Tabelle enthält die wichtigsten Daten aller Schichten der Konstruktion:

#		Material	λ [W/mK]	R [m²K/W]	Temperatur [°C] min	 max	Gewicht [kg/m²]	Tauwasser [Gew%]
		Wärmeübergangswiderstand (DIN 4108-3)		0,250	18,2	20,0		
1	5,8 cm	Leichtbeton	0,420	0,138	17,2	18,2	104,4	0,0
2	5 cm	AGEPAN Flex	0,037	1,351	7,4	17,2	2,0	0,0
3	5 cm	Isover Cladisol 032	0,030	1,667	-4,7	7,4	1,4	0,0
		Wärmeübergangswiderstand (DIN 4108-3)		0,040	-5,0	-4,7		
	15,8 cm	Gesamtes Bauteil		3,326			107,9	

Hier klicken, um das Bauteil auf www.u-wert.net zu bearbeiten.

Außenwand

Außenwand, U=0,301 W/m²K
erstellt am 1.3.2015 13:40

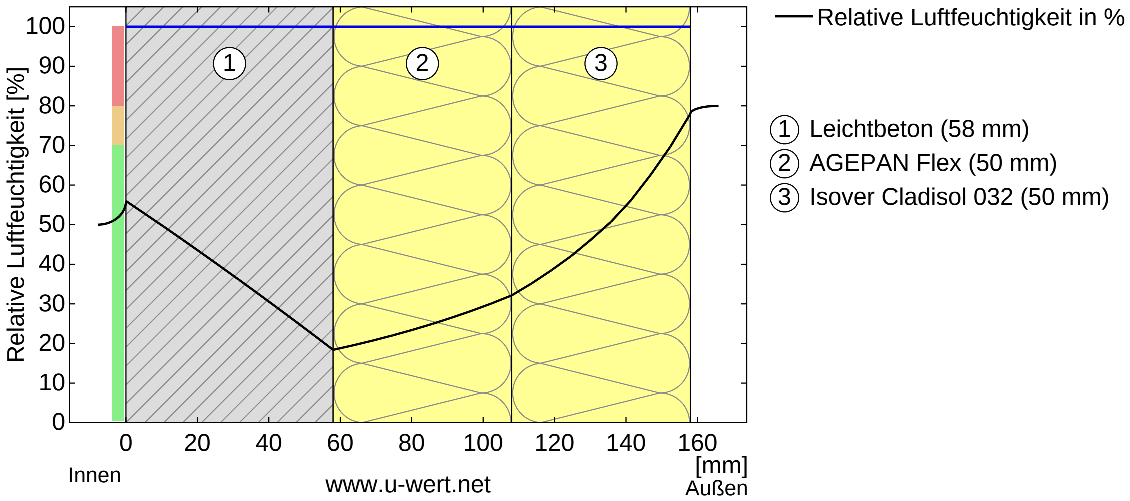
Feuchteschutz

Unter den angenommenen Bedingungen bildet sich kein Tauwasser.

#		Material	sd-Wert [m]	Tauwasser [kg/m²]	Tauwasser %	Trocknungsdauer Tage	Gewicht [kg/m²]
1	5,8 cm	Leichtbeton	4,06	-	0,0		104,4
2	5 cm	AGEPAN Flex	0,15	-	0,0		2,0
3	5 cm	Isover Cladisol 032	0,05	-	0,0		1,5
	15,8 cm	Gesamtes Bauteil	4,26			0	107,9

Luftfeuchtigkeit

Die Oberflächentemperatur der Wandinnenseite beträgt 18,2 °C was zu einer relativen Luftfeuchtigkeit an der Oberfläche von 56% führt. Unter diesen Bedingungen sollte nicht mit Schimmelbildung zu rechnen sein.
Das folgende Diagramm zeigt die relative Luftfeuchtigkeit innerhalb des Bauteils.



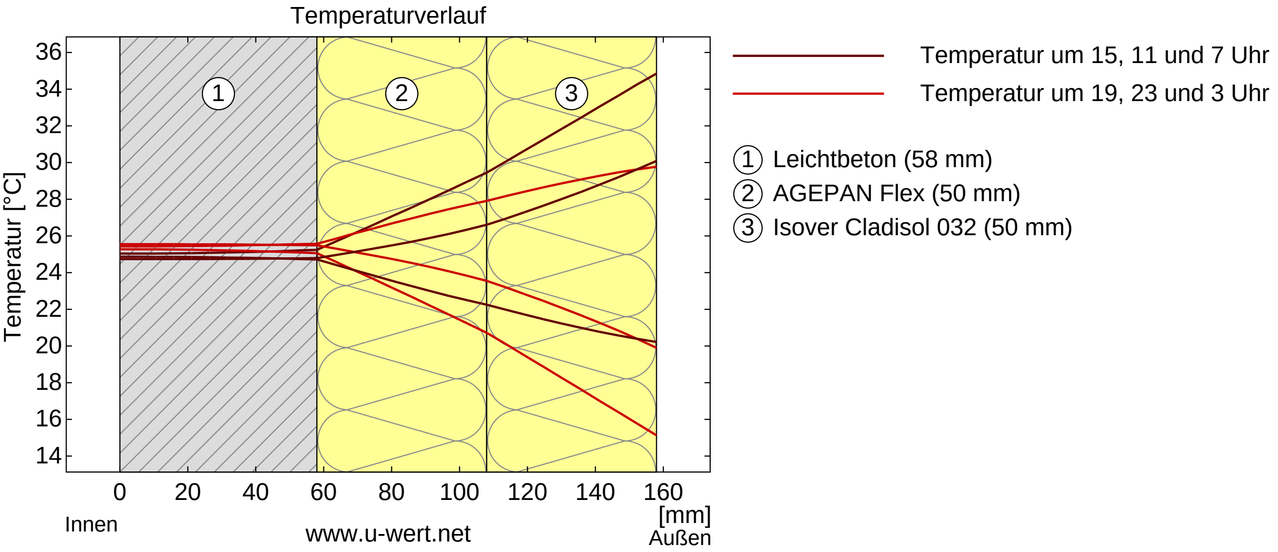
Hier klicken, um das Bauteil auf www.u-wert.net zu bearbeiten.

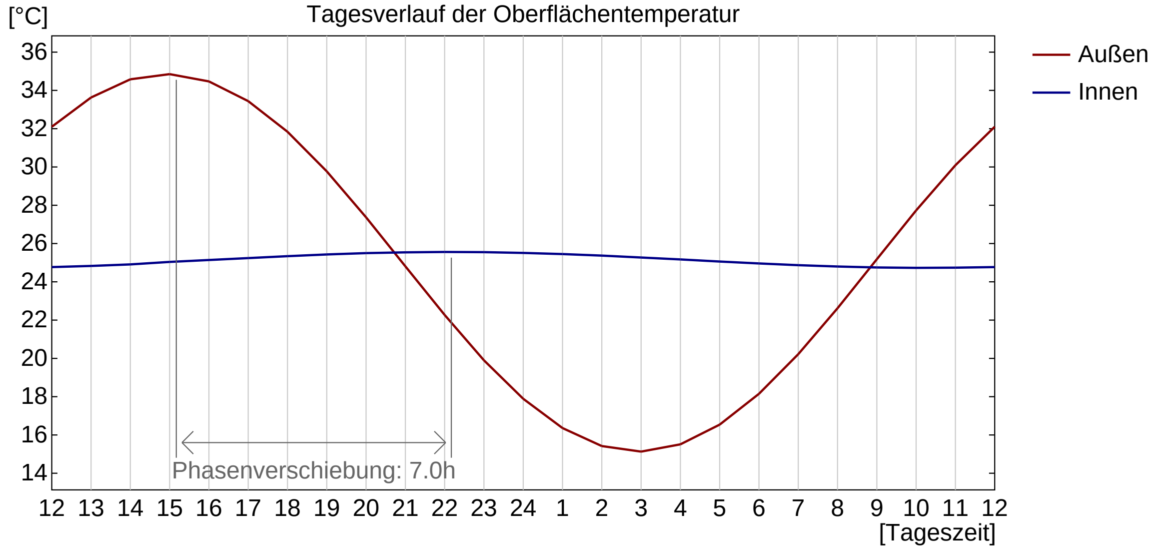
Außenwand

Außenwand, U=0,301 W/m²K
erstellt am 1.3.2015 13:40

Hitzeschutz

Für die Analyse des sommerlichen Hitzeschutzes wurden die Temperaturänderungen innerhalb des Bauteils im Verlauf eines heißen Sommertages simuliert:





Obere Abbildung: Temperaturverlauf innerhalb des Bauteils zu verschiedenen Zeitpunkten. Jeweils von oben nach unten, braune Linien: um 15, 11 und 7 Uhr und rote Linien um 19, 23 und 3 Uhr morgens.
Untere Abbildung: Temperatur auf der äußeren (rot) und inneren (blau) Oberfläche im Verlauf eines Tages. Die schwarzen Pfeile kennzeichnen die Lage der Temperaturhöchstwerte. Das Maximum der inneren Oberflächentemperatur sollte möglichst während der zweiten Nachthälfte auftreten.

Phasenverschiebung*	7,0h	Zeitpunkt der maximalen Innentemperatur:	22:15
Amplitudendämpfung**	23,8	Temperaturschwankung auf äußerer Oberfläche:	19,7 °C
TAV***	0,042	Temperaturschwankung auf innerer Oberfläche:	0,8 °C

* Die Phasenverschiebung gibt die Zeitdauer in Stunden an, nach der das nachmittägliche Hitzemaximum die Bauteilinnenseite erreicht.
** Die Amplitudendämpfung beschreibt die Abschwächung der Temperaturwelle beim Durchgang durch das Bauteil. Ein Wert von 10 bedeutet, dass die Temperatur auf der Außenseite 10x stärker variiert, als auf der Innenseite, z.B. außen 15-35°C, innen 24-26°C.
*** Das Temperaturamplitudenverhältnis TAV ist der Kehrwert der Dämpfung: TAV = 1/Amplitudendämpfung

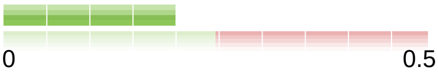
Annex 2

Calculation of U-value for the wall (100mm of insulation) based on „U-Wert Rechner”

Außenwand

Außenwand, U=0,200 W/m²K
erstellt am 1.3.2015 13:40

U = 0,200 W/m²K
(Wärmedämmung)

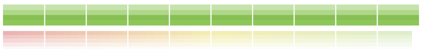


EnEV Bestand*: U<0,24 W/m²K

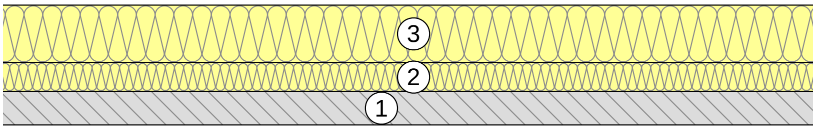
Kein Tauwasser
(Feuchteschutz)

Kein Tauwasser

TA-Dämpfung: 37,6
(Hitzeschutz)

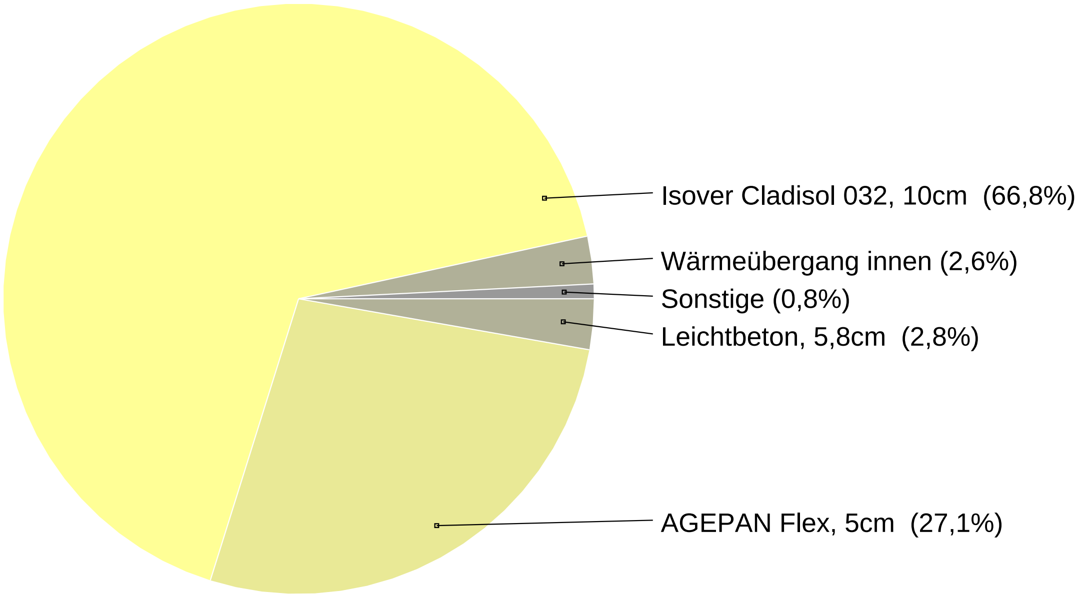


Temperaturamplitudendämpfung: 37.6
Phasenverschiebung: 8.0h



① Leichtbeton (58 mm)
② AGEPAN Flex (50 mm)
③ Isover Cladisol 032 (100 mm)

Beitrag einzelner Schichten zur Wärmedämmung



Raumluft:	20°C / 50%	Tauwasser:	0,000 kg/m²	Wärmekapazität:	112 kJ/m²K
Außenluft:	-5°C / 80%	Trocknungsdauer:	0 Tage	Wärmekapazität innen:	103 kJ/m²K
Oberflächentemp.:	18,8 °C	sd-Wert:	4,3 m	Gewicht:	109 kg/m²
Dicke:	20,8 cm				

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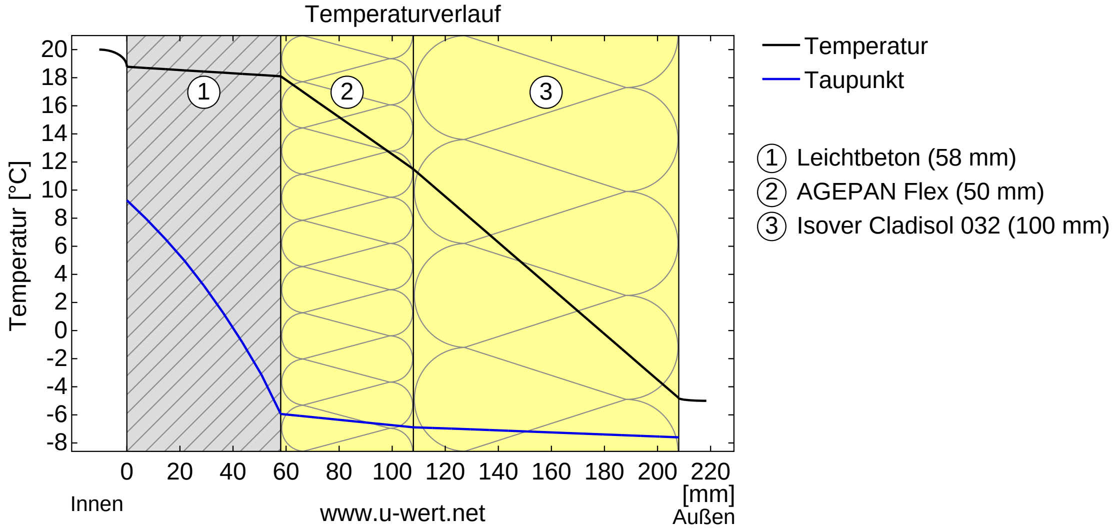
*Vergleich mit dem Höchstwert gemäß EnEV 2014 für erstmaligen Einbau, Ersatz oder Erneuerung von Außenwänden (Anlage 3, Tabelle 1, Zeile 1).

Hier klicken, um das Bauteil auf www.u-wert.net zu bearbeiten.

Außenwand

Außenwand, U=0,200 W/m²K
erstellt am 1.3.2015 13:40

Temperaturverlauf / Tauwasserzone



Verlauf von Temperatur und Taupunkt innerhalb des Bauteils. Der Taupunkt kennzeichnet die Temperatur, bei der Wasserdampf kondensieren und Tauwasser entstehen würde. Solange die Temperatur des Bauteils an jeder Stelle über der Taupunkttemperatur liegt, entsteht kein Tauwasser. Falls sich die beiden Kurven berühren, fällt an den Berührungspunkten Tauwasser aus.

Schichten (von innen nach außen)

Folgende Tabelle enthält die wichtigsten Daten aller Schichten der Konstruktion:

#		Material	λ [W/mK]	R [m²K/W]	Temperatur [°C] min	max	Gewicht [kg/m²]	Tauwasser [Gew%]
		Wärmeübergangswiderstand (DIN 4108-3)		0,250	18,8	20,0		
1	5,8 cm	Leichtbeton	0,420	0,138	18,1	18,8	104,4	0,0
2	5 cm	AGEPAN Flex	0,037	1,351	11,5	18,1	2,0	0,0
3	10 cm	Isover Cladisol 032	0,030	3,333	-4,8	11,5	2,9	0,0
		Wärmeübergangswiderstand (DIN 4108-3)		0,040	-5,0	-4,8		
	20,8 cm	Gesamtes Bauteil		4,993			109,3	

Hier klicken, um das Bauteil auf www.u-wert.net zu bearbeiten.

Außenwand

Außenwand, U=0,200 W/m²K
erstellt am 1.3.2015 13:40

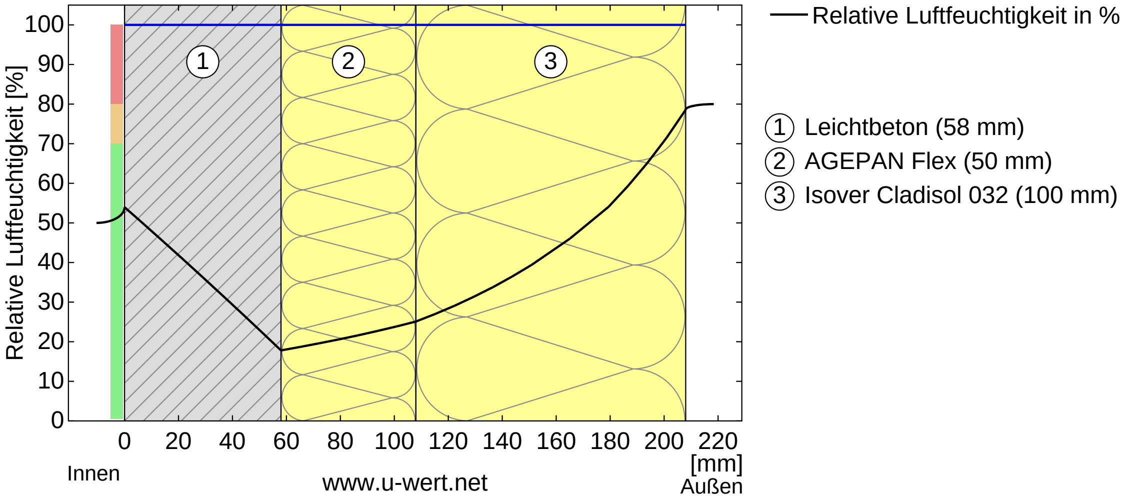
Feuchteschutz

Unter den angenommenen Bedingungen bildet sich kein Tauwasser.

#		Material	sd-Wert [m]	Tauwasser [kg/m²]	Tauwasser %	Trocknungsdauer Tage	Gewicht [kg/m²]
1	5,8 cm	Leichtbeton	4,06	-	0,0		104,4
2	5 cm	AGEPAN Flex	0,15	-	0,0		2,0
3	10 cm	Isover Cladisol 032	0,10	-	0,0		2,9
	20,8 cm	Gesamtes Bauteil	4,31			0	109,3

Luftfeuchtigkeit

Die Oberflächentemperatur der Wandinnenseite beträgt 18,8 °C was zu einer relativen Luftfeuchtigkeit an der Oberfläche von 54% führt. Unter diesen Bedingungen sollte nicht mit Schimmelbildung zu rechnen sein.
Das folgende Diagramm zeigt die relative Luftfeuchtigkeit innerhalb des Bauteils.



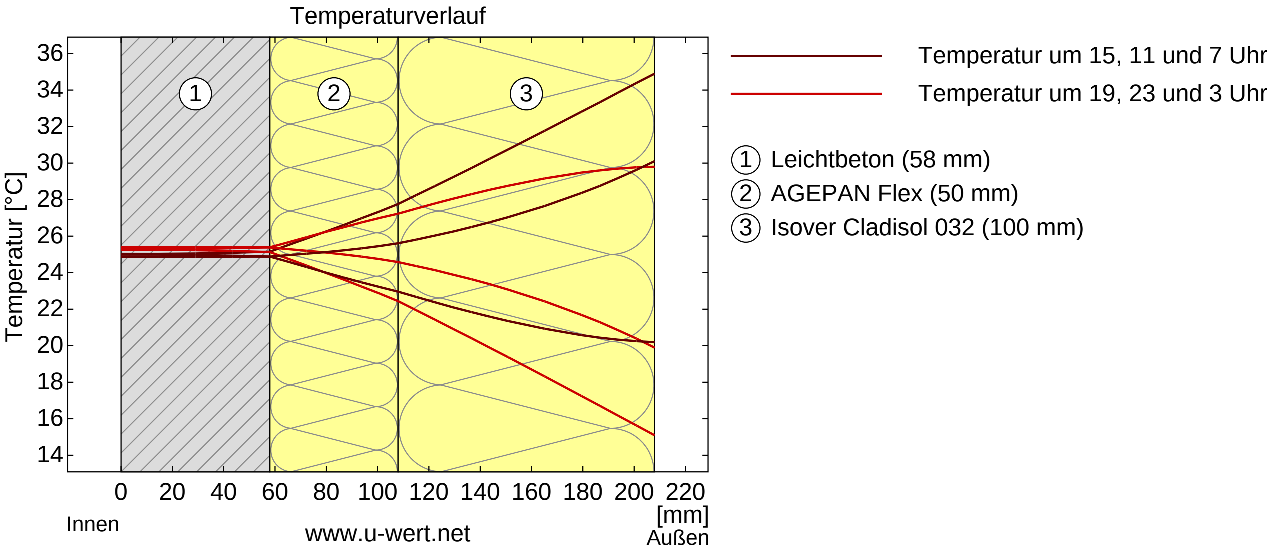
Hier klicken, um das Bauteil auf www.u-wert.net zu bearbeiten.

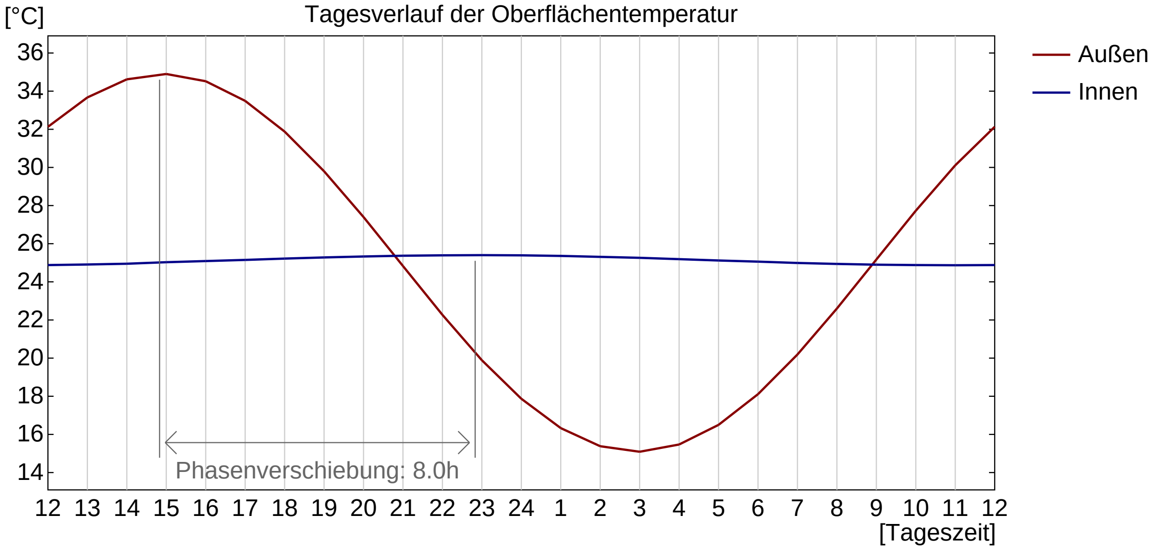
Außenwand

Außenwand, U=0,200 W/m²K
erstellt am 1.3.2015 13:40

Hitzeschutz

Für die Analyse des sommerlichen Hitzeschutzes wurden die Temperaturänderungen innerhalb des Bauteils im Verlauf eines heißen Sommertages simuliert:





Obere Abbildung: Temperaturverlauf innerhalb des Bauteils zu verschiedenen Zeitpunkten. Jeweils von oben nach unten, braune Linien: um 15, 11 und 7 Uhr und rote Linien um 19, 23 und 3 Uhr morgens.
Untere Abbildung: Temperatur auf der äußeren (rot) und inneren (blau) Oberfläche im Verlauf eines Tages. Die schwarzen Pfeile kennzeichnen die Lage der Temperaturhöchstwerte. Das Maximum der inneren Oberflächentemperatur sollte möglichst während der zweiten Nachthälfte auftreten.

Phasenverschiebung*	8,0h	Zeitpunkt der maximalen Innentemperatur:	22:45
Amplitudendämpfung**	37,6	Temperaturschwankung auf äußerer Oberfläche:	19,8 °C
TAV***	0,027	Temperaturschwankung auf innerer Oberfläche:	0,5 °C

* Die Phasenverschiebung gibt die Zeitdauer in Stunden an, nach der das nachmittägliche Hitzemaximum die Bauteilinnenseite erreicht.

** Die Amplitudendämpfung beschreibt die Abschwächung der Temperaturwelle beim Durchgang durch das Bauteil. Ein Wert von 10 bedeutet, dass die Temperatur auf der Außenseite 10x stärker variiert, als auf der Innenseite, z.B. außen 15-35°C, innen 24-26°C.

*** Das Temperaturamplitudenverhältnis TAV ist der Kehrwert der Dämpfung: TAV = 1/Amplitudendämpfung

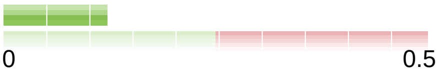
Annex 3

Calculation of U-value for the wall (200mm of insulation) based on „U-Wert Rechner”

Außenwand

Außenwand, U=0,120 W/m²K
erstellt am 1.3.2015 13:39

U = 0,120 W/m²K
(Wärmedämmung)

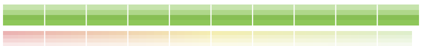


EnEV Bestand*: U<0,24 W/m²K

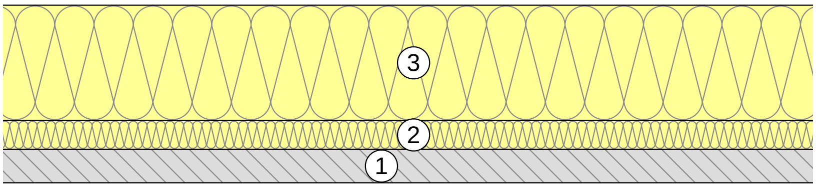
Kein Tauwasser
(Feuchteschutz)

Kein Tauwasser

TA-Dämpfung: 70,9
(Hitzeschutz)

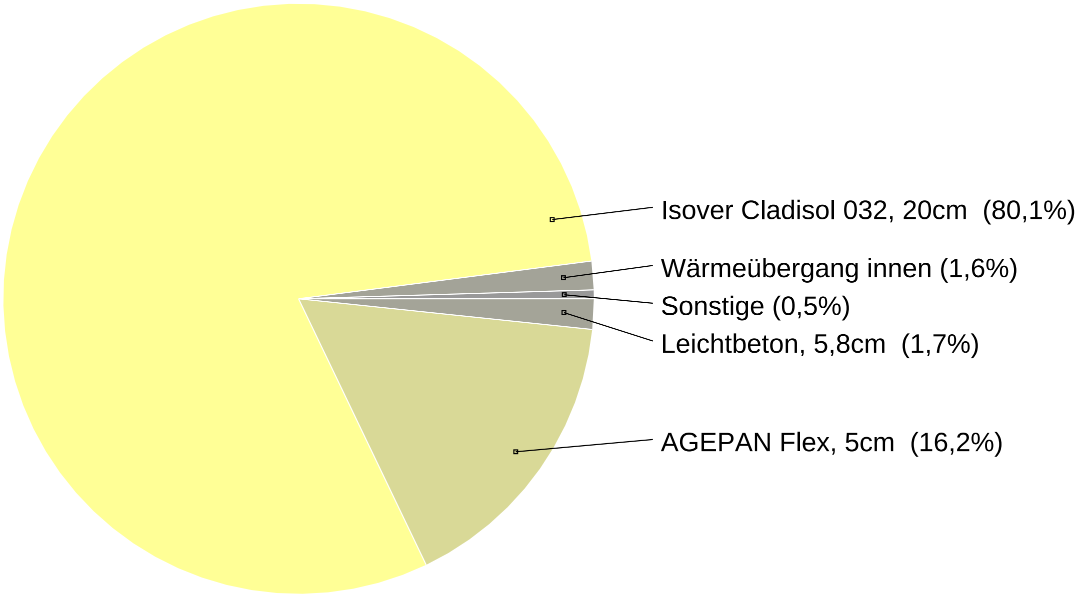


Temperaturamplitudendämpfung: 70.9
Phasenverschiebung: 9.5h



① Leichtbeton (58 mm)
② AGEPAN Flex (50 mm)
③ Isover Cladisol 032 (200 mm)

Beitrag einzelner Schichten zur Wärmedämmung



Raumluft:	20°C / 50%	Tauwasser:	0,000 kg/m²	Wärmekapazität:	115 kJ/m²K
Außenluft:	-5°C / 80%	Trocknungsdauer:	0 Tage	Wärmekapazität innen:	107 kJ/m²K
Oberflächentemp.:	19,3 °C	sd-Wert:	4,4 m	Gewicht:	112 kg/m²
Dicke:	30,8 cm				

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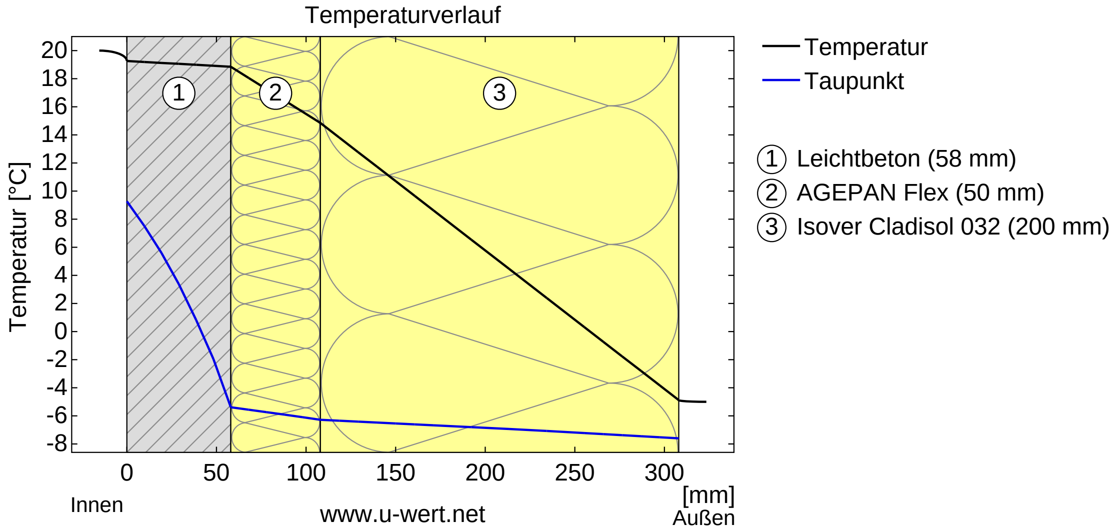
*Vergleich mit dem Höchstwert gemäß EnEV 2014 für erstmaligen Einbau, Ersatz oder Erneuerung von Außenwänden (Anlage 3, Tabelle 1, Zeile 1).

Hier klicken, um das Bauteil auf www.u-wert.net zu bearbeiten.

Außenwand

Außenwand, U=0,120 W/m²K
erstellt am 1.3.2015 13:39

Temperaturverlauf / Tauwasserzone



Verlauf von Temperatur und Taupunkt innerhalb des Bauteils. Der Taupunkt kennzeichnet die Temperatur, bei der Wasserdampf kondensieren und Tauwasser entstehen würde. Solange die Temperatur des Bauteils an jeder Stelle über der Taupunkttemperatur liegt, entsteht kein Tauwasser. Falls sich die beiden Kurven berühren, fällt an den Berührungspunkten Tauwasser aus.

Schichten (von innen nach außen)

Folgende Tabelle enthält die wichtigsten Daten aller Schichten der Konstruktion:

#		Material	λ [W/mK]	R [m²K/W]	Temperatur [°C] min	max	Gewicht [kg/m²]	Tauwasser [Gew%]
		Wärmeübergangswiderstand (DIN 4108-3)		0,250	19,3	20,0		
1	5,8 cm	Leichtbeton	0,420	0,138	18,9	19,3	104,4	0,0
2	5 cm	AGEPAN Flex	0,037	1,351	14,9	18,9	2,0	0,0
3	20 cm	Isover Cladisol 032	0,030	6,667	-4,9	14,9	5,8	0,0
		Wärmeübergangswiderstand (DIN 4108-3)		0,040	-5,0	-4,9		
	30,8 cm	Gesamtes Bauteil		8,326			112,2	

Außenwand

Außenwand, U=0,120 W/m²K
erstellt am 1.3.2015 13:39

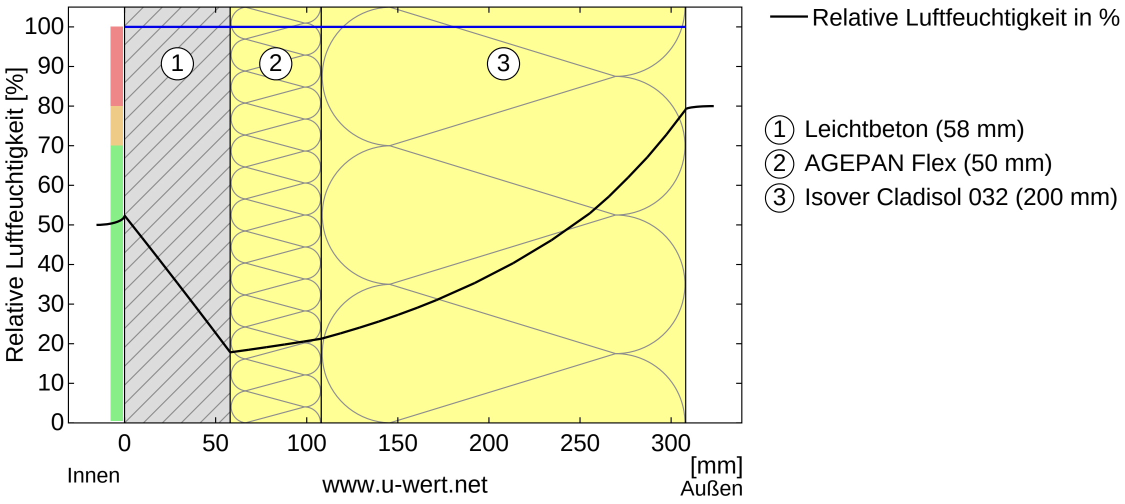
Feuchteschutz

Unter den angenommenen Bedingungen bildet sich kein Tauwasser.

#		Material	sd-Wert	Tauwasser		Trocknungsdauer	Gewicht
			[m]	[kg/m²]	%	Tage	[kg/m²]
1	5,8 cm	Leichtbeton	4,06	-	0,0		104,4
2	5 cm	AGEPAN Flex	0,15	-	0,0		2,0
3	20 cm	Isover Cladisol 032	0,20	-	0,0		5,8
	30,8 cm	Gesamtes Bauteil	4,41			0	112,2

Luftfeuchtigkeit

Die Oberflächentemperatur der Wandinnenseite beträgt 19,3 °C was zu einer relativen Luftfeuchtigkeit an der Oberfläche von 52% führt. Unter diesen Bedingungen sollte nicht mit Schimmelbildung zu rechnen sein.
Das folgende Diagramm zeigt die relative Luftfeuchtigkeit innerhalb des Bauteils.

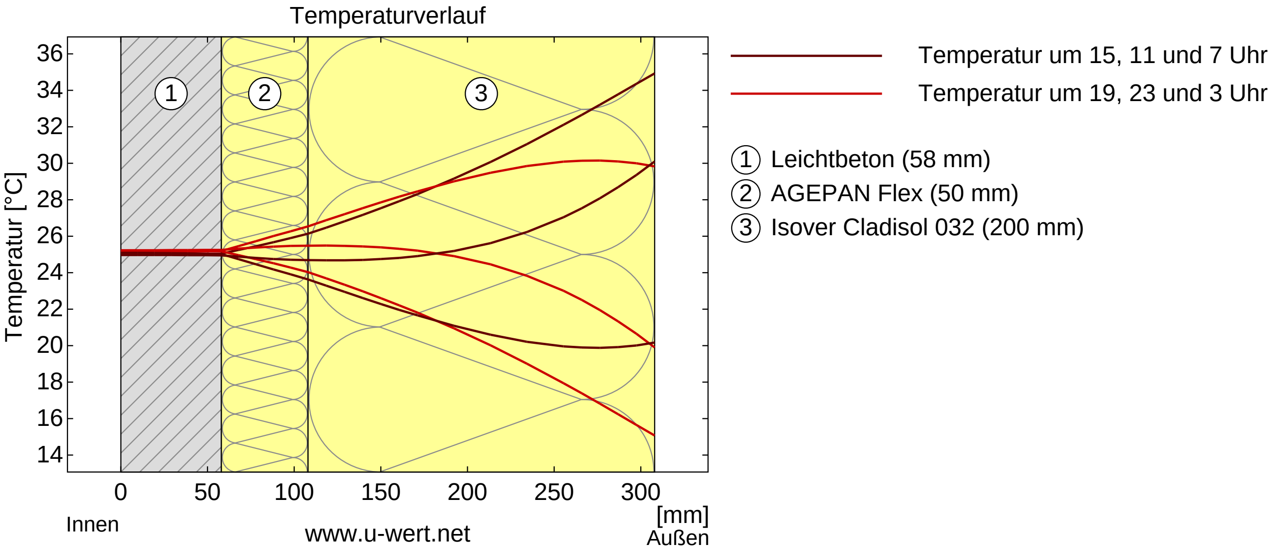


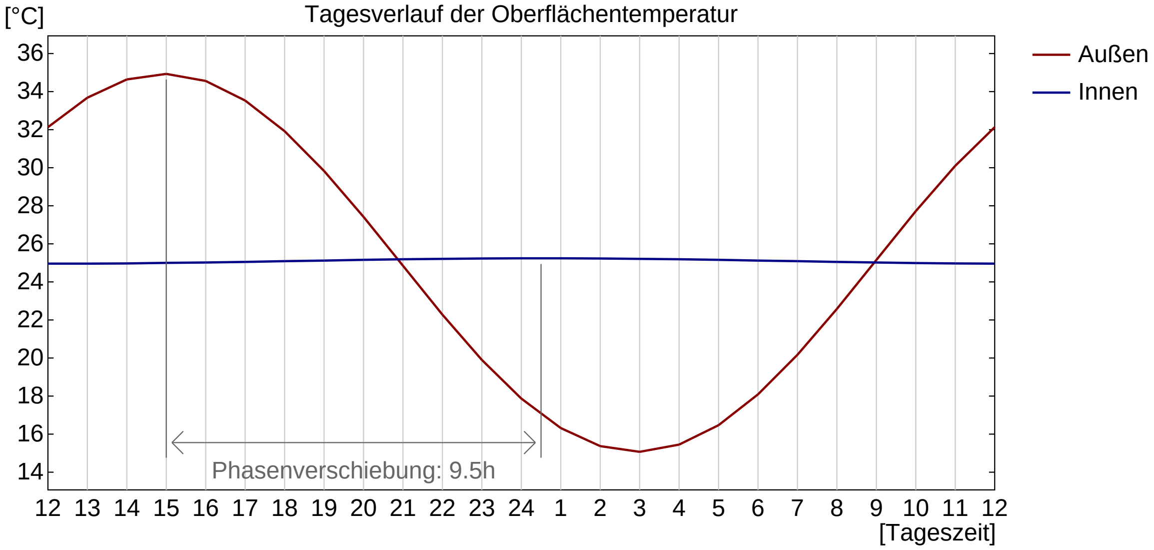
Hier klicken, um das Bauteil auf www.u-wert.net zu bearbeiten.

Außenwand

Hitzeschutz

Für die Analyse des sommerlichen Hitzeschutzes wurden die Temperaturänderungen innerhalb des Bauteils im Verlauf eines heißen Sommertages simuliert:





Obere Abbildung: Temperaturverlauf innerhalb des Bauteils zu verschiedenen Zeitpunkten. Jeweils von oben nach unten, braune Linien: um 15, 11 und 7 Uhr und rote Linien um 19, 23 und 3 Uhr morgens.
Untere Abbildung: Temperatur auf der äußeren (rot) und inneren (blau) Oberfläche im Verlauf eines Tages. Die schwarzen Pfeile kennzeichnen die Lage der Temperaturhöchstwerte. Das Maximum der inneren Oberflächentemperatur sollte möglichst während der zweiten Nachthälfte auftreten.

Phasenverschiebung*	9,5h	Zeitpunkt der maximalen Innentemperatur:	0:30
Amplitudendämpfung**	70,9	Temperaturschwankung auf äußerer Oberfläche:	19,9 °C
TAV***	0,014	Temperaturschwankung auf innerer Oberfläche:	0,3 °C

* Die Phasenverschiebung gibt die Zeitdauer in Stunden an, nach der das nachmittägliche Hitzemaximum die Bauteilinnenseite erreicht.
** Die Amplitudendämpfung beschreibt die Abschwächung der Temperaturwelle beim Durchgang durch das Bauteil. Ein Wert von 10 bedeutet, dass die Temperatur auf der Außenseite 10x stärker variiert, als auf der Innenseite, z.B. außen 15-35°C, innen 24-26°C.
*** Das Temperaturamplitudenverhältnis TAV ist der Kehrwert der Dämpfung: TAV = 1/Amplitudendämpfung

Hier klicken, um das Bauteil auf www.u-wert.net zu bearbeiten.

Annex 4

ENTRANZE cost database

(*) Nominal thermal conductivity of the new insulation layer λ=0,034 W/mK

							Germany						
							MATERIAL COSTS	LABOUR COSTS	BUSINESS PROFIT and GENERAL EXPENDITURE	TOTAL COSTS	PROFESSIONAL FEES [if applicable]	DISPOSAL COSTS	Final Costs
Measure	Constructive solution	Description of the measure	Variants	Cost Criteria	Unit	Code	COST OF MEASURE	COST OF MEASURE	[% of MC+LC]	[MC+LC+BP&GE]	[% of MC+LC]	DISPOSAL COST OF MEASURE	MC + LC + BP&GE + PF + Disposal
ROOF INSULATION	BASE REFURBISHMENT LEVEL OF ROOF	Renovation of the exterior layer of the roof (tile or tar or ...) for aesthetic/functional/security reasons	-	<500m^2 of roof	€/m^2	1	17,8	46,1	10,0	70,3	10,0		76,7
				>500m^2 of roof	€/m^2	2	17,8	46,1	10,0	70,3	10,0		76,7
	Removal of the roof and refit by adding a new layer of insulation (when repairing or renovation works of flat or sloping roofs)	In flat roofs: All material layers up to the position of thermal insulation (over the waterproofing layer) will be removed. In addition, over the new thermal insulation layer, a protecting and a finishing layer (gravel, paving…) will be installed. In sloping roofs: The tiles, battens and waterproofing layer will be removed. Then, new insulation will be added over the slab/framework and new waterproofing layer, vapor barrier, battens and tiles over the insulation will be installed.	5 cm of thermal insulation	<500m^2 of roof	€/m^2	3	129,8		10,0	142,8	10,0		155,8
				>500m^2 of roof	€/m^2	4	113,6		10,0	125,0	10,0		136,4
			15 cm of thermal insulation	<500m^2 of roof	€/m^2	5	132,8		10,0	146,1	10,0		159,3
				>500m^2 of roof	€/m^2	6	126,4		10,0	139,0	10,0		151,7
			30 cm of thermal insulation	<500m^2 of roof	€/m^2	7	148,1		10,0	162,9	10,0		177,7
				>500m^2 of roof	€/m^2	8	143,0		10,0	157,3	10,0		171,6
	Addition of a thermal insulation layer over the last slab in contact with unconditioned space (attic)	This measure is only possible in buildings with unconditioned space (attic) above the concrete slab/framework of the highest floor. As this space is supposed to have not transit, the thermal insulation layer does not need to be protected by another material layer.	5 cm of thermal insulation	<500m^2 of roof	€/m^2	9			10,0		10,0		
				>500m^2 of roof	€/m^2	10			10,0		10,0		
			10 cm of thermal insulation	<500m^2 of roof	€/m^2	11	3,3	3,2	10,0	7,1	10,0	0,0	7,7
				>500m^2 of roof	€/m^2	12	3,3	3,2	10,0	7,1	10,0	0,0	7,7
			15 cm of thermal insulation	<500m^2 of roof	€/m^2	13	7,9	5,4	10,0	14,6	10,0		15,9
				>500m^2 of roof	€/m^2	14	7,9	5,4	10,0	14,6	10,0		15,9
			20 cm of thermal insulation	<500m^2 of roof	€/m^2	15	17,1	9,9	10,0	29,7	10,0		32,4
				>500m^2 of roof	€/m^2	16	17,1	9,9	10,0	29,7	10,0		32,4
			25 cm of thermal insulation	<500m^2 of roof	€/m^2	a	21,64	12,17	10,00	37,19	10,00	0,00	40,57
				>500m^2 of roof	€/m^2	b	21,64	12,17	10,00	37,19	10,00	0,00	40,57
			30 cm of thermal insulation	<500m^2 of roof	€/m^2	17	26,2	14,4	10,0	44,7	10,0		48,8
				>500m^2 of roof	€/m^2	18	26,2	14,4	10,0	44,7	10,0		48,8
	Insulation below the last concrete slab	Installation of a thermal insulation layer inside the false ceiling of the last conditioned storey of the building. In those cases when a false ceiling exists, it will be necessary to replace it so as to be able to install the insulation. If there was not false ceiling, it would be necessary to create one.	10 cm of thermal insulation	<500m^2 of roof	€/m^2	19			10,0		10,0		
				>500m^2 of roof	€/m^2	20			10,0		10,0		
			20 cm of thermal insulation	<500m^2 of roof	€/m^2	21			10,0		10,0		
				>500m^2 of roof	€/m^2	22			10,0		10,0		

(*) Nominal thermal conductivity of the new insulation layer λ=0,034 W/mK

							Germany						
							MATERIAL COSTS	**LABOUR COSTS**	**BUSINESS PROFIT and GENERAL EXPENDITURE**	**TOTAL COSTS**	**PROFESSIONAL FEES [if applicable]**	**DISPOSAL COSTS**	**Final Costs**
Measure	**Constructive solution**	**Description of the measure**	**Variants**	**Cost Criteria**	**Unit**	**Code**	**COST OF MEASURE**	**COST OF MEASURE**	**[% of MC+LC]**	**[MC+LC+BP&GE]**	**[% of MC+LC]**	**DISPOSAL COST OF MEASURE**	**MC + LC + BP&GE + PF + Disposal**
EXTERNAL WALL INSULATION	**BASE REFURBISHMENT LEVEL OF WALLS**	Renovation of the exterior layer of the walls (plaster or tile or ...) for aesthetic/functional/security reasons	-	<500m^2 of wall	€/m^2	23	**7,1**	**10,8**	**10,0**	**19,7**	**10,0**		**21,5**
				>500m^2 of wall	€/m^2	24	**7,1**	**10,8**	**10,0**	**19,7**	**10,0**		**21,5**
	External insulation (ventilated façade)	The external insulation is made by adding thermal insulation to the external surface of the façade. Thermal insulation will be protected by a new external layer attached, through a substructure, to the existing structure or building façade. Between the insulation and the external layer there will be a highly ventilated air chamber which will protect the building from solar radiation.	5 cm of thermal insulation	<500m^2 of wall	€/m^2	25			**10,0**		**10,0**		
				>500m^2 of wall	€/m^2	26			**10,0**		**10,0**		
			10 cm of thermal insulation	<500m^2 of wall	€/m^2	27			**10,0**		**10,0**		
				>500m^2 of wall	€/m^2	28			**10,0**		**10,0**		
			20 cm of thermal insulation	<500m^2 of wall	€/m^2	29			**10,0**		**10,0**		
				>500m^2 of wall	€/m^2	30			**10,0**		**10,0**		
	External insulation (EIFS System)	EIFS is a lightweight synthetic wall cladding that includes foam plastic insulation and thin synthetic coatings.	5 cm of thermal insulation	<500m^2 of wall	€/m^2	31			**10,0**		**10,0**		
				>500m^2 of wall	€/m^2	32			**10,0**		**10,0**		
			10 cm of thermal insulation	<500m^2 of wall	€/m^2	33	**30,1**	**35,9**	**10,0**	**72,6**	**10,0**		**79,2**
				>500m^2 of wall	€/m^2	34	**30,1**	**35,9**	**10,0**	**72,6**	**10,0**		**79,2**
			15 cm of thermal insulation	<500m^2 of wall	€/m^2	35	**40,5**	**35,9**	**10,0**	**84,1**	**10,0**		**91,7**
				>500m^2 of wall	€/m^2	36	**40,5**	**35,9**	**10,0**	**84,1**	**10,0**		**91,7**
			20 cm of thermal insulation	<500m^2 of wall	€/m^2	37	**50,9**	**35,9**	**10,0**	**95,5**	**10,0**		**104,2**
				>500m^2 of wall	€/m^2	38	**50,9**	**35,9**	**10,0**	**95,5**	**10,0**		**104,2**
			25 cm of thermal insulation	<500m^2 of wall	€/m^2	**c**	56,12	35,91	10,00	101,23	10,00	0,00	110,43
				>500m^2 of wall	€/m^2	**d**	56,12	35,91	10,00	101,23	10,00	0,00	110,43
			30 cm of thermal insulation	<500m^2 of wall	€/m^2	**e**	58,72	35,91	10,00	104,09	10,00	0,00	113,56
				>500m^2 of wall	€/m^2	**f**	58,72	35,91	10,00	104,09	10,00	0,00	113,56
	Filling air chamber with thermal insulation	Thermal insulation will be installed into the existing air chamber. The thickness of the thermal insulation will depend on the air chamber thickness.	5 cm of thermal insulation	<500m^2 of wall	€/m^2	39			**10,0**		**10,0**		
				>500m^2 of wall	€/m^2	40			**10,0**		**10,0**		
			10 cm of thermal insulation	<500m^2 of wall	€/m^2	41			**10,0**		**10,0**		
				>500m^2 of wall	€/m^2	42			**10,0**		**10,0**		
			20 cm of thermal insulation	<500m^2 of wall	€/m^2	43			**10,0**		**10,0**		
				>500m^2 of wall	€/m^2	44			**10,0**		**10,0**		

(*) Nominal thermal conductivity of the new insulation layer λ=0,034 W/mK

								Germany						
								MATERIAL COSTS	LABOUR COSTS	BUSINESS PROFIT and GENERAL EXPENDITURE	TOTAL COSTS	PROFESSIONAL FEES [if applicable]	DISPOSAL COSTS	Final Costs
	Measure	Constructive solution	Description of the measure	Variants	Cost Criteria	Unit	Code	COST OF MEASURE	COST OF MEASURE	[% of MC+LC]	[MC+LC+BP&GE]	[% of MC+LC]	DISPOSAL COST OF MEASURE	MC + LC + BP&GE + PF + Disposal
MEASURES TO REDUCE HEATING LOADS		Internal insulation (adding thermal insulation on the internal face of the wall)	Addition of thermal insulation, vapor barrier and a new inner plaster layer on the internal surface of the wall. The larger the insulation thickness, the greater the reduction in the useful floor area in the building. (IN ITALY INTERNAL LAYER IN GYPSUM PANEL)	5 cm of thermal insulation	<500m^2 of wall	€/m^2	45			10,0		10,0		
					>500m^2 of wall	€/m^2	46			10,0		10,0		
				10 cm of thermal insulation	<500m^2 of wall	€/m^2	47			10,0		10,0		
					>500m^2 of wall	€/m^2	48			10,0		10,0		
				15 cm of thermal insulation	<500m^2 of wall	€/m^2	49			10,0		10,0		
					>500m^2 of wall	€/m^2	50			10,0		10,0		
		Internal insulation (remove inner skin of the cavity wall and replace it by a new skin with thermal insulation)	Remove the inner skin of the cavity wall and then create a new skin, separated by an air chamber from the external skin, and composed by thermal insulation, brick masonry and plaster inside.	5 cm of thermal insulation	<500m^2 of wall	€/m^2	51			10,0		10,0		
					>500m^2 of wall	€/m^2	52			10,0		10,0		
				10 cm of thermal insulation	<500m^2 of wall	€/m^2	53			10,0		10,0		
					>500m^2 of wall	€/m^2	54			10,0		10,0		
				15 cm of thermal insulation	<500m^2 of wall	€/m^2	55			10,0		10,0		
					>500m^2 of wall	€/m^2	56			10,0		10,0		
	FLOOR SLAB OR FRAMEWORK INSULATION (WHEN IS IN DIRECT CONTACT WITH THE OUTSIDE AMBIENT AIR OR WITH UNCONDITIONED SPACES)	Installation of insulation in the inner of the floor slabs or frameworks	Removal of the existing layers over the concrete slab. Installation over the insu-lation of a concrete screed, a vapour barrier and finally the finishing layer/s (ce-ramic tiles, wood, etc). For this solution it is necessary to have enough ceiling height, and it could be necessary to adapt the height of all doors and to raise the parapets and electric sockets.	5 cm of thermal insulation	<500m^2 of floor	€/m^2	57	39,9	2,2	10,0	46,2	10,0		50,4
					>500m^2 of floor	€/m^2	58	39,9	2,2	10,0	46,2	10,0		50,4
				10 cm of thermal insulation	<500m^2 of floor	€/m^2	59	51,1	3,4	10,0	60,0	10,0		65,4
					>500m^2 of floor	€/m^2	60	51,1	3,4	10,0	60,0	10,0		65,4
				15 cm of thermal insulation	<500m^2 of floor	€/m^2	61			10,0		10,0		
					>500m^2 of floor	€/m^2	62			10,0		10,0		
		Installation of insulation in the outer of the floor slabs	Installation of a layer of thermal insulation below the first conditioned plant of the building and a plaster or gypsum panel.	5 cm of thermal insulation	<500m^2 of floor	€/m^2	63	26,1		10,0	28,7	10,0		31,3
					>500m^2 of floor	€/m^2	64	25,2		10,0	27,8	10,0		30,3
				10 cm of thermal insulation	<500m^2 of floor	€/m^2	65	33,6		10,0	36,9	10,0		40,3
					>500m^2 of floor	€/m^2	66	33,6		10,0	36,9	10,0		40,3
				15 cm of thermal insulation	<500m^2 of floor	€/m^2	67	47,0		10,0	51,7	10,0		56,4
					>500m^2 of floor	€/m^2	68	47,0		10,0	51,7	10,0		56,4
	INSULATION OF THE GROUND FLOOR IN CONTACT WITH THE GROUND	Installation of a thermal insulating layer on top of concrete ground floor in contact with the ground	Removal of the existing layers over the concrete slab. Installation of the thermal insulation and, over the insulation a concrete screed, a vapour barrier and finally the finishing layer/s (ceramic tiles, wood, etc). For this solution it is necessary to have enough ceiling height, and it could be necessary to adapt the height of all doors and to raise the parapets and electric sockets.	5 cm of thermal insulation	<500m^2 of floor	€/m^2	69	30,0	14,5	10,0	49,0	10,0		53,4
					>500m^2 of floor	€/m^2	70	30,0	14,5	10,0	49,0	10,0		53,4
				10 cm of thermal insulation	<500m^2 of floor	€/m^2	71	50,0	14,5	10,0	71,0	10,0		77,4
					>500m^2 of floor	€/m^2	72	50,0	14,5	10,0	71,0	10,0		77,4
				15 cm of thermal insulation	<500m^2 of floor	€/m^2	73			10,0		10,0		
					>500m^2 of floor	€/m^2	74			10,0		10,0		

(*) Nominal thermal conductivity of the new insulation layer λ=0,034 W/mK

							Germany						
							MATERIAL COSTS	LABOUR COSTS	BUSINESS PROFIT and GENERAL EXPENDITURE	TOTAL COSTS	PROFESSIONAL FEES [if applicable]	DISPOSAL COSTS	Final Costs
Measure	**Constructive solution**	**Description of the measure**	**Variants**	**Cost Criteria**	**Unit**	**Code**	COST OF MEASURE	COST OF MEASURE	[% of MC+LC]	[MC+LC+BP&GE]	[% of MC+LC]	DISPOSAL COST OF MEASURE	MC + LC + BP&GE + PF + Disposal
PERIMETER INSULATION		Vertical perimeter insulation to a depth of approximately 1m (according to the drawings). For this solution is necessary to make a trench to a depth enough in order to insert insulation panes.			€/m	75			10,0		10,0		
IMPROVE THE AIR PERMEABILITY OF THE ENVELOPE	improvement for traditional masonry (brick/concrete constructions)	Installation of a new internal plaster layer (min 1 cm) over the existing one, plus an air stop band in correspondence of the connection element ("wall-ceiling", "wall-floor", "wall-wall (angular)"), plus an air stop element where the building plant crosses the building element (pipe, ventilation, etc...), plus a sealing electric box and tube. After works, verification costs are applicable (e.g. blower door test, Air Leakage Testing Audits, etc.).	-	<500m^2 of floor	€/m^2	76	25,4	13,3	10,0	42,5	10,0		46,4
				>500m^2 of floor	€/m^2	77	25,4	13,3	10,0	42,5	10,0		46,4
	improvement for wood/prefabricated wall	Removal and replacement of the internal layer, plus air stop band in correspondence of the connection element ("wall-ceiling", "wall-floor", "wall-wall (angular)"), plus air stop element where the building plant crosses the building element (pipe, ventilation, etc...), plus sealing electric box and tube. After works, verification costs are applicable (e.g. blower door test, Air Leakage Testing Audits, etc.).	-	<500m^2 of floor	€/m^2	78	25,5	13,4	10,0	42,8	10,0		46,7
				>500m^2 of floor	€/m^2	79	25,5	13,4	10,0	42,8	10,0		46,7
IMPROVE THE THERMAL QUALITY OF THE WINDOW	**BASE REFURBISHMENT LEVEL OF WINDOWS**	Repair/restoration the old window components (glasses and frames) for aesthetic/functional/security reasons	-	<100m^2 of window area	€/m^2	80	36,7	32,1	10,0	75,7	10,0		82,6
				>100m^2 of window area	€/m^2	81	36,7	32,1	10,0	75,7	10,0		82,6
	Window glazing substitution	Windows glazing substitution, keeping the actual frames.	Double glass with air cavity (16mm) New thermal transmittance value of glazing U$_g$= 2,7 W/m²K; g= 0,78; T$_{vis}$= 0,82	<100m^2 of window area	€/m^2	82			10,0		10,0		
				>100m^2 of window area	€/m^2	83			10,0		10,0		
			Double glass with air cavity (16mm) and a low-e glass New thermal transmittance value of glazing U$_g$= 1,7 W/m²K; g= 0,72; T$_{vis}$= 0,81	<100m^2 of window area	€/m^2	84			10,0		10,0		
				>100m^2 of window area	€/m^2	85			10,0		10,0		
			Triple glass with argon cavity (2x16mm) and low-e glass New thermal transmittance value of glazing U$_g$= 1,0 W/m²K; g= 0,64; Tvis= 0,74	<100m^2 of window area	€/m^2	86			10,0		10,0		
				>100m^2 of window area	€/m^2	87			10,0		10,0		
	Window replacement	Replacement of the old single-glazed or double-glazed windows by highly efficient, airtight double-glazing windows. This solution will therefore improve the tightness.	Double glass with air cavity (16mm) New thermal transmittance value of glazing U$_g$= 2,7 W/m²K; g= 0,78; T$_{vis}$= 0,82 New thermal transmittance value of frame U$_f$=2,2 W/m^{2}K	<100m^2 of window area	€/m^2	88			10,0		10,0		
				>100m^2 of window area	€/m^2	89			10,0		10,0		
			Double glass with air cavity (16mm) and a low-e glass New thermal transmittance value of glazing U$_g$= 1,7 W/m²K; g= 0,72; T$_{vis}$= 0,82 New thermal transmittance value of frame U$_f$=1,4 W/m^{2}K	<100m^2 of window area	€/m^2	90	260,9		10,0	287,0	10,0		313,1
				>100m^2 of window area	€/m^2	91	260,9		10,0	287,0	10,0		313,1
			Triple glass with argon cavity (16mm) and a low-e glass New thermal transmittance value of glazing U$_g$= 1,0 W/m²K; g= 0,64; T$_{vis}$= 0,74 New thermal transmittance value of frame U$_f$=1,0 W/m^{2}K	<100m^2 of window area	€/m^2	92	175,0	120,0	10,0	324,5	10,0		354,0
				>100m^2 of window area	€/m^2	93	175,0	120,0	10,0	324,5	10,0		354,0
			Triple glass with argon cavity (18mm) and a low-e glass New thermal transmittance value of glazing U$_g$= 0,65 W/m²K; g= 0,6; T$_{vis}$= 0,733 New thermal transmittance value of frame U$_f$=0,95	<100m^2 of window area	€/m^2	94	214,0	120,0	10,0	367,4	10,0		400,8
				>100m^2 of window area	€/m^2	95	214,0	120,0	10,0	367,4	10,0		400,8
	Double window (Adding a new window to the existing one)	Addition of a new window in the wall thickness maintaining the existing one. The new window will be installed in the opposite alignment of the wall to the existing one.	New window with simple glazing with thermal transmittance value (frame + glazing) U$_w$= 5 W/m²K	<100m^2 of window area	€/m^2	96			10,0		10,0		
				>100m^2 of window area	€/m^2	97			10,0		10,0		
			New window with double glazing with thermal transmittance value (frame + glazing) U$_w$= 2,7 W/m²K; g= 0,78; Tvis= 0,82W/m²K	<100m^2 of window area	€/m^2	98			10,0		10,0		
				>100m^2 of window area	€/m^2	99			10,0		10,0		
	Sealing of joints	The weather-stripping around the perimeter of the frame seals the window, eliminating drafts and creating a thermal barrier. Reduce air permeability of the window at least to 3rd class (9 m³/hm²) of the standard "EN 12207 Windows and doors - Air permeability - Classification".	Reduce air permeability of the window up to 3rd class (9 m³/hm²) of the standard "EN 12207 Windows and doors Air permeability - Classification"	<100m^2 of window area	€/m^2	100			10,0		10,0		
				>100m^2 of window area	€/m^2	101			10,0		10,0		