Evaluation of energy renovation measures and review of problems and solutions regarding metering and billing of heat consumption

A Case study of a residential building in Zagreb

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Synopsis:

In this Master thesis an evaluation of energy renovation measures and of chosen solutions for solving problems regarding metering and billing of heat consumption are presented. For this purpose, a case study of a residential building in Zagreb has been chosen. An extensive literature review, data collection, and a numerical modelling have been carried out to present potential solutions.
Apart from presenting the current situation in the residential sector, in both the EU and Croatia, a methodology behind the data collection and the model have been given with the main aim of representing the model which corresponds to the real-life case.
After the validation of the model, renovation scenarios have been developed to evaluate the most cost-effective solution. Results include heat savings, investment costs and the payback time of all solutions.
Furthermore, several options for solving problems regarding the metering and billing methodology have been selected and examined by comparing the investment costs and the possibility for fostering incentives for heat savings by changing habits and behaviour of the residents.
Lastly, a critical discussion is presented to reflect on assumptions, limitations, and decisions made together with the conclusion to sum up the outcomes of energy renovation and remodelling of the existing metering and billing methodology.

Preface

This Master thesis was written by a student of the Master program Sustainable Energy Planning and Management at Aalborg University, as a part of the 4th semester. The project was written from June 2, 2016 to September 1, 2017.

Reading Instruction

Sections, Tables and Figures are numbered chronologically in accordance to a chapter number (e.g. the first figure in Chapter 2 is numbered 2.1, the next is numbered 2.2, and so forth). Explanatory text to figures and tables can be found in the related captions.

The Harvard Referencing System has been chosen for references. The references used in the text have labels of the type [Author, Year]. All the references are listed in the Reference Chapter at the end of the report.

Monetary values and numerical representations

All monetary values in this report are represented in Croatian Kuna (HRK). One Euro (1 EUR) is equivalent to 7.406 HRK, according to the Croatian National Bank (September 1, 2017).

Values displayed in tables and graphs are rounded depending on their magnitude. Since the calculations were performed with the original values, slight discrepancies may arise when comparing the results displayed in this report.

Acknowledgements

The author would like to thank Poul Alberg Østeergard, his mentor, for his suggestions and supervision throughout the creation of the Thesis. It was not an easy assignment to give advices and to monitor the progress without a proper face-to-face meeting.

Next, the author would like to thank a company called "Alfa-inzenjering Ltd" for providing information, access to their database of conducted energy audits and for participating in interviews. Without them, data collection would be a significantly heavier task to perform. Also, the author would like to thank to a company called "Ista Ltd" for providing information regarding the implementation process and investment costs of flux calorimeters and heat allocators.

Last but not least, the author wants to thank to all family members and friends who have been a never-ending source of motivation throughout the whole education process. Without them and without Nevenka Hendrih none of this would be possible.

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Abbreviations and Acronyms

CES	Croatian Energy System
$CFRS2$	Climate Forecast System Reanalysis
CO_2	Carbon Dioxide
$DD-method$	Degree - day method
DHW	Domestic hot water
EC	European Commission
EED	European Energy Directive
$EEOS$	Energy Efficiency Obligation Scheme
$EIHP$	Energy institute Hrvoje Požar
$EPBD$	Energy Performance in Buildings Directive
EPS	Expanded polystyrene
EU	European Union
$EU-27$	European Union before Croatia joined (27 members)
$EU-28$	European Union after Croatia joined (28 members)
$FZOEU$	Fond za zastitu okolisa i energetsku ucinkovitost (The Environmental Protection and Energy Efficiency Fund)
GDP	Gross Domestic Product
GHG	Greenhouse gas emissions
GtCO2e	Gigatonnes of equivalent carbon dioxide
HEP	Hrvatska Elektroprivreda (Croatian Energy Company)
HRK	Hrvatska kuna (Croatian kuna)
IEA	International Energy Agency
$IPCC$	Intergovernmental Panel on Climate Change
kWh	kilo-Watt hour
$Mtoe$	Million Tonnes of Oil Equivalent
MWh	Mega-Watt hour

$O\&Mcosts$	Operation and Maintenance costs
PVC	Polyvinyl chloride
RES	Renewable Energy Sources
RS_{e}	External surface resistance
RS_{i}	Internal surface resistance
SHF_{air}	Specific heat factor for air
T_{a}	Ambient air temperature
T_{indoor}	Indoor temperature
T_{ref}	Reference temperature
UK	United Kingdom
$UNEP$	United Nations Environment Programme
$UNFCCC$	United Nation Framework Convention on Climate Change
WHO	World Health Organisation
XPS	Extruded polystyrene

Introduction 1

Since human activities have begun to be evaluated, it has been concluded that, over the last few decades, they are one of the main factors and contributors of climate change caused by an increase of carbon dioxide concentration in the atmosphere[EIHP, 2014a] [Duić et al., 2005]. According to Pacheco et al. [2017], climate change is the most important problem nowadays due to numerous negative consequences such as sea level rise, heat waves, health problems. Once it was undeniable that mankind has contributed significantly to climate change, a proper energy transition became a crucial step in combating GHG emissions, on both the national and supranational level [IPCC, 2016]. As a part of human activities, the energy sector is characterised as a crucial sector which has to be included in order to properly tackle climate change. The energy sector should be prioritized since it accounts for two-thirds of global GHG emissions [IEA, 2013]. There are numerous reasons for the current situation, from the amount of energy consumed, certain ways of energy generation (and fuel used) to the lack of energy efficiency in all sectors.

Furthermore, according to the WHO [2014], the population is growing rapidly which will lead to an increase in energy demand across all sub-sectors, by approximately 2% per year [GEA, 2012]. If present trends continue, the global energy demand and environmental problems are expected to rise by more than one-third over the next twenty years [IEA, 2013]. In addition to this, an increase in fuel dependency in unavoidable since 1/3 of imported fuels come from Russia and 1/3 of imported gas and oil come from other unstable areas such as Middle East countries [Krajačić et al., 2011]. Therefore, it is clear that the energy system needs to be modelled and changed to secure a supply of energy in a sustainable way without adding carbon which eventually can lead to GHG emission reduction [Østergaard and Andersen, 2016].

To tackle climate change, the EU has agreed on several ambitious goals and formulated several strategies on both the short (2020) and the long term (2030 and 2050). Apart from the ultimate goal of reducing GHG emissions by 80-95 % by 2050, there are goals of increasing RES consumption and of increasing energy savings [European Commission, 2014a]. If one implements RES, fossil fuel dependency can be reduced and less fuels is needed (and imported) which apart from environmental benefits has economic benefits as well. On the other side, focusing more on the demand side of the energy system, by implementing energy savings, one needs less energy. Following the fact that the cheapest (and the best) energy is the energy which does not need to be produced [European Commission, 2016b], it is very beneficial to invest in this area which can immediately mitigate a lot of problems without changing the supply side in terms of large investments [Pacheco et al., 2017].

For instance, according to IEA's report Yang [2013], energy efficiency policies and implementation of numerous measures saved around 49% of energy use between 1973 and 1998 in 11 countries, while a further potential of 20% of savings is predicted by the end of 2030. Moreover, energy efficiency is characterised as the most feasible way to improve competitiveness of any market and to reduce the impact of both existing and future economic crisis, especially those which can be caused by volatile energy prices [Lund and Hvelplund, 2012]. According to Billington et al. [2012], retrofitting can play a crucial role in economic recovery in the UK and can be a possible solution for combating energy poverty.

As a significantly large part of the energy sector, the building sector, which consists of the residential and the services sector, is responsible for a very high energy consumption on a global level (30% of total energy consumption) which is expected to grow [Lopez-Gonzalez et al., 2016]. According to Wang and Holmberg [2014], the existing buildings account for 30-40% of the total energy utilisations in cities. In terms of CO_2 emissions, the building sector accounts for approximately 33% of energy-related CO_2 emissions worldwide [Ürge-Vorsatz et al., 2012]. When it comes to the EU, existing buildings account for approximately 41% of the energy consumption and are responsible for 35.8% of CO_2 emissions [Filippidou et al., 2016]. In absolute numbers, 448.4 Mtoe and 1,253 Mt CO_2, respectively. A lack of energy efficiency and an increase in the heat demand resulted in an increase from 400 to 450 Mtoe over the past 20 years [Marina Economidou et al., 2011] with the danger of increasing more and more over the time due to increase in population and floor space. With a significant share of energy consumption, it is clear that the building sector has to be improved through energy renovation which is instrumental for reaching the long term goals [Saheb et al., 2015].

It is important to highlight that the existing buildings have to be renovated since they will dominate for the next 50 years with a negligible share of new buildings which have stricter building codes and must fulfil stricter energy performance requirements. According to Xing et al. [2011], the share of new buildings will always be insufficient to make a significant change in the whole building sector. On top of that, according to Ascione et al. [2015], 14% of the EU-27 building stock dates from before 1919, and about 12% dates between 1919 and 1945. It is undeniable that the majority of the current EU building stock has very low energy efficiency since most of those are built back in 1970s when building codes were non-existent. Therefore, without high-standard energy retrofits, energy use and corresponding GHG emissions could be "locked-in" for the future and could be increased for more than one-third by 2050 [GEA, 2012].

The residential sector, as a part of the building sector, represents approximately 66% of the energy consumption and 61.2% of the emission of the total building sector in the EU [European Commission, 2014b]. In other words, residential buildings account for more than 20% of total energy consumption in the EU and is responsible for 313.4 Mt CO_2 annually [Sadineni et al., 2011]. The share varies from country to country, based on the current situation, already implemented energy efficiency measures, national strategies, climate conditions etc. For instance, in Sweden, 40% of the final energy consumption is used in the existing building stock (with 60% of it classified as energy for residential buildings, mostly for space heating and hot water) [SEA, 2015]. In Germany, according to McKenna et al. [2013], households are responsible for about a third of the final energy demand.

In the Italian case, buildings account for 35% of the final energy consumption, with 66% of this quantity as the residential sector's demand [ENEA, 2012]. On the EU level, the average consumption of the residential sector is 134 kWh/m^2 which is classified as energy class D [Lukic et al., 2015]. Numerous reports presents methodologies and possible scenarios for energy renovations which deal with the building envelope, heating and cooling technologies through energy efficient building concepts which can achieve a significant energy savings by 2020 [European Commission, 2017a]. Many of those state that the energy renovation in the existing dwellings provide unique opportunities for reducing energy consumption and GHG emissions [Filippidou et al., 2016; Sadineni et al., 2011; Copiello, 2016; Wu et al., 2016; UNFCCC, 2015; Ürge-Vorsatz and Novikova, 2008], while the most optimistic prediction states that building upgrades with energy savings and a proper building envelope can achieve savings up to 80% over 45 years [Tommerup and Svendsen, 2006].

In terms of climate policy goals and ambitions which can enable a proper energy transition and energy savings, 2016 brought the very first binding climate deal on a world scale (the Paris Agreement) which has a direct impact on national energy roadmaps and strategies. It gives a clear and an ambitious direction for investments into innovations, prioritizes a successful transition to a clean energy future and gives legislative proposals which cover energy efficiency, renewable energy, the design of the electricity market and the security of energy supply [European Commission, 2016b]. It is important to mention that energy efficiency is listed as a top priority of the Paris Agreement (Putting energy efficiency first!). The role of the EU in the Paris Agreement is to lead towards the low-carbon energy system since the EU is the third largest emitter of GHG emissions globally. Apart from changing the electricity, heating and cooling sectors, energy efficiency can contribute to a large extent in combating climate change and achieving EU goals [Welsch et al., 2017]. According to the Energy Union Vision, the residential sector is an essential part of a proper energy transition since it has the biggest potential for achieving better security of energy supply, more transparent energy bills and lower expenses [European Commission, 2017d].

In last few decades, the EU has played an important and active role in finding proper solutions to the climate problems. The European Commission (EC) has set climate goals and has established the energy policy for the short term (2020 [European Commission, 2017a]) and the long term 2030 [European Commission, 2017b] and 2050 [European Commission, 2017c] which are as follows:

- a reduction of 20% of GHG in comparison to 1990 was put as a mandatory request for Member States (MS) by the end of 2020; increase the share of RES to at least 20% of consumption; achieve energy savings of 20%
- a 40% drop of GHG emissions in comparison to 1990 (each MS can define its own way of achieving it) until 2030; at least 27% share for RES; at least 27% improvement in energy efficiency
- a more ambitious and rigorous reduction until 2050 of 80-95% in comparison to 1990 which implies significant integration of RES; implementation of large-scale energy efficiency measures and transition to passive houses

Two major European Directives for improving the existing energy system in terms of energy efficiency and achieving the above-mentioned goals are The Energy Performance in Buildings Directive (EPBD) and the European Energy Directive (EED). The EPBD aims to accelerate building renovation, raise public awareness and amount of information for investors by reinforcing energy performance certificates and, lastly, to subsidy renovations thought its Annexes [European Commission, 2016a]. The reason for creating this Directive is an embarrassingly low rate of renovation (barely 1% - 223 million m^2 of building floor) which, in other words means, that it would take a century to upgrade the existing building stock to modern energy levels which fulfils the EU's goals [European Commission, 2016a]. The other Directive, EED, puts forward legally binding measures to use energy more efficiently in all links of the energy chain - from the transformation to the end-use through Articles [European Commission, 2013b]. It states that energy efficiency should be recognized as one of the most cost-effective ways to combat climate change and to secure supply of energy.

Through Article 7, the European Commission (EC) obliges each country to either establish an energy efficiency obligation scheme (EEOS) or use alternative policy measures to achieve a certain targeted amount of energy savings. This Article is the main carrier of this Directive with half of the energy savings which should be achieved. Article 8 is responsible for promotion of energy audits, while Articles 9-11 are dealing with another relevant problem - metering and billing of energy. Article 9 requires that final customers have a meter which will accurately reflect their real energy consumption, especially for multi-apartment and multi-purpose buildings, Article 10 gives final customers a right to detailed information on their energy consumption, while Article 11 gives a right for final customers to receive bills and billing information free of charge [European Commission, 2013a]. In other words, each customer, according to these Articles, must pay for the actual energy consumption, in a transparent way [Kiss, 2013]. The reason why is this so important is the existing metering and billing methodology in multi-apartment buildings, as explained in Section 1.3 and Chapters 2 and 5.

These two Directives are the main policy drivers in reducing energy consumption in buildings with already proven effectiveness in all Member States which implemented their Articles and obligations. For instance, according to Filippidou et al. [2016], 16.8% of dwellings have improved their label class by using seven renovation measures in The Netherlands, while Ireland had met 39% of its 2020 target by the end of 2014 [Collins and Curtis, 2016]. Also, there are now twelve active EEOSs which are implemented through Article 7 and are responsible for end-use energy efficiency [Rosenow and Bayer, 2017].

1.1 The current situation in the Croatian energy system (CES)

As the newest Member State of the EU, Croatia has slowly started to implement EU's Directives (EED and EPBD) in order to successfully transform its energy system. According to Bertoldi et al. [2015], Croatia stated in the 2014 National Energy Efficiency Action Plan (NEEAP): *"In order to achieve the specified target, the Republic of Croatia has* *opted for a combination of the two (EEOS and the application of alternative measures). The cumulative energy savings target for the 2014-2020 period is 54,250 PJ of which alternative policy measures should save 32,094 PJ, while EEOS should achieve 22,156 PJ of energy savings."* Apart from energy savings, the Croatian economy can be boosted to a large extent by performing energy renovation of the existing building stock, in both residential and service sectors [Popescu et al., 2012]. This statement is derived from the fact that Croatia imports around the half of its energy needs for heating and electricity, as presented in Figure 1.1 - self-supply was evaluated to 57.1% in 2015. In Croatia, the national electrical company HEP spent around 1,943 million HRK for import of electricity and 1,799 million HRK for import of fuels for energy production in the same year [HEP, 2015]. These two figures accounted for 16% of total Croatian expenditures in 2015 (7% of GDP). In other words, dealing with the import in the energy sector in terms of its reduction should be recognized as an important problem worth addressing and solving.

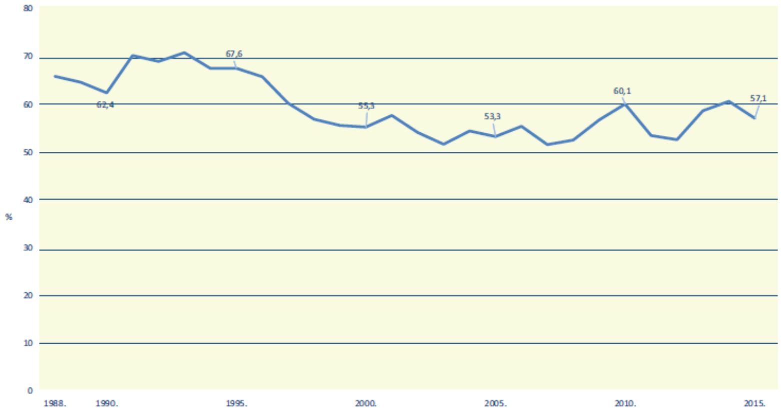

Figure 1.1: Self-supply of energy in Croatia, [EIHP, 2014b]

It is unavoidable that, without energy efficiency measures, the share of import will increase in the future. Therefore, if current trends are not changed, Croatia will become more and more dependent on foreign countries which can have volatile energy prices and directly impact the Croatian economy. Furthermore, in 2005, it was stated that around 1% of GDP is lost per year due to lack of energy efficiency [Ministry of Economy Labour and Entrepreneurship, 2010]. As in all European countries, energy efficiency measures are needed since the CES is responsible for around 3/4 of GHG emissions in Croatia. Also, reduction of usage of primary energy via energy efficiency has to be performed since the CES uses 16% more primary energy per GDP unit than on the average in the EU-27 [Ministry of Economy Labour and Entrepreneurship, 2009]. In the Energy Strategy of the Republic of Croatia, energy efficiency has been classified as the ultimate tool for combating problems in the energy sector and for achieving both national and EU's goals [Connolly et al., 2015].

The Croatian residential sector is one of the most interesting in terms of combating climate change, along with the industry and the transport, since it is one of the largest energy consumers (75 PJ per year - around 40% of final energy demand [Pukšec et al., 2013] - higher than the EU average). The reason for lies in the fact that the Croatian industry never recovered to its pre-Civil War level, which increased the share of the residential sector in the overall energy consumption [Pukšec et al., 2014]. Another reason for is lack of building regulations and neglecting existing building codes which has resulted in high energy consumption and high energy bills. Since energy consumption heavily depends on technical characteristics, type of heating and cooling, appliances and lightings, one should look into those segments to improve the existing situation.

The current situation in Croatian households can be seen in Figure 1.2 where the biggest share of energy used is for space heating. However, over the last few decades, several energy renovation initiatives have been implemented which slightly decreased the share to 68% with a rate of -0.15% per year in the last decade. This high share is due to the fact that the majority of both single and multi family buildings were built before 1987 with no or minimal thermal insulation (energy class E or even lower) [Ministry of Construction and Physical planning, 2017]. In other words, the average energy consumption for heating is accounted from 150 to 200 kWh/m2. It should be mentioned that 65% of households are classified as family houses, while the rest (around 50 million m2 of area) is accounted for apartment buildings, mostly in continental area [EIHP, 2014a].

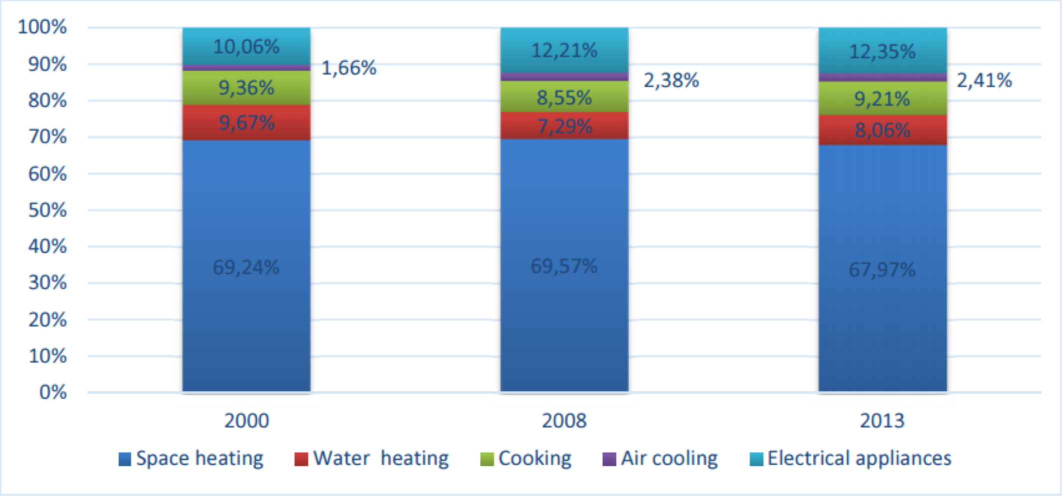

Figure 1.2: End-use of energy in Croatian residential sector, [Alenka Kinderman Loncarevic, 2015]

Energy audits and a creation of energy certificates of buildings, as well as renovation of both family houses and apartment buildings has been recognized as a top priority in Croatian energy strategies, laws and initiatives, mainly since the above-mentioned adoption of EED and EPBD. Since March, 2014 (before Croatia joined the EU), the Government established a Fund for Environmental Protection and Energy Efficiency (FZOEU) which has the main goal of increasing energy efficiency in all sub-sectors of the CES. The biggest attention was given to the residential sector through advising and subsidising (over 270 million HRK) [Ministry of Construction and Physical planning, 2017]. After ascension to the EU, the budget drastically increased together with the share of co-financing. However, there are several demands for applied projects to be accepted - achieved energy savings, share of living area, share of unheated area and energy class of the building.

1.2 Heating in the Croatian residential sector

Energy efficiency measures in the residential sector of Croatia (and in the EU) are a crucial step in achieving desirable outcomes in the future energy system according to EU's Strategies for 2020, 2030 and 2050. With a variety of possible approaches and with a different scope (extent) of measures, one can reduce energy demand and achieve significant energy savings. However, according to Connolly et al. [2015], heat savings are very cost-effective at the beginning, but become more expensive on a unit basis (i.e. €/kWh) to implement more heat savings. It is clear that, at some point, the cost of additional heat savings surpasses the feasibility of transformation of the supply side of the system to a more sustainable version. Therefore, it can happen that it is cheaper to supply heat than to keep saving it after several implemented energy efficiency measures. In other words, it is not the most cost-effective option to upgrade the existing building stock to energy class A since the cost-benefit ratio is not as feasible as, for instance, upgrade to energy class B or C. The best possible outcome should be evaluated by analysing different scenarios.

The problem becomes even more complex if one aims to renovate apartment building which are mostly built before 1987 when building codes were non-existent in the CES. There is no thermal insulation of walls, while windows are in very poor condition - the whole building envelope is insufficient regarding energy efficiency. Another reason for aiming at apartment building is the fact that they are the preferred type of building in capital of Croatia, Zagreb due to density of population [Gradski ured za strategijalno planiranje i razvog Grada, 2012]. Many of those buildings share same problems regarding energy efficiency, as it will be explained in Chapter 2. There are usually multiple owners in apartment buildings who either live in their own apartments or rent them. In a situation like this, it is very complex to perform any energy renovation measures due to low public awareness and neglecting attitude towards the effectiveness of energy savings, while the owners have the right to refuse any energy efficiency improvements. Therefore, it is crucial to present them the possibility of improvements and expected savings, both from a technical and an economic point of view.

Remodelling the building envelope is usually the best possible approach for achieving energy savings since space heating is the most energy intense end-use in EU homes and apartments and accounts for around 70 % of end-use energy in residential sector. If one includes heat generation via fossil fuels, volatile prices and share of import of energy in Croatia, it can be seen that there are numerous benefits of energy renovation which results with reduction of energy demand.

Another important problem, directly related to apartment buildings, has to be highlighted. In almost all buildings built during the Communism-era (until the late 1990s), heat metering and billing is very inefficient, unfair and presents one more barrier to efficient use of energy. The apartment buildings connected to district heating network mostly have two calorimeters - one on the inlet pipe and one on the outlet pipe of the building which measure heat consumption for space heating and domestic how water (DHW) preparation, as it will be explained more afterwards. Later, heat consumption is divided per area (m2) of each apartment or per number of people. In that way, owners do not pay for the actual consumption per apartment, but for the averaged consumption. Negative consequences are numerous, from a lack of incentives for energy savings per apartment since the effectiveness of energy renovation measures per one apartment are almost negligible (if only one apartment improves its envelope), to unfair metering and billing where "right of every person to pay for what is consumed" is seriously disrupted. Therefore, this problem has to be properly addressed and solved, as it analysed in Chapters 2 and 5.

1.3 Problem formulation

As seen so far, the Croatian residential sector, as a part of the building sector, is responsible for a very high share of heat consumption which is expected to grow due to the increase of population and the increase of living standard. The reason for this high share is a lack of energy efficiency (low energy performance of buildings) which is the reason for high energy bills. Although new buildings have strict building codes and standards, their share in the total building stock is negligible and is insufficient to meet the EU's energy saving goals. Therefore, a focus should be put on the existing buildings. In areas with higher density of population, such as in Zagreb, massive multi-apartment buildings were built with fifty or more apartments in one complex. The majority of those buildings were built before 1987 (during the Communism-era) when no building codes existed. Because of that, the multi-apartment buildings were built with no or minimal thermal insulation and energy inefficient windows and doors which do not preserve heat. Furthermore, an upgrade of the existing building stock to a higher energy level class should be preformed in the most cost-effective way bearing in mind that energy class A is not always the most feasible option since heat savings become more expensive on a unit basis with more heat saving implementation. Infeasible implementation of heat savings can result in surpassing the feasibility of transforming of the supply side of the system instead.

Another group of problems should be pointed out. In almost all buildings built in the Communism-era, heat metering and billing of heat consumption is both inefficient and unfair. Regarding metering of heat consumption for space heating, consumption is averaged per m^2, while metering of heat consumption for DHW preparation is averaged per person. In a lot of building complexes, there are only four calorimeters (two for space heating and two for DHW preparation) which measure heat consumption in, for instance, five buildings (or 200ish apartments). If metering is not performed in a proper way, billing for the same consumption is not fair - people do not pay for what they actually consume, but for averaged consumption per m^2 or per person.

In sum, the problems can be summarised into following main points:

- A high share of energy inefficient apartment buildings (with a very low energy performance class) which results with high energy bills and high energy losses
- Unfair metering and billing of heat consumption in multiple-apartment buildings for space heating and DHW preparation that give no incentives for performing heat savings and results in not paying for the actual consumption per apartment

1.4 Research question

Understanding the previously defined problems in Section 1.3 regarding energy efficiency measures and the metering and billing of heat consumption, this thesis aims to find the best possible approach to perform a proper renovation of a typical residential building in Zagreb and to solve problems regarding the metering and billing methodology. To be more concrete, several combinations of energy efficiency measures will be evaluated in order to find the most cost-effective option. Reasons for choosing a selected building are given in Chapter 2. Therefore, in this thesis, the following problems are investigated:

What is the most cost-effective combination of end-use heat savings in order to renovate a typical apartment building in Zagreb to achieve a higher energy class?

What is the best approach in solving problems regarding metering and billing of consumed heat while considering technical and economic limitations of a typical apartment building in Zagreb?

1.5 Thesis structure

This report consists of seven main chapters, each further divided into following sections and subsections. A diagram of the structure can be found in Figure 1.3 which can be followed for the clarification purposes.

Chapter 1 introduces the research topic with the background and contextual information upon which the problem is defined. Main problems are summarised in problem formulation which serves as the basis for research question(s).

Chapter 2 gives a description of a case study - a residential building in Zagreb which is chosen for the further investigation with the aim of giving proper solutions to the defined problems in Chapter 1 - energy renovation and problems regarding the metering and billing methodology in a residential building.

Chapter 3 consists of the methods used in the report to investigate the problem. Main topics are the case study methodology, data collection, conducted interviews, technological screening and a creation of the heat demand model for scenario analysis in Excel (overview of formulas, restrictions and simplifications).

Chapter 4 presents scenarios created for the analysis of different applied energy efficiency measures along with relevant technical and economic characteristics. This Chapter is built upon methodology described in Chapter 3. Also, it gives a detailed overview of results for each scenario in terms of technical improvements and costs. On top of that, a comparison between scenarios is presented and explained to find out the most cost-effective approach for renovation of selected case study after the reference scenario is validated.

Chapter 5 presents the existing metering and billing methodology, a general overview of problems regarding the metering and billing of heat consumption, shortly presented in

Chapters 1 and 2, and of possible technical solutions (options) according to literature overview and technological screening.

After the presented work, Chapters 6 and 7 synthesizes the presented analyses of energy renovation and solutions of problems regarding the metering and billing methodology, along with the discussion of limitations set in the analysis. The main observations and conclusions are presented for the purpose of answering the research questions.

At the end, the report also contains a list of used literature and references cited throughout the thesis using the Harvard Referencing Style. In addition, Appendix is given which consists of an example for heat demand calculation (for a random hour in a random day) and of the existing billing methodology for a single apartment (on a monthly basis).

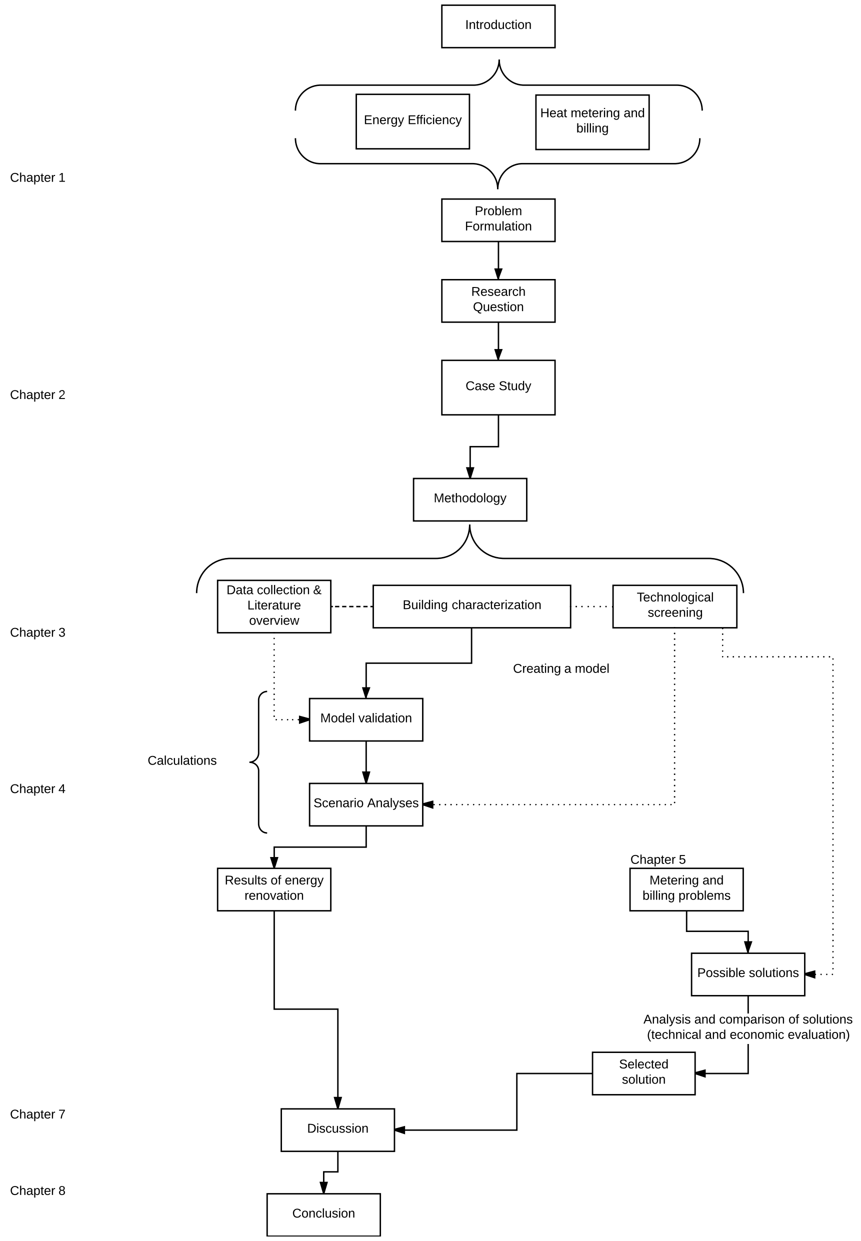

Figure 1.3: Thesis Outline

A case study of the residential building in Zagreb

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If one wants to develop an in-depth understanding of the current situation, there is a necessity of using case studies which can provide an exploratory and descriptive view of problems [Baxter and Jack, 2008] - in this case a lack of energy efficiency and problems regarding the metering and billing of heat consumption in the residential building. The first step in forming a case study requires a definition of the case under the study, which in this thesis takes the form of reducing the heat demand through the implementation of energy efficiency measures and achieving a fair metering and billing of consumed heat. To follow, the type of case study design should be considered in terms of the unit of study - this is, whether single or multiple entities are examined - and if any supplementary data are embedded or not in order to expand the understanding of the case [Yin, 2012]. In this sense, the single-case of typical residential building in Zagreb is chosen, which is presented in Figure 2.4. The choice is the result of following:

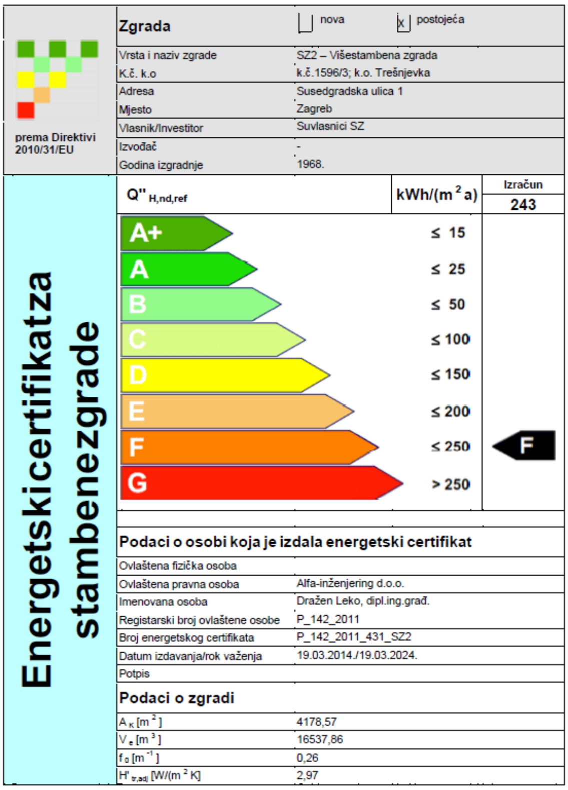
- Data availability
  Necessary information are obtained from a family member of the author who is a tenant representative and has a clear insight in all bills in the building. Also, technical information and suggestions are obtained from the energy certificate, as presented in the Figure 2.1 and from the energy audit report [Alfa-inzenjering, 2014b].

- Low energy performance of this type of buildings
  As it can be seen in Figure 2.1, the selected building has an energy class E which indicates a very low energy performance with 243 kWh/m2 of the heat demand. This heat demand is the result of insufficient thermal insulation of the building envelope which needs to be improved.

- Familiarity with problems regarding energy efficiency and metering
  Since a family member of the author is a tenant representative and the author has lived in this building for 15 years, a very clear insight can be obtained with specific problems - technical, economic and social which needs to be addressed and solved, as mentioned in Section 1.3.

- Possibility of replication of solutions/conclusions from this thesis
  If one excludes family houses, this type of building is a typical residential building in Zagreb built during the Communism. According to Gašparović and Božić [2005],

there is more than fifty complexes similar to this one in Zagreb, while an architect who designed this three-building complex, Slavko Jelinek, made plans for more than thirty residential complexes in his career [DAZ, 2000]. Therefore, there is a possibility of replicating conclusions and technical solutions from this thesis in order to solve similar problems in other buildings. In other words, the same approach and solutions can be taken into account in other similar projects.



Energetskicertifikatza stambenezgrade

prema Direktivi 2010/31/EU

Zgrada	☐ nova ☒ postojeća
Vrsta i naziv zgrade	SZ2 – Višestambena zgrada
K.č. k.o	k.č.1596/3; k.o. Trešnjevka
Adresa	Susedgradska ulica 1
Mjesto	Zagreb
Vlasnik/Investitor	Suvlasnici SZ
Izvođač	-
Godina izgradnje	1968.

$Q''_{H,nd,ref}$	kWh/(m^{2}a)	Izračun 243
A+	≤ 15	
A	≤ 25	
B	≤ 50	
C	≤ 100	
D	≤ 150	
E	≤ 200	
F	≤ 250	F
G	> 250	

Podaci o osobi koja je izdala energetski certifikat	
Ovlaštena fizička osoba	
Ovlaštena pravna osoba	Alfa-inženjering d.o.o.
Imenovana osoba	Dražen Leko, dipl.ing.građ.
Registarski broj ovlaštene osobe	P_142_2011
Broj energetskog certifikata	P_142_2011_431_SZ2
Datum izdavanja/rok važenja	19.03.2014./19.03.2024.
Potpis	

Podaci o zgradi	
A_K [m^2]	4178,57
V_e [m^3]	16537,86
f_0 [m^{-1}]	0,26
$H'_{tr,adj}$ [W/(m^{2}K]	2,97

Figure 2.1: Energy certificate of the selected building [Alfa-inzenjering, 2014a]

This case study is descriptive in terms of presenting information regarding the heat demand, the building envelope and the existing metering and billing methodology as follows.

2.1 Heat demand

Taking a closer look into the building's characteristic and technical specification for the metering and billing shows the existing situation in terms of energy consumption, metering and billing problems. Currently, 168 people live in the building, of which 120 live in their own apartment and the rest are tenants in rented apartments. The building consists of seventy (70) apartments divided in four apartments per floor with the exception of the upper floor (only two apartments), while the rest is the shared terrace of 100 m^2. The apartments are divided into three sizes: 54 m^2, 56 m^2 and 72 m^2. The total living area of all apartments (total heated area) is 4104 m^2, while shared corridors, staircase and basement (250 m^2) are not heated. Since the heat producer and distributor, HEP-toplinarstvo Ltd is obligated to provide all end-users with information regarding consumption, monthly consumption and bills are obtained from the tenant representative. According to obtained data, total delivered heat in 2016 was slightly less than 800 MWh which was delivered from the local district heating plant, while the contracted capacity for meeting heat demand in the building was 312.73 kW. The local district heating network can be classified as 2nd generation of district heating, where heat carrier is pressurised hot water with the temperature above 100 °C which is preheated in gas-fired central station and then reheated by using countercurrent heat exchangers on-site. It is important to mention that the figure (800 MWh) includes DHW preparation which is prepared in the local DH plant to 30 °C and then additionally heated up to 45 °C on-site (two countercurrent heat exchangers in the building's basement). The overall costs for produced and delivered heat was 246,775 HRK divided among variable costs (heat consumption) and fixed costs (maintenance, additional costs). Energy bills are explained in Section 2.3.

2.2 Envelope

Regarding the building envelope, the situation varies from one apartment to the other since some of owners already have performed energy renovation measures to some extent in terms of new windows, as showed in Figure 2.2, further details in Chapter 4. Therefore, as it can be seen in Figure 2.4, several apartments have better windows (PVC double layered glass) than others with better thermal characteristics than the standard wooden ones (one layered glass), installed in last few decades. Also, same as for windows, several owners replaced old entrance doors with newer as presented in Figure 2.3 which contributes to energy performance of the whole buildings. On the other side, there is no thermal insulation of exterior walls in all apartments which is the main reason for big heat losses since walls consist of 23.5 cm thick reinforced concrete blocks only which are plastered. Also, there is neither floor nor ceiling insulation between apartments (except concrete blocks) which significantly contributes to this problem.

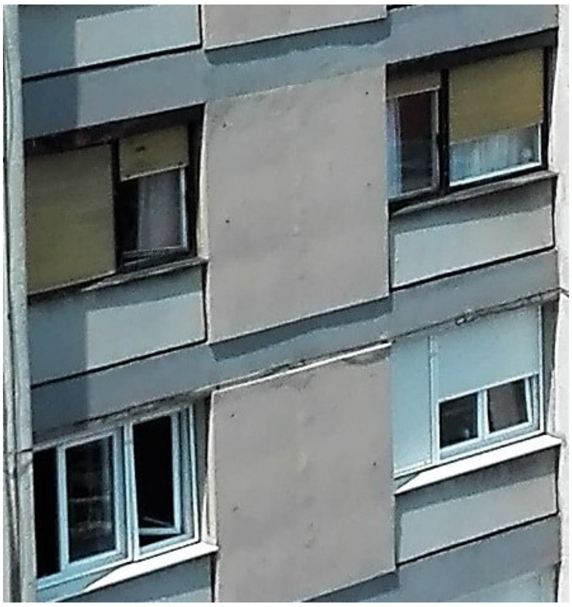


Figure 2.2: An example of old and new windows *(Photo from field visits)*

Figure 2.3: An example of old and new entrance doors of apartments *(Photo from field visits)*

On top of that, there is no wall insulation between apartments and unheated areas of the building such as staircase, shared corridor on each floor and basement. It is important to mention that each staircase has a row of single glazed windows on each floor, as it can be seen in Figure 2.4 between two main pillars of the building. Walls in the basement are 70 cm thick and made of reinforced concrete blocks. The terrace is divided into an insulated (10 cm of EPS layer) and uninsulated part (bigger part). Lastly, as a result of the existing situation, coefficients of heat losses through the building envelope are showed in Table 2.1. It can be seen that the biggest losses are due to lack of thermal insulation of walls (60% of total losses), which can be perceived as the biggest potential for energy renovation, along with losses by ventilation (15%) and through other openings (16%) due to old windows and doors. All additional information are given and analysed in Chapter 4.

Table 2.1: Heat losses through the building envelope [Alfa-inzenjering, 2014a]

Type of losses	W/K
Losses through walls	8,940
Losses through uninsulated flat roof	810
Losses through insulated flat roof	34
Losses thought the ground	413
Losses by ventilation	2,183
Losses through other openings	2,388
Total	14,768

Figure 2.4: The selected residential building in Zagreb *(Photo from field visits)*

2.3 The metering and billing of heat consumption for space heating and DHW preparation

It is important to note that the selected building is a part of three building complex which has a complex metering and billing methodology. All three buildings are connected to the same inlet and outlet calorimeters which meter heat consumption for DHW preparation for all apartments. The consumption is then averaged per person and charged per number of people in each apartment. Regarding the metering of heat consumption for space heating, since November 2016, each building in the complex has their own inlet and outlet calorimeters. Before that, all three buildings were connected to the shared calorimeters (just as for the metering of heat consumption for DHW preparation), but billing of heat consumption for space heating was averaged per m^2 of apartment (of total area of all three buildings), instead of per person and charged per each apartment. After installed calorimeters were tested and commissioned, heat consumption for space heating is averaged per m^2 for each building separately and charged per each apartment. An installation of individual calorimeters for DHW is considered by tenant representatives and negotiations are under way with the relevant heat producer and distributor (HEP - Toplinarstvo Ltd). Details and an actual example of metering and billing of heat demand for space heating and DHW preparation in the selected building will be explained in Chapter 5, along with the specific problems.

Regarding the billing of heat consumption, the author did not manage to meet with relevant stakeholder (HEP - Toplinarstvo) which produces and supplies heat to the building. However, the prices are obtained from a published document by HEP-toplinarstvo Ltd and by collecting and observing energy bills for the author's apartment. Moreover, a methodology behind the metering and billing of heat consumption has been studied and presented in Chapter 3. An example of real calculation on a monthly basis will be presented in Appendix A. For now, it should be said that there are separate models for capacity used, space heating and DHW preparation, along with sub-models. According to HEP [2014], several tariffs exist for consumers, of which a tariff Tg1 is set for the residential sector. Also, based on the heat carrier (hot water or pressurised steam), there is sub-tariff or tariff model - in this case, TM1 (residential building which uses pressurised hot water). A billing of heat consumption per apartment is divided into six items, as presented in Table 2.2.

Table 2.2: Billing of heat consumption in the selected building *(Photo from field visit)*

Description of costs	Unit	Amount	Price/unit	Total
Energy for production of heat	kWh	606	0.1525	92.42
Energy for distribution of heat	kWh	606	0.0175	10.61
Capacity used for production of heat	kW/month	4.267	2.3	9.81
Capacity used for distribution of heat	kW/month	4.267	3.45	14.72
Costs for delivery of heat	HRK/month	1	7.02	7.02
Costs for DHW preparation	m^2	56	0.69	38.64
Total (excluding Tax)				173.22
Tax (25%)				43.31
TOTAL				216.53

On a scale of the whole building, costs for producing and delivering heat, and for operation and maintenance costs (O&M) could be explained as follows. Firstly, a tenant representative has to make a contract with HEP-toplinarstvo regarding the capacity used for heat production in a local district heating plant. Based on contracted capacity, O&M costs are defined as a constant value per month (5123 HRK for the whole building), while fuel costs are defined by Croatian energy regulatory agency - for this type of district heating and of the building, fuel price is set to 0.17 HRK/MWh of supplied heat. In 2016, a local district heating supplied around 800 MWh of heat which cost 246,775 HRK (tax included).

Methodology 3

In order to investigate and answer the research questions presented in Section 1.4, different methods, tools and techniques have been used. In that light, this chapter covers these with a focus on composition and appropriateness in the context. The chapter starts by describing case study theory and methodology since a case study of a typical residential building in Zagreb forms the major a part of the thesis based on which the research questions are answered. Following that, the methods for data collection are presented in terms of interviews, technical specifications, energy bills and weather data as all of these are necessary for the heat demand calculation and for the analysis of the metering and billing methodology. Also, a methodology behind the created heat demand model is explained.

For energy renovation purposes, a technological screening is performed to obtain a certain number of alternatives regarding wall improvements, new windows and improvement of envelope of unheated areas. Therefore, a methodology in terms of literature review for technological screening is explained. Also, the methodology used for solving problems regarding the metering and billing methodology is given. Finally, there is a presentation of a methodology for business-economic analysis (financial indicators) used for a comparison of different alternatives in Chapters 4 and 5.

3.1 Case study - theory and methodology

The case study methodology allows the exploration and understanding of complex issues and can be considered a robust research method when a holistic, in-depth investigation is needed [Yin, 2009]. The reason for the recognition of case study as a research method is that researchers have become more concerned about the limitations of other methods. By using the case study methodology, a researcher can go beyond the quantitative statistical results and explain both the process and outcome of a phenomenon through complete observation, reconstruction and analysis of the case(s) under investigation [Zainal, 2007]. It is designed to bring out the details from multiple standpoints by using multiple source of data. In other words, it is the most flexible of all research designs, allowing the researcher to retain the holistic characteristics of real-life events while investigating empirical events [Schell, 2006], within events' context using a variety of data sources [Tellis, 2007].

As it was stated above, the case study approach is an approach to research a certain phenomenon within its context using a variety of data sources in order to ensure that a problem is not explored thorough one lens (in only one direction). The case study method enables a researcher to closely examine the data within a specific context, usually in a small geographical area or very limited subjects of the study [Zainal, 2007]. In other words, a case study observes the data at the micro level, especially when a big sample is difficult to either process or obtain [Yin, 2009]. For instance, a case study helps researchers to understand complex issues through experience and knowledge of previous researches. At the simplest level, the case study provides descriptive accounts of one or more cases, but can also be used to achieve experimental isolation of one or more selected problems within a real-life context [Schell, 2006].

This approach should be used [Yin, 2009]:

- When the focus of the study is to answer how, what or why questions - when explanatory or descriptive questions are formulated
- When multiple sources of evidence are used
- When one wants to cover context because the author believes they are relevant to the phenomenon under study

The first step in case study research is to create a firm research focus by forming questions about the problems which will be studied, as presented in Section 1.3. The questions are targeted to a limited number of events or conditions and their inter-relationships [Tellis, 2007]. To create those questions, a literature review is conducted which establishes what research has been previously done and leads to more insightful questions about the problem. After forming a firm focus, type of case study and approach is determined - exploratory, explanatory, descriptive, collective etc. Also, the researcher must consider if it is prudent to conduct a single case study or if a better understanding of the phenomenon will be gained through conducting a multiple case study [The University of Texas, 2017]. A single case study is used for a problem related to a specific area or specific situation, while a multiple-case study includes more single cases. In that way, the unit of analysis is set where one or two issues are chosen for understanding of the examined system and relevant problems. It is important to consider what the case will not include in order to avoid too broad questions or a topic with too many objectives. In that light, boundaries should be set on a case by time and place, time and activity and/or by definition and context (or combination of those) [Baxter and Jack, 2008]. Also, instruments and data gathering approaches are selected.

As for this study, a descriptive single case study is chosen in terms of selecting a single apartment building in Zagreb. Relevant data have been obtained as explained in Section 3.2, while a spread sheet has been used as a analytical tool for creating a heat demand model, as presented in 3.3.1. This case (reference scenario) is then compared to the real-life data (energy bills), obtained by data collection in order to validate a created model. Furthermore, in order to answer the research questions, several scenarios have been made to evaluate the most cost-effective option for energy renovation and several options to solve problems regarding the metering and billing methodology. The reason for selecting the case study approach should be emphasized. Firstly, as mentioned above, this approach is used when the focus of the study is to answer how and what questions which is fulfilled by setting descriptive questions as the research questions. Also, multiple sources are used in terms of data collection and the creation of model. Lastly, as mentioned in the last bullet, this approach is relevant for this study since the data are used within the context - energy renovation and solving problems regarding the metering and billing of heat consumption. All the data collected is obtained with the assumption that it is relevant for this study, while excess of information (and unnecessary information) has been removed. An energy renovation in terms of replacing the building envelope is a relevant phenomenon when one wants to tackle energy (heat) savings in the residential buildings. Therefore, it can be concluded that this approach is appropriate approach in solving problems given in Chapter 1.4.

Regarding advantages of using a case study method, firstly, the examination of data is usually handled within the contest of its use - within the situation in which problems take place. Unlike the experiment, where a focus is put on a limited number of variables, case study examines a specific problem in a specific environment which would not maybe occur in any other surrounding due to, for instance, climate condition, behaviour of people etc [Zainal, 2007] Secondly, variations in terms of approaches in different categories of case studies allow for both quantitative and qualitative analyses of the data. By using a different type of case study and different approaches, different outcomes can be achieved. Lastly, the case study approach can explain the complexities of situations and describe the data in real environment which may not be understandable through other types of research such as experimental or survey research.

On the other side, the case study also has several disadvantages. It can happen that the researchers allow that biased views or evidences influence the direction of the findings and conclusions [Zainal, 2007]. Also, case studies provides an insufficient basis for scientific generalisation since they are focused on a specific problem on a micro level. Lastly, often they can be characterised as being too long, difficult to conduct and producing a lot of documentation which can be a big disadvantage (if data is not handled properly). Regarding this thesis, it would be inaccurate to make a generalisation regarding energy renovation measures and the metering and billing methodology based on the outcome of analysis in Chapter 4, but the same approach and the methodology could be replicated in order to give answers to different research questions. Consequences of using this approach are mentioned and discussed in Chapter 6.

To sum up, the above-explained case study methodology can be applicable in this project in order to get answers to the research questions presented in Section 1.4. By using a descriptive single case study as in this project, specific energy renovation problems, as well as problems regarding the metering and billing of heat consumption can be thoroughly explained. As mentioned above, an examination of real data is done which confirm that the selected case study is a reliable model of the real life situation which is later used for the analysis of different possible solutions (scenarios). Also, different focuses can be set in the case study methodology and thus, different outcomes can be achieved which greatly complements with scenario approach -different goals can be set and achieved through modelling of the created system. Just as in any case study, boundaries have been set by using specific research questions which directly defined scope and delimitations of the analysis. This can be perceived as both an advantage and a disadvantage - the author already knew what outcome is the aim of the study, but new knowledge, insights and replicable data are obtained for the future.

3.2 Data collection

For the purpose of presenting and analysing the existing situation in the selected residential building, certain data have to be obtained and processed. In this section, applied data gathering methods are explained with an explanation of the necessity for reliable sources and adequate estimations and assumptions.

3.2.1 Literature review

In the first phase of the thesis, different sources in the literature are considered and explored to gain a better and in-depth understanding of the topic - energy renovation, metering and billing heat consumption in the residential buildings. An identification and a selection of different sources in the literature is performed by searching different research databases such as ScienceDirect [Elsavier, 2017] and ResearchGate [Madisch et al., 2017] where keywords relevant for this study are used. For more specific relevant data, Croatian government websites are visited, as well as websites of the Croatian national energy company (HEP Ltd) and of the Energy Institute Hrvoje Požar since other sources gave limited results on a more specific level. This search was conducted in Croatian, since most of the literature are official reports available only in Croatian.

3.2.2 Interviews

Relevant information about specific problems in the selected case has been collected by performing interviews with a tenant representative and a company conducted the energy audit and created the energy certificate for the selected building - Alfa-inzenjering [2014a]. This method was selected to address specific issues and to get a better insight on a micro level. Both of the interviews can be classified as semi-structured interviews where a set of questions were prepared, but were not handed directly. Instead of this, questions were asked progressively, while the interviewees were put in charge of the interview with a full freedom of leading a fluent conversation. In that way, more knowledge is gained since interviewees are not bounded and can develop area of interest that the author did not anticipate or know about, especially regarding problems in the existing metering and billing methodology where the tenant representative provided with a lot of useful data. It should be mentioned that interviews were not recorded and transcribed.

During these interviews, a lot of data necessary for the heat demand model are obtained such as technical characteristics of the building, costs of several energy renovation options and details the regarding metering and billing of heat consumption, as presented in Chapters 4 and 5. Data mentioned above is crucial for a proper validation of the model. The author could have done other interviews, but did not manage to set up appointments with the governmental bodies and HEP - Toplinarstvo, an energy company which produces and supplies heat to the selected building and which created the existing billing methodology.

3.2.3 Weather data

For the purpose of estimating heat demand (presented in Section 3.3.1), different weather parameters needs to be obtained. The relevant data consists of ambient temperature for applying the degree-day (DD) method, and solar irradiance to estimate to which extent sun radiation contributes to covering (reducing) the heat demand. These parameters are extracted on an hourly basis for the whole year, for the purpose of establishing an hourly heat demand model. Obtained data is based on Climate Forecast System Reanalysis 2 (CFRS2) data which are extracted from a software tool EnergyPRO 4, developed by EMD International A/S [2017]. The basic principle of CFSR2 is to combine real world observations of weather station networks and measurements derived from a satellite which are numerically predicted for each one-half degree of horizontal resolution [The National Center for Atmospheric Research, 2017]. A location in the map (in EnergyPRO) can be picked to gather weather data for available years. In the case of this project, the closest data point for Zagreb was found at 16°9'E and 45°41'N, which is a location of a hydrometeorological stations at Velika Gorica which is approximately 20km further south-east from the building's actual location, according to Google Maps. It should be mentioned that climate condition in Velika Gorica is the same as in Zagreb.

3.2.4 Technical specifications of the apartment building

Besides of weather data, technical characteristics of the residential building are needed for creating the heat demand model. These information are obtained by observing the building during the field trip, but the majority of data was provided by Alfa-inzenjering [2014a] in their energy audit report [Alfa-inzenjering, 2014b]. Most of information needed for establishing the heat demand model can be seen in Table 3.1. Formulas used in the model are presented in Section 3.3.1, while the actual data for each apartment and the whole building are given in Chapter 4 (in numbers). It should be mentioned that several numbers have either been simplified or estimated, such as heat transfer coefficients, due to lack of information and unavailability to meet with a company which is in charge for maintaining of the building. It should be mentioned that indoor walls have not been renovated in any apartment yet. Therefore, all apartments are more or less similar with the same rooms disposition.

Table 3.1: Technical characteristics of the apartment building for establishing the heat demand model [Alfa-inzenjering, 2014b]

Building part	Information needed
Exterior walls	Total area, heat transfer coefficient, thickness, material
Interior walls	Total area, heat transfer coefficient, thickness, material
Windows	Type and number, heat transfer coefficient, total area
Apartment's floor and ceiling	Total area, heat transfer coefficient, thickness, material
Building's roof	area of insulated roof, area of uninsulated roof, thickness, material, heat transfer coefficient
Basement area (unheated)	Total area, thickness of walls, material of walls, temperature
Staircase area (unheated)	Total area, temperature
Staircase's windows	Type, heat transfer coefficient, total area
Corridor	total area, temperature
Other information	Total heated area, area of apartments, temperature in each room, room height, heat losses

3.3 Energy renovation model

Apart from data collection and literature review, an energy renovation model is created in Microsoft Excel and established to simulate a real life situation in the selected residential building regarding heat consumption. Also, the model serves for estimation of benefits from implementing heat savings measures. To create a model, data gathered and obtained in data collection serve as input parameters, as explained in Section 3.3.1. These inputs include building envelope characteristics, thermal comfort, heat demand, monthly heating bills etc. The results of the model have then been compared with the real data to validate the created model. All gathered data is used for validation of heat demand calculations which serves as evidence of data reliability. On top of that, there is a possibility for assessing different energy renovation alternatives (scenarios) by changing building envelope characteristics to assess the energy saving potential for the selected residential building. An estimation of heat savings after implementing improvements have been carried by changing numbers in the energy renovation model to asses the most cost-effective alternative. A summarized presentation of this process is showed in Figure 3.1. It should be mentioned that, if the real1 heat demand and the calculated heat demand do not match, revalidation of data is done by changing temperatures in unheated areas and assumed U-values of different parts of the building envelope.

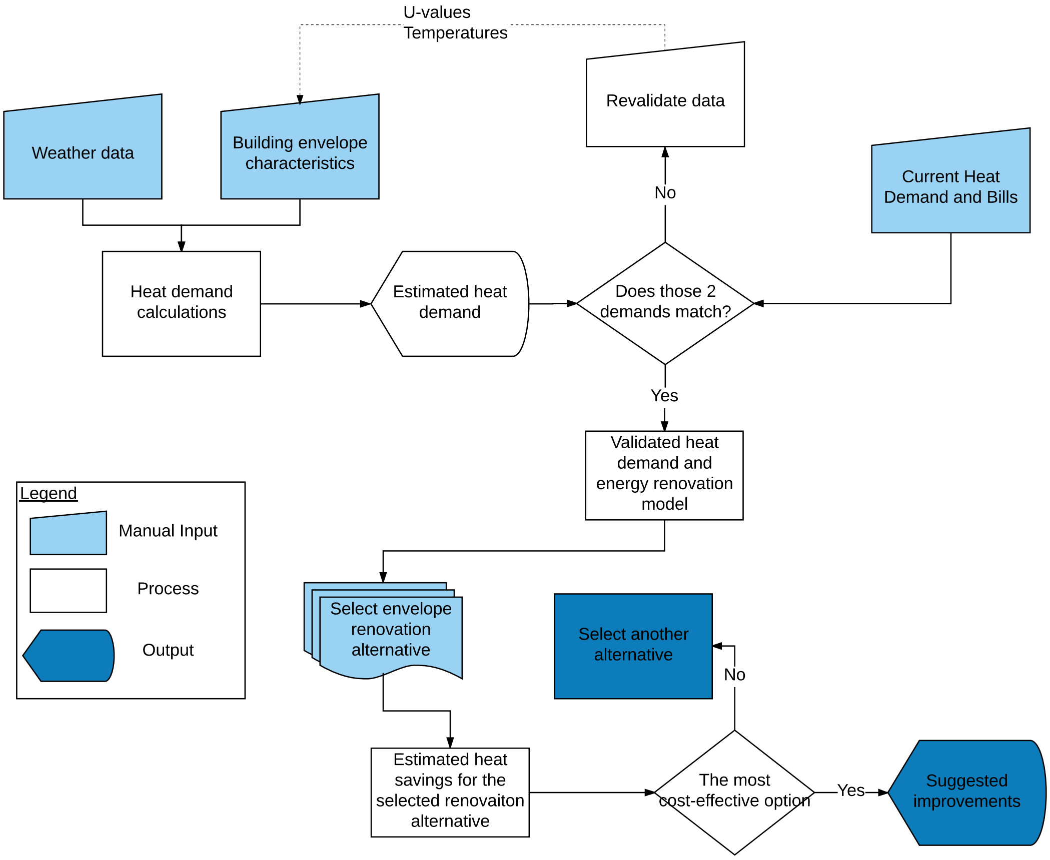


Figure 3.1: Energy renovation model work-flow

3.3.1 Heat demand calculation

As it can be seen in Figure 3.1, heat demand calculation (estimation) is built upon building envelope characteristics, namely the material of walls, windows, floors and ceilings, as well as their dimensions. After gathering data, one can estimate their heat transfer coefficient which shows how much energy is lost through the envelope due to bad energy efficiency performance. Firstly, before setting up a model limitations, simplifications and basic characteristic of the model should be given, as follows:

- The created model is an hourly model which calculates heat demand on hourly basis, using technical characteristics of the selected building and obtained ambient temperature from energyPRO.
- This model is a steady state model - it has fixed temperatures, while heat capacity of apartments and walls, as well as of furniture in the apartments are neglected.
- Since all apartments have the same heating option and exactly the same radiators (without thermostatic valves), it can be assumed that all apartments have the same indoor temperature - theoretically, there is no heat flow between apartments. However, dissipated heat in the apartments is not the same due to a position of each apartment and influence of unheated areas in the building. It should be noted that all rooms in the apartments are heated.

- Unheated areas are identified in the building - basement, corridors on each floor, staircase and elevators. Temperature of each unheated area is calculated in a relation with indoor and outdoor (ambient) temperature while taking into account ventilation losses. as well as thermal properties of walls and position of unheated areas in the building. For instance, corridors are under bigger influence of indoor temperature since they are surrounded by apartments' walls. Estimated relations for each unheated areas will be presented below.
- Heat losses are calculated per apartment and then summarized for the whole building. Also, in the model, heat losses are divided based on the side of the world and on the type of heat transfer (through walls, windows or doors).
- All apartments on the same side of the building have the same layout since no major renovations have been performed in terms of changing the building envelope and of changing the layout of inner walls.
- The presented model does not include heat demand for preparation of DHW since building envelope has no effect on consumption of DHW, but the number of people in the apartments and their habits, behaviour and water consumption.
- As presented below, ventilation losses and solar gains are simplified to a single formula for each loss/gain per hour. Ventilation losses are based on the time needed for full exchange of all air inside the apartments, while solar gains are calculated using the solar irradiation, obtained from energyPRO. Coefficients used in formulas are either obtained or estimated, based on technical characteristics of different parts of the building envelope.

As it was mentioned, a heat demand is calculated per apartment, classified per type of heat transfer through different parts of building envelope such as walls, windows, doors, floors and ceilings, as seen in Equations 3.2, 3.3 and 3.4, respectively. For each formula, the measure of relative heat energy at each hour is needed. This measure is estimated as degree days (DD), which is the difference between indoor ($\mathrm{T_{indoor}}$) and outdoor (ambient) temperature ($\mathrm{T_a}$), assuming the latter is lower than a balance reference temperature ($\mathrm{T_{ref}}$) of 10 °C - set in this model, as showed in Equation 3.1.

$$DD = \begin{cases} 0, & \text{if } T_a \geq T_{ref} \\ T_{indoor} - T_a, & \text{otherwise} \end{cases} \tag{3.1}$$

After estimating the degree-day, the next step is to calculate the heat flow through different parts of building envelope. The main characteristic in equations below is heat transfer coefficient (U) which can be explained as a coefficient that describes how well the heat has been conducted (in Watts) through one square meter of a structure divided by the difference in temperature across the structure [GreenTAG, 2017]. By using the equations below, heat flow through walls, windows and doors can be calculated. It can be noticed that all three equations are the same in their essence, with the difference of using appropriate U-value of different parts of the building envelope and the related area.

$$q_{walls} = U_{walls} \cdot A_{walls} \cdot DD \tag{3.2}$$

$$q_{windows} = U_{windows} \cdot A_{windows} \cdot DD \tag{3.3}$$

$$q_{doors} = U_{doors} \cdot A_{doors} \cdot DD \tag{3.4}$$

To summarize the heat flow through the building envelope to atmosphere, a single formula is used as seen in Equation 3.5.

$$q_{envelope} = q_{walls} + q_{windows} + q_{doors} \tag{3.5}$$

Apart from the building envelope, heat flow components are estimated which accounts the effects of ventilation and incoming solar radiation for each apartment, as presented in Equations 3.6 and 3.7. It should be mentioned that ventilation rate ($\mathrm{v_r}$) is assumed, based on the apartments' layout, type of windows and doors, same as solar gain coefficient which is heavily dependant on type of windows (single glazed or double glazed, insulation type, orientation etc). Also, it should be mentioned that $\mathrm{SHF_{air}}$ is a constant (0.33) which is calculated by multiplying specific heat capacity of air, density of air and then transformed from kJ/h to J/s (Watts).

$$q_{vent} = SHF_{air} \cdot A_{apartment} \cdot h_{apartment} \cdot v_r \cdot DD \tag{3.6}$$

$$q_{solar} = g_s \cdot A_{windows} \cdot I \tag{3.7}$$

Regarding the heat transfer to unheated areas, as explained above, temperatures of each area are calculated on an hourly basis in relation to indoor and outdoor temperatures in a certain ratio, based on influence of both indoor and outdoor temperature on that unheated area. Therefore, temperature in corridors, staircase and basement are calculated by using ratios presented in Equations 3.8, 3.9 and 3.10. Those ratios were assumed based on the author's evaluation during the field visit. By evaluating the influence of indoor and ambient temperature on unheated areas, ratios are created and changed in order to validate the model, as presented in Figure 3.1.

$$T_{corridor} = 0.8 \cdot T_{indoor} + 0.2 \cdot T_a \tag{3.8}$$

$$T_{staircase} = 0.7 \cdot T_{indoor} + 0.2 \cdot T_a + 0.1 \cdot T_{corridor} \tag{3.9}$$

$$T_{basement} = 0.5 \cdot T_{indoor} + 0.4 \cdot T_a + 0.1 \cdot T_{corridor} \tag{3.10}$$

Once temperatures are estimated, heat flow to unheated areas can be calculated by using the same approach as for heat flow through walls, windows and doors to the atmosphere. In this case, instead of using $\mathrm{T_a}$ in Degree-day, above calculated temperatures are used for respective areas, as showed in Equations 3.11, 3.12 and 3.13. It is important to mention that temperature in elevators is estimated to be the same as in corridors, while Equation 3.13 is calculated for the ground floor only, by using U-value of floor of the apartments.

$$q_{corridor} = U_{walls} \cdot A_{walls} \cdot DD \tag{3.11}$$

$$q_{staircase} = U_{walls} \cdot A_{walls} \cdot DD \tag{3.12}$$

$$q_{basement} = U_{floor} \cdot A_{windows} \cdot DD \tag{3.13}$$

Same as for building envelope, it is convenient to summarize heat flows to unheated areas to a single number, by using Equation 3.14.

$$q_{unheated} = q_{corridor} + q_{staircase} + q_{basement} \tag{3.14}$$

After calculating all components of heat flow, as for a single apartment, the overall heat flow is calculated as a sum or difference of all components accordingly to ventilation losses or heat gains from solar irradiance, as given in Equation 3.15.

$$q_{apartment} = \begin{cases} q_{envelope} + q_{unheated} + q_{vent} - q_{solar}, & \text{if } q_{envelope} + qunheated + q_{vent} > 0 \\ 0, & \text{otherwise} \end{cases} \tag{3.15}$$

In the end, the total heat demand for the selected building is calculated as a sum of heat demands for all apartments, as seen in Equation 3.16.

$$q_{building} = \sum q_{apartment} \tag{3.16}$$

DD: Degree-day [°C]
U: Heat transfer coefficient [W/m^{2}K]
A: Area [m^2]
q_{vent}: ventilation heat flow [kW]
q_{solar}: heat flow from solar radiation [kW]
$q_{envelope}$: building envelope heat flow [kW]
$h_{apartment}$: apartment height [m]
v_r: ventilation rate [0.5/h]
g_s: solar gain [-]
I: solar radiation [W/m^2]
SHF_{air}: Specific heat factor for air [W]
$q_{apartment}$: heat demand of a single apartment [kW]
$q_{building}$: total heat demand of the selected building [kW]

These results are compared to the actual heat demand obtained from energy bills, and validated, as presented in Section 4.2. In each scenario, presented in Chapter 4, a respective heat demand is calculated by using the same methodology, but new building envelope components and their characteristics are considered, as presented in Section 4.3 - different heat transfer coefficients (improved). As a result, certain heat savings are achieved in comparison to the current (actual) situation. The difference between heat demand in scenarios and actual heat demand in the current situation can be classified as energy savings which are calculated per apartment and then summarized for the whole building, as seen in Equations 3.17 and 3.18.

$$Heat\ Savings\text{ - }apartment = Q_{apartment,current} - Q_{apartment,improvements} \tag{3.17}$$

$$Heat\ Savings = \sum Q_{HeatSavings-apartment} \tag{3.18}$$

In the end, it should be mentioned that temperatures in the basement, corridor and staircase are changing according to insulation of those parts of the building. Therefore, an influence of indoor temperature and outdoor temperature varies from scenario to scenario (if energy renovation of unheated area is included), as it is presented in the results in Chapter 4. Also, it is important to highlight that only the ground floor benefits from insulating of basement in a model like presented since heat capacity of walls and dynamic state model are excluded. However, as presented later, heat losses are reduced significantly by insulating basement and other unheated areas.

3.3.2 Financial indicators

Following the heat demand model in which heating savings could be modelled and assessed, those heat savings have to be somehow translated into monetary terms to compare the cost-effectiveness of each technological improvement analysed in scenarios [Ardalan, 2012]. To achieve this, costs of using different type of building envelope insulation, labour costs and cash flows have to be taken into account.

Thus, if one wants to estimate the monetary value of the heat savings achieved through energy renovation showed in Section 3.3.1, savings are calculated as the difference between the costs before the renovation and after the renovation, as shown in Equation 3.19. Total costs consists of constant costs of operation and maintenance (O&M) and fuel costs. If an energy renovation is preformed, only fuel costs are changed, while O&M costs will remain the same. As it will be presented later, the O&M costs are divided equally per apartments in terms of additional costs, while fuel costs are distributed by using two ratios - the "area ratio" and the "occupancy" ratio, divided into two tariffs (four items) in the energy bills. In a case of a proper energy renovation with a certain heat savings, all residents should experience significant financial savings, even with the existing metering and billing methodology. The reason for this is that the existing metering methodology is based on real consumption which divided per apartment by averaging it per m^2 or per person. However, some of the apartments would benefit less due to their position in the building (near unheated areas or the terrace). Even in that situation all apartments would have a significantly lower heat consumption in comparison to the heat consumption before any energy renovation. Therefore, it can be concluded that all residents will experience benefits in a financial way.

$$Heat\ Savings\ [HRK] = Total\ Costs_{before} - Total\ Costs_{after} \tag{3.19}$$

Regarding expected investments, the price of the material and labour costs are taken into account, based on the area in which energy renovation takes place, as seen in Equation 3.20. Presented investments are calculated per apartment and then summarized for the whole building.

$$Heat\ Savings\ Investment\ [HRK] = Price\ of\ Material + Labour \tag{3.20}$$

Lastly, for the purpose of comparing the yield of each investment, a simple payback time, as seen in Equation 3.21, is calculated for each scenario. The simple payback time is presented as the ratio between investment costs and monetary value of the respective heat savings [Ardalan, 2012].

$$Payback\ Time = \frac{Heat\ Savings\ Investment}{Heat\ Savings} \tag{3.21}$$

For the end, it should be mentioned that these calculations did not considered discounted cash flow. The reason for excluding discount rate and for using a simple payback time method is that energy renovations, besides of energy savings, have multiple social, health and living comfort benefits. Also, energy renovations of the residential sector have been recognized in Croatia as crucial step (in new energy efficiency directive) and have become mandatory in the capital city. Consequences of using this approach are presented in Chapter 4 and thoroughly discussed in Chapter 6.

3.4 Metering and billing of heat consumption

Apart from the presented energy renovation methodology and estimation of heat savings by implementing new technologies, a methodology behind solving problems regarding the metering and billing of heat consumption have to be described as well. The metering and billing methodology is given in Figure 3.2 where work flow for applying different alternatives can be found. Firstly, the current situation is evaluated - a methodology behind metering of heat demand for space heating and DHW preparation is analysed, as well as models (tariffs) behind the billing methodology. Data regarding current situation is gathered and evaluated separately for the metering and the billing to detect problems. Those two methodologies are analysed in next two sections as follows. After detecting problems, several alternatives (options) are evaluated to achieve desired outcomes - paying for the actual heat consumption for both space heating and DHW preparation.

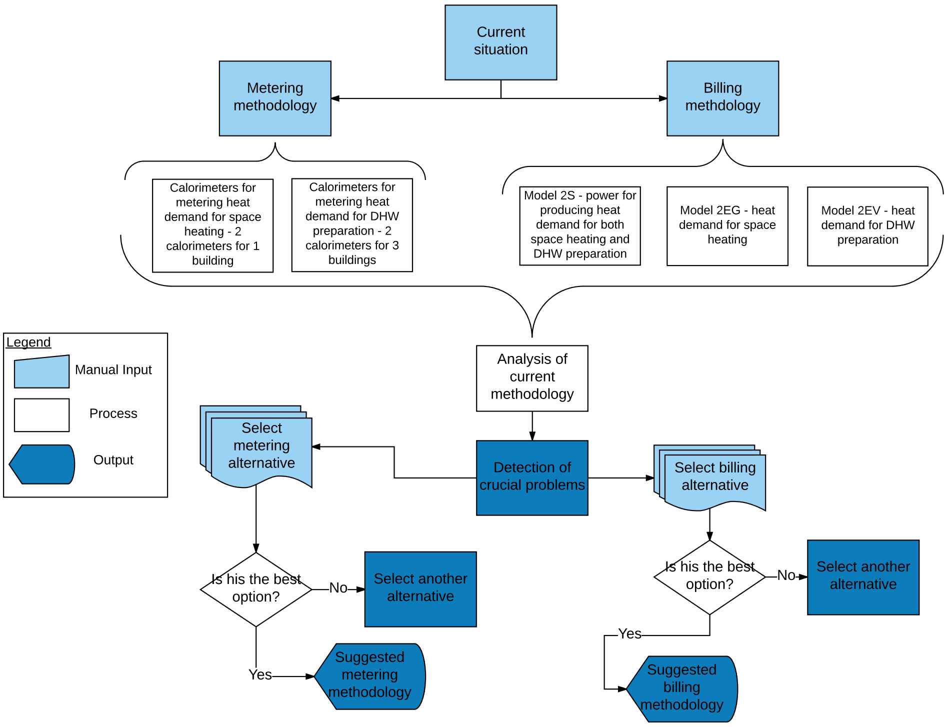


Figure 3.2: Work flow for evaluation of metering and heating alternatives in the selected residential building

3.4.1 Metering

As explained shortly in Chapter 2, metering of heat consumption is divided into two sections - metering of heat demand for space heating in the apartments and metering of heat demand for DHW preparation. For this purpose, calorimeters were installed - separately for each metering. Currently, there is a pair of shared calorimeters for DHW preparation which measures heat consumption for all three buildings (more than 200 apartments), while for metering heat demand for space heating, each building has their own inlet and outlet calorimeters for measuring heat consumption. The first step is to present a current situation.. After presenting the current methodology, relevant issues are outlined in order to explain what are the main problems which needs to be solved.

To solve problems regarding metering metering, several alternatives have been investigated and taken into account as possible solutions. Those alternatives will be elaborated according to the following parameters:

- Technology applied in a selected alternative - measurement units and working regime
- Advantages and disadvantages in comparison to the existing situation and other alternatives
- Costs of implementation (and comparison of costs between alternatives)
- Consequences of implementing each alternative regarding fostering of incentives for heat savings by changing habits and behaviour of the residents

As presented, each alternative is explained with appropriate advantages and disadvantages, as well in terms of costs and consequences of implementation since payback time and cost-effectiveness of this part of investment cannot be measures as for energy renovation model. There is neither heat savings nor any other savings, but achieving more fair metering where each apartment pays its real heat consumption. On the other hand, each presented option is evaluated in terms of fostering of incentives for heat savings by changing habits and behaviour of residents. It should be kept in mind that the billing methodology is closely related to the selected metering options - if measuring units are installed in each apartment or on each radiator, billing methodology will be closely related to those metering units, while, if no devices are installed, the billing methodology will be based on averaging the consumption by using a certain ratio. Chosen alternatives and further elaboration are pre presented in Chapter 5.

3.4.2 Billing

After improving the metering methodology, an appropriate billing methodology has to be set up to provide consumers with adequate tariff models. At the moment, the billing for space heating is related to area of each apartment, while heat consumption for DHW preparation is related to number of people in each apartment. This methodology is created by using several tariff models, as explained in Chapters 2 and 5. Models 2S for capacity usage, 2EG for space heating and 2EV for DHW preparation needs to be analysed to detect problems and give adequate solutions. As mentioned above, the methodology behind billing is strongly related to chosen metering methodology since type of measurement units can create different tariffs, models and basic units. Same as for the metering technology, the current situation is outlined to to detect relevant issues which needs to be solved by adding/removing certain parts of energy bill. After detecting those problems, the billing methodology can be modified:

- Possible improvements for the existing billing methodology
- Possible billing methodology after implementing new metering solutions
- Comparison of different alternatives - advantages and disadvantages
- Impact of the selected billing methodology on fostering of incentives for heat savings by changing habits and behaviour of residents

As it can be seen in Sections 3.4.1 and 3.4.2, the main aim of solving problems regarding the metering and billing of heat consumptions is achieving fair energy bills, following the statement - each apartment should pay for its actual consumption. Therefore, the aim of this section is not to find the most cost-effective option as in energy renovation model, but to create a model for the metering and billing where people will be charged for their real consumption. It should be immediately noted that, in a situation like this, some apartments will pay more than the others due to its orientation, area, influence of unheated areas etc. For instance, apartments i.e. on the ground floor would pay more since they are above the unheated basement, while the apartments on the first or second floor are not in the same situation. In a situation like that, the flats on the ground floor have higher heat losses due to lower temperature in the unheated basement and higher U-value of the basement's ceiling. However, the author's initial aim is to create a model where everyone will pay their real consumption since the author have a option that only that could force owners to become more rational which will end with positive behavioural changes towards achieving energy savings. Also, if owners would pay for their real consumption, numerous energy efficiency incentives would have already been implemented since people would be dissatisfied with their energy bills. Therefore, it can be stated that the author is well aware of this problem which are elaborated later in Chapter 6.

3.5 Technological screening

In order to perform an energy renovation of a building and to solve problems regarding the metering and billing methodology, various technologies have to be implemented. Since there are numerous technologies which can be presented as a possible option, it is necessary to narrow the number of options instead of conducting calculations and different scenarios for all of them due to the time frame and complexity. Therefore, a technological screening is needed to obtain a certain (sufficient) number of alternatives. Thus, different manufacturers' suggestions for both building envelope, and the metering and billing of heat consumption are analysed. Also, suggestions from the energy audit report are taken into account as possible solutions in technological screening [Alfa-inzenjering, 2014b]. This step can be recognized as a very important one valid data regarding the technical characteristics and costs is needed for realistic energy renovation calculations and improvement of the billing and metering methodology. Gathered data for energy renovation is presented in Chapter 4, while data for solving problems regarding the metering and billing of heat consumption is given in Chapter 5.

Energy renovation 4

Within this chapter, a description of technical and economic consequences of energy renovation is given in terms of achieving heat savings and lowering energy bills. Firstly, collected data is presented, as well as the most common problems in the selected residential building within the same section. Afterwards, a validation of the model detailed in Chapter 3 is presented by comparing results from the model with real life data, obtained from different sources and elaborated in Section 3.2. After the model is validated, implemented technologies in scenarios are given and explained with the relevant technical and economic characteristics. The first three scenarios consists of replacing a single part of the building envelope, while other scenarios cover combinations of first three solutions with the aim to check if a certain combination of technologies is more cost-effective than a certain technology solely. Lastly, results of different energy efficiency measures (scenarios) are presented with the aim of estimating the most cost-effective option - overview of costs for each of scenarios is given along with the simple payback time. It is important to state that the calculations and the created model are strictly related to the specific residential building's data.

4.1 Data analysis

As it is presented in Chapter 3, the first step in assessing possible alternatives is gathering reliable data. Technical characteristics about apartments and unheated areas, energy bills and relevant common problems in the selected building have been obtained and analysed. Moreover, additional information and suggestions have been provided by Alfa-inzenjering which conducted an energy audit a few years ago. Collected data has been systematized in Tables 4.1 and 4.2, where necessary data for establishing an energy renovation model are given. As it can be seen, U-values of all parts of building envelope are presented which are either obtained or estimated, as well as temperatures and areas. It should be mentioned that a simplification is made regarding windows in the apartments where all windows are classified as either wooden or PVC windows with the U-value of either 3.6 W/m^{2}K for old wooden windows or 1.8 W/m^{2}K for PVC windows. Regarding walls, it can be seen that the building's envelope consists of reinforced concrete in all parts with either very thin or no thermal insulation at all. Furthermore, a situation regarding the building's roof should be explained. As it is presented, there are two parts of which one is properly insulated (above apartments on the terrace), while the other one is insulated poorly with the U-value of 2 W/m^{2}K (above the apartments on the sixteenth floor; can be accessed).

Table 4.1: Technical characteristics of the apartment building for feeding a created energy renovation model [Alfa-inzenjering, 2014b]

Building part	Information needed
Exterior walls	$A_{\text{total}} = 2{,}493\ \text{m}^2$, $U = 3.49\ \text{W/m}^2\text{K}$ 2 cm lime-cement mortar 20 cm reinforced concrete 2 cm lime-cement mortar
Interior walls	$U = 3.49\ \text{W/m}^2\text{K}$ 2 cm lime-cement mortar 20 cm reinforced concrete 2 cm lime-cement mortar
Windows	$A_{\text{total}} = 980\ \text{m}^2$ old windows - $U = 3.6\ \text{W/m}^2\text{K}$ (wooden) PVC windows - $U = 1.8\ \text{W/m}^2\text{K}$
Apartment's floor and ceiling	$A = A_{\text{apartment}} = 54/56/76\ \text{m}^2$ $U = 2.55\ \text{W/m}^2\text{K}$ 2 cm lime-cement mortar 16 cm reinforced concrete 4 cm cement screeds 2 cm ceramic tiles
Building's roof	$A_1 = 120\ \text{m}^2$, $U_1 = 0.36\ \text{W/m}^2\text{K}$ 2 cm lime-cement mortar 20 cm reinforced concrete 0.04 cm Knauf ceiling insulation 10 cm EPS 0.5 cm PVC hydro-tape $A_2 = 100\ \text{m}^2$, $U_2 = 2\ \text{W/m}^2\text{K}$ 2 cm lime-cement mortar 20 cm reinforced concrete 0.8 cm bitumen tape 0.2 cm PE foil 3 cm sand and gravel 4 cm concrete with gravel
Basement area (unheated)	T_{basement} = Equation 3.10 $A_{\text{floor}} = 350\ \text{m}^2$, $U_{\text{floor}} = 2.61\ \text{W/m}^2\text{K}$ 5 cm cement screeds + 30 cm concrete $A_{\text{walls}} = 170\ \text{m}^2$, $U_{\text{walls}} = 2.2\ \text{W/m}^2\text{K}$ 2 cm lime-cement mortar 80 cm reinforced concrete 0.8 cm bitumen tape $n_{\text{windows}} = 15$, $A_{\text{window}} = 1\ \text{m}^2$, $U_{\text{windows}} = 4\ \text{W/m}^2\text{K}$

Table 4.2: Technical characteristics of the apartment building for feeding a created energy renovation model [Alfa-inzenjering, 2014b]

Building part	Information needed
Staircase area (unheated)	$A_{\text{per floor}} = 15$ m^2, $T_{\text{staircase}}$ = Equation 3.9
Staircase's windows	Single-glazed windows with metal casing n = 740, A = 0.18 m^2, U = 4 W/M^{2}K
Corridor	T_{corridor}= Equation 3.8, $A_{\text{per floor}} = 21$ m^2
Other information	$A_{\text{apartment}} = 54/56/76$ m^2 (minor changes in the ground floor) T_{indoor} = 22°C, T_{ref} = 10°C, h_{room} = 2.5 m

It should be mentioned that U-values presented in Tables 4.1 and 4.2 include a resistance of surface layers (R_{si} and R_{se}). This resistance occurs when heat transfer exists at the boundary between structural elements and air - it becomes more complex because more types of heat transfers are included (convention, conduction and radiation). Such boundaries exist in this case where the warm air meets the internal surface of the external wall or where the cold air meets the external surface of the external walls. To include this complex heat transfer properly, it is recognized as a resistance to heat flow and have been labelled as the internal and the external surface resistance, R_{si} and R_{se} respectively [The Netherlands Standardization Institute, 2015]. Both R_{si} and R_{se} values can be seen in Table 4.3.

Table 4.3: Surface resistance [The Netherlands Standardization Institute, 2015]

Surface resistance [m^{2}K/W]	Direction of heat flow		
	Upwards	Horizontal	Downwards
R_{si}	0,10	0,13	0,17
R_{se}	0,04	0,04	0,04

Before the explanation of common problems in the selected building, three layouts are presented to show schemes of the apartments, relevant U-values and other data used in the energy renovation model. Firstly, the ground floor layout is given in Figure 4.1 where the area of apartments can be seen, as well as unheated areas, number of windows and their respective areas. It is important to mention that only the ground floor has the entrance staircase as presented and has no balconies. Furthermore, typical floor is showed in Figure 4.2, in this case, first floor. Regarding apartments' areas, there is a big apartment with area of 76 m^2, while other apartments are very similar to those at the ground floor. The reason for this is that other floors has no entrance staircase which creates a bigger living area. Figure 4.2 also presents a layout of all other sixteen floors, except for the terrace. Lastly, terrace layout is showed in Figure 4.3 to present the differences in comparison to other floors. It can be seen that this floor consists of two apartments only and a terrace (can be accessed) with the area of 100 m^2. The terrace consists of common area for all owners and a machine rooms for elevators. In addition to all layouts, a height of each floor is given, as well as the position of basement in the first layout. Also, heat transfer to the atmosphere on the last floor should be explained. Regarding sixteenth floor, two apartments are under common terrace which is poorly insulated. Therefore, those two apartments have certain heat losses. Regarding the two apartments on the terrace (seventeenth floor), one of them has an additional external wall, while both of them are "in the contact with the ambient temperature" through their ceilings. This is one of the reasons why the common terrace should be properly insulated, as presented below.

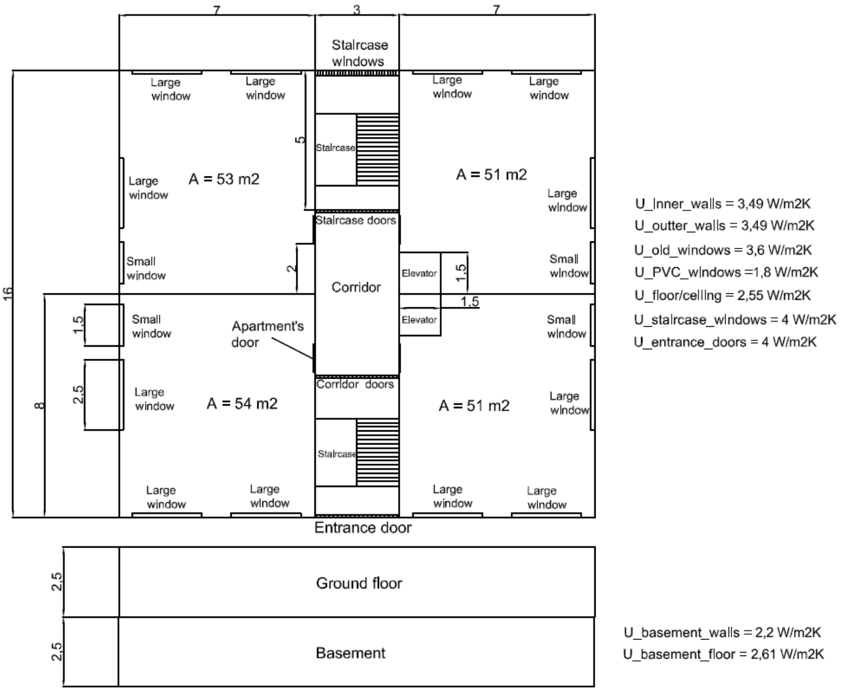


Figure 4.1: Ground floor layout

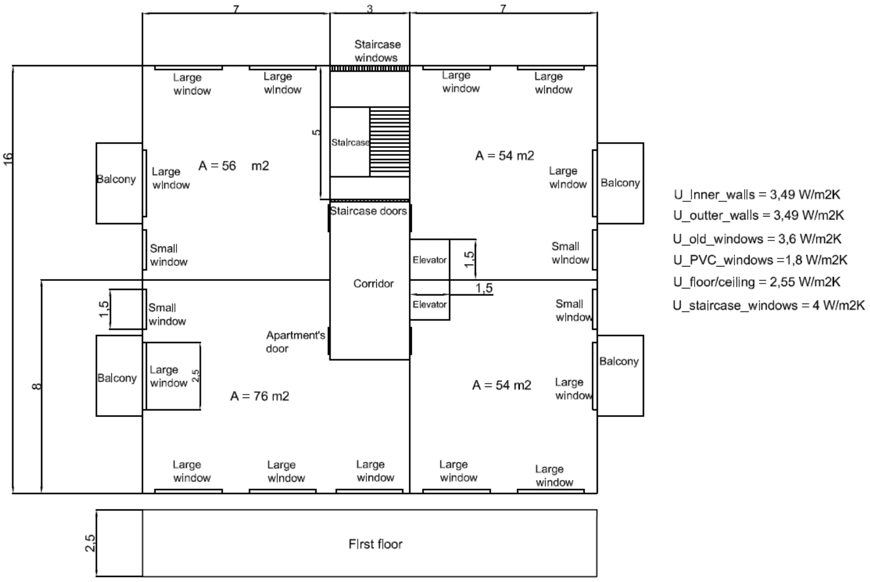


Figure 4.2: First floor layout

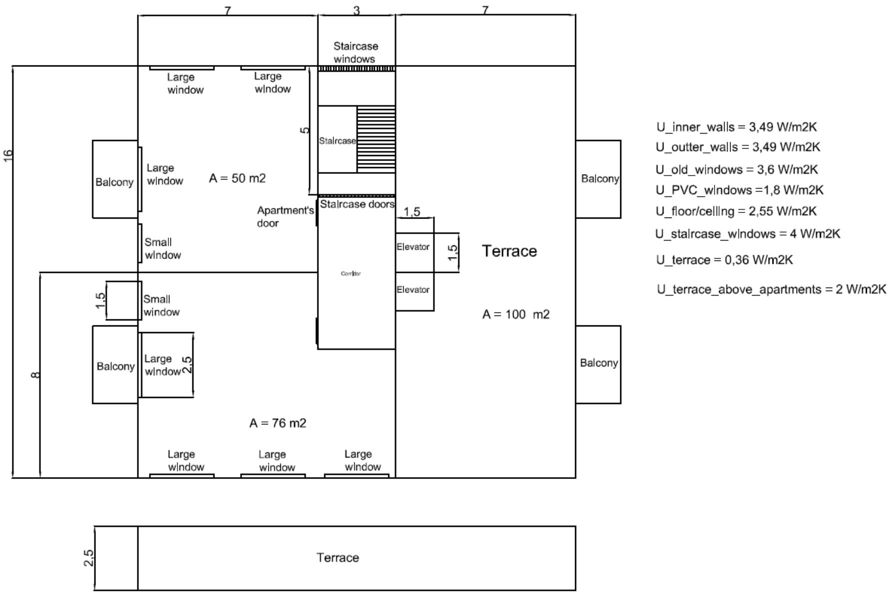


Figure 4.3: Terrace layout

Besides of technical data in terms of areas, U-values and temperatures, common problems in the building should be highlighted and illustrated to present areas which are aimed to be improved by energy renovation measures. Firstly, external walls can be characterised as a crucial part of the building envelope which needs to be improved due to the fact that U-value and materials used are insufficient and provide neither heat savings nor thermal comfort. Also, it is relevant to mention that external walls are not double walls with "room" for insulation in between (as in majority of the EU countries). Instead of this, as presented in Table 4.1, external walls consist of reinforced concrete and lime-cement mortar. The area of external walls is around 2200 m^2 and can be seen in Figures 4.5 and 4.4 - either in between windows or at corners as a big surface.

Figure 4.4: External walls as corner surfaces

Figure 4.5: External walls between windows

Furthermore, another problematic part of the building envelope are old wooden windows, presented in Figure 4.6. Most of existing wooden windows have not been replaced for decades. Also, those windows have big problems with ventilation losses, noise cancellation and regulation of thermal comfort which are all relevant problems for performing a proper energy renovation in terms of implementing newer, more energy efficient PVC windows, as presented in Section 4.4. However, a following thing should be clarified. When one is looking at windows as a part of the building envelope, they should not be treated as a homogeneous part, but as glass and frame part. Usually, a huge improvement can be made by changing glass only (or frame). However, in this situation where the majority of existing wooden windows are few decades old, frames are rotted, while single layer do not have any influence in heat conservation or mildew perseverance, wooden windows will be treated as a homogeneous part and will be replaced fully (both frames and glass). The reason for distinguishing this is that old wooden frames are often made of high-quality wood which has better ventilation rate than newer PVC windows. Although the ventilation rate will be lower than now, new PVC windows will significantly improve the U-value and life quality.

Figure 4.6: An example of a wooden window

As already mentioned, there is a part of terrace with a poor insulation (U = 2 W/m^{2}K) which causes significant heat losses in apartments next to the terrace and apartments below the terrace. A renovation of this part of the terrace was also recognized as a mandatory energy efficiency measure in the energy audit performed by Alfa-inzenjering [Alfa-inzenjering, 2014b]. Also, this area has insufficient hydro insulation which will be accounted in several scenarios since the implementation of a proper hydro insulations is planned within a next few months before the next winter period.

Figure 4.7: A part of the terrace with a poor insulation (U = 2 W/m^{2}K)

Lastly, staircase windows are shown in Figure 4.8 which are also recognised as an area which needs to be improved by retrofitting of the building envelope. The reason for implementing new windows can be found in both area of staircase windows (A = 111 m^2) and U-value of those windows (U = 4 W/m^2K) which is a consequence of windows' type - single-glazed glass windows with the metal casing. Due to their poor energy performance, the apartments (and the whole building in general) have significant heat losses since all staircase area influence on internal walls, corridors and the unheated basement. A poor energy performance can be improved by implementing new technology, as presented in Section 4.3.

Figure 4.8: Staircase windows at the first floor

4.2 Model validation

While the methodology and description behind the heat demand model has been presented in Section 3.3.1, the purpose of this section is to validate the created model by comparing results of the same with the real data. This step is of great importance since only a validated model is appropriate for the heat demand estimations which occur after a certain energy efficiency measure is implemented. Therefore, for the purposes of this comparison, the model validation is presented in table 4.4. Firstly, the real heat demand should be more elaborated. As mentioned in Chapter 2, total heat demand for both space heating and DHW preparation in 2016 was around 800 MWh - to be more concrete, 779,636 kWh. According to data obtained, 80% is accounted for space heating, while the rest is consumed for preparation of DHW. Therefore, 639,709 kWh is used for achieving desired indoor temperature in the selected building. If real data is compared with the results of the created model, it can be seen that a difference (in %) between these two numbers is 3.2% which is the acceptable deviation.

Although the created model gives similar results as obtained through data collection, several segments of model should be addressed and discussed, both in here and in Chapter 6. Firstly, atmosphere temperature (T_a) is not chosen for the exact location of the selected building, but from the nearby satellite-city of Velika Gorica which has similar climate

Table 4.4: Heat demand model validation

	Heat demand [kWh]
Reference scenario	661,105
Data	639,709
Deviation [%]	3,2

conditions as Zagreb. Furthermore, the model is not dynamic, but steady static. In other words, effects of heat capacity of walls and things in the apartments are not accounted in the heat demand model which creates a certain deviation from the real data. The reason for this certain deviation is that people and things in the apartments emit energy, while walls have heat capacity ("storage" of heat). Because of that, walls create so-called "time lag" - if they store heat in warmer periods of the day, they will emit it during the period when inner temperature is lower and vice versa. Also, instead of real temperatures of unheated areas (measured), those are estimated by using several equations as presented in Chapter 3. It is important to mention that indoor temperature of all apartments and all rooms in the apartments are assumed to be the same which creates a situation in which there is no heat transfer between apartments and rooms in the apartments. All of these assumptions will be thoroughly elaborated in Chapter 6 with relevant consequences. For now, it can be stated that even with those assumptions and limitations, this model is accurate for the purposes of scenario analyses in this thesis.

At the end of the model validation, heat losses through all parts of the building envelope should be presented for the existing situation. Therefore, percentages for each part are given in Figure 4.9.

As it can be seen, more than half of heat losses are due to a very poor condition of external walls, 58% respectively. The percentage which presents heat losses through windows shows losses through all windows, both old wooden and already installed PVC windows. Regarding losses to terrace and basement, those shares are relatively small since only eight apartments in total are related to those losses - four apartments on the ground floor, two apartments on the sixteenth floor and two apartments on the last floor (terrace). The unheated basement by itself has relatively big heat losses since it has almost no insulation (10%). Lastly, staircase windows which have been selected later as an energy efficiency measure achieve 4% of total heat losses in the building.

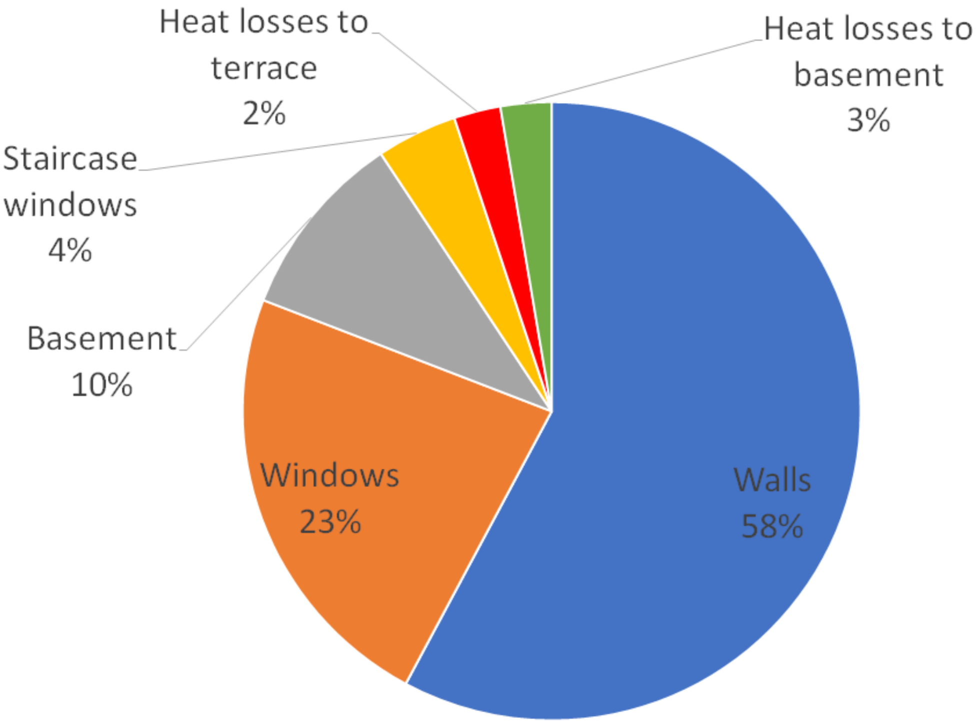


Figure 4.9: Heat losses through parts of the building envelope

4.3 Technological screening for energy renovation

Before describing the results of energy renovation, implemented technologies in energy renovation scenarios have to be presented in terms of prices, the reason for implementation and technical characteristics. The reason for such an explanation is that numerous possible approaches and different solutions exist for achieving heat savings. Therefore, it is important to explain which measures are relevant for the purposes of this project and implemented in Section 4.4. In this section, relevant technologies for energy renovations are covered in terms of changing walls, windows, floors and ceilings, basement envelope and staircase windows. Consequences of applying these technologies and of excluding other parts of the building envelope from energy renovation alternatives are given in Chapter 6.

Wall insulation

A first reviewed technology for the energy renovation is an additional insulation of external walls. As presented in Section 4.1, the condition of existing external walls is not sufficient and needs to be improved to achieve heat savings. Large heat losses are recognized since there is no façade (58% of total heat losses). Heat losses can be reduced by implementing various wall insulation solutions. The U-value of existing external walls is 3.49 W/m^2K, consisting of lime-cement mortar and reinforced concrete. By having more energy efficient external walls, condensation problems which can cause mildew and overheating of the apartments can be reduced. Therefore, external walls insulation is one of the most important energy renovation measures in the selected residential building.

The chosen technology for the improvement of external walls is a mineral wool which has become a popular option due to the good U-value (0.45 W/m^{2}K), better inflammability and steam diffusion, as well as competitive price (280 HRK/m^2). It should be mentioned that this price includes 12 cm thick layer of mineral wool, adhesive agent (base coat render), glass mesh, flattering mass, primer and finish, as well as costs of labour [IKoma, 2017]. An example of above-presented technology can be seen in Figure 4.10.

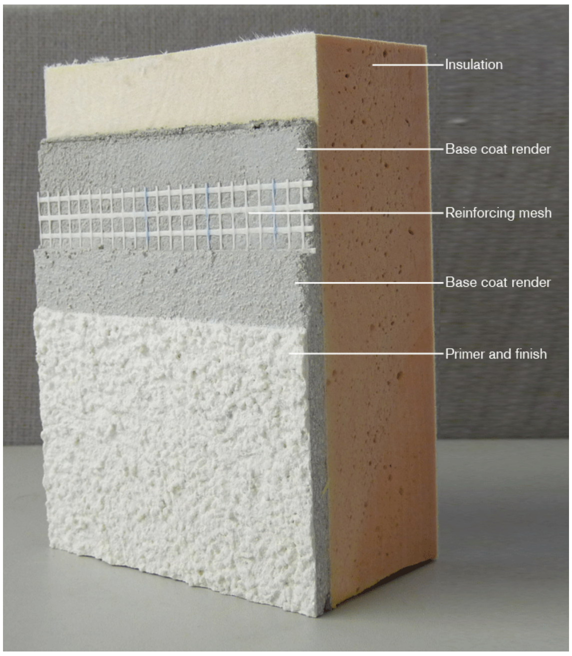


Figure 4.10: An example of a mineral wool insulation

Windows

The next technology taken into account is the replacement of wooden windows which are in a poor condition - U-value is estimated to 3.6 W/m^{2}K, while living comfort is seriously disrupted based on owners' feedback and author's elaboration during the field visit.A majority of the existing wooden windows are single-layered glass windows - many of them have not been changed for decades. On the other hand, several apartments already implemented new PVC double-layered glass windows which have better technical characteristics (U = 1.8 W/m^{2}K) and secure better living comfort in the apartments. A Croatian branch of the German company Gealan was contacted which provided with their own catalogue of PVC windows. A model called Gealan S 8000 IQ is selected as the energy renovation measure for old windows and can be seen in Figure 4.11. The price of this model is 1000 HRK/m^2, while it can be described as double-layered glass window with air chamber between layers as an additional insulation layer [Skelin Mont, 2017]. By implementing this model, U-value would be improve to 1.8 W/m^{2}K. As mentioned before, old wooden windows are fully replaced (both glass and frame). As a result, ventilation rate is reduced since new PVC windows are more air tight than old windows. Also, inner glass surface temperature is expected to increase (in case of new double-layered glass windows). However, since life quality and the U-value is improved drastically (heat savings are achieved), new PVC windows are chosen as an improvement.

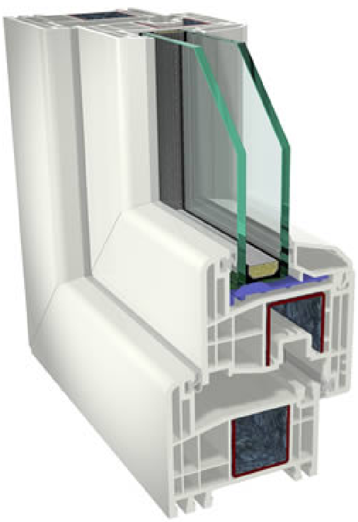


Figure 4.11: Windows model Gealan S 8000 IQ [Skelin Mont, 2017]

Terrace insulation

Another part of the building envelope which has been recognized as a problematic in terms of the energy performance is a part of terrace above apartments on the last floor, as already presented in Figure 4.7. This part has area of 100 m^2 and includes area above the apartments, machine room for elevators and a part of accessible terrace for owners. With the U-value of 2 W/m^2, this area should be insulated to reduce heat losses through ceilings of the apartments. The chosen energy renovation measure is applying 20 cm of extruded polystyrene foam (XPS) and PVC hydro tape under the existing layer of sand, gravel and concrete which ensures U-value of 0.35 W/m^2K. The price of the selected improvement is 250 HRK/m^2 which includes costs of labour as well. XPS can be seen in Figure 4.12.

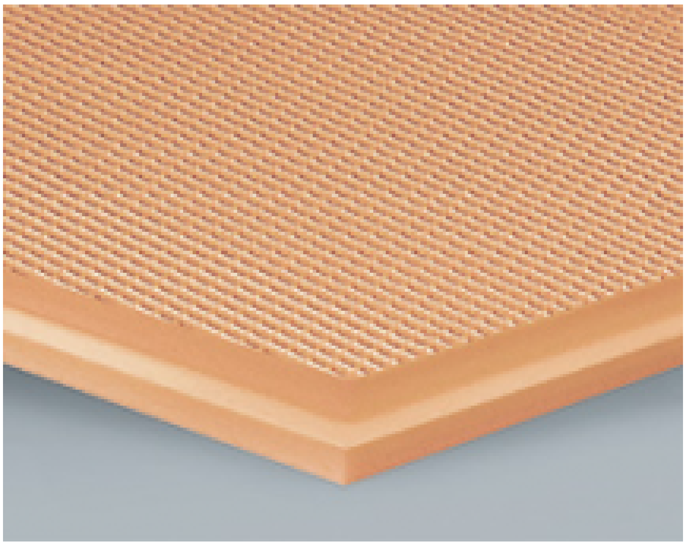


Figure 4.12: XPS foam [Knauf Insulation, 2017]

Floors/Ceilings

Apart with the retrofitting of walls and windows, the ground floor should be renovated in terms of insulating envelope to unheated basement (apartments' floor/basement ceiling). This part of the building has an U-value of 2.55 W/m^{2}K and causes big heat losses since the basement is unheated and has lower temperature than T_{indoor}. Under the existing layer of cement screeds and ceramic tiles, 15 cm of XPS should be integrated which lowers the U-value to 0.35 W/m^{2}K and greatly reduce heat losses. This energy renovation measure costs around 150 HRK/m^2 [Knauf Insulation, 2012].

Basement floors and walls

Regarding the unheated basement, apart from ceiling as presented above, walls and floor are classified as a poor segment of the envelope in terms of energy performance. Therefore, from the existing U-values of 2.2 W/m^{2}K for walls and 2.61 W/m^{2}K for floor, by implementing the same technology as for exterior walls (12 cm mineral wool) and as for apartments' floor (15 cm of XPS), the U-values can be reduced to 0.45 W/m^{2}K and 0.35 W/m^{2}K. The price of implementing both technologies are already stated above - 280 HRK/m^2 for walls and 150 HRK/m^2 (labour costs included).

Staircase windows

The last technology reviewed in technological screening for energy renovation is the replacement of old metal frame and single-layered glass windows in the staircase area. With the U-value of 4 W/m^{2}K and with the inability to be opened, these windows with total area of 111 m^2 can be recognized as a potential problem for big heat losses and insufficient ventilation of air in this unheated area. Therefore, to improve energy performance and increase the quality of air, new staircase windows should be implemented. The same catalogue was used as for windows in the apartments and following solution was chosen. Instead of having 740 small windows ($A = 0.18$ m^2), bigger windows would be implemented with area of 1 m^2. Those windows would be a single-layered glass PVC windows with the U-value of 2,1 W/m^{2}K which can be opened manually. The price of this type of PVC window is 500 HRK/m^2. It should be mentioned that total window area would be lowered from 110 m^2, while the difference would be transformed to external walls with the same technical characteristics as above-presented external walls. The price of replacing windows with external walls is estimated to 350 HRK/m^2 which includes costs of labour as well. This price is higher than the renovation of external walls presented above since 20 cm of reinforced concrete has to be accounted as well.

4.4 Results of the energy renovation

After presenting the energy renovation model in Chapter 3 and validating it by comparing results with the real (actual) data in Section 4.2, the next step is to evaluate the feasibility of chosen alternatives in Section 4.3. Results of the improvements are calculated using the model described above by evaluating different scenarios which includes either one technology solely or combination of more of them. It is worth mentioning that whole building and all parts of the building envelope are aimed to be improved. Therefore, there is no partial improvement or, for instance, windows or external walls. The goal of this section is to get an approximate estimation of the required investment for each scenario, possible heat savings and a payback time for each solution. Firstly, an overview of chosen scenarios is given which is followed by comparison and explanation of results.

Therefore, as mentioned above, several technologies presented in Section 4.3 have been implemented in the model in various combinations which are then analysed and compared. Combinations in scenarios can be seen in Table 4.5.

Table 4.5: Overview of different alternatives

Name	Improvement
Scenario I	Wall insulation
Scenario II	Windows
Scenario III	Basement (floor, walls, ceiling) + Terrace + Staircase windows
Scenario IV	Walls + Windows
Scenario V	Walls + Unheated areas
Scenario VI	Windows + Unheated areas
Scenario VII	Walls + Windows + Unheated areas

Following the above presented scenarios in Table 4.5, an overview of existing and new characteristics in terms of U-value and costs of implementing new technologies can be seen in Table 4.6. On top of that, area of all parts which are included in the renovation process is presented in order to present the potential of the full scale renovation. It is interesting to mention that a measure which improves the U-value the most is the renovation of external walls (from 3.49 to 0.45 W/m^{2}K). Also, it can be seen that all parts of the building envelope are improved significantly where U-value is reduced for at least 2 W/m^{2}K. The last column gives "economic efficiency" which is the ratio between investment costs and difference between existing and new U-value. By looking at that ratio, it is possible to evaluate which part of the building envelope has the lowest investment costs to save 1 W per m^2. A full heat savings potential can be calculated by multiplying the economic efficiency and the area of each part. Lastly, it should be stated that higher heat savings measures means higher investments costs as already explained in Chapter 2. Therefore, through different figures, heat demand, heat savings, investment costs and a payback time are presented for different alternatives to analyse and compare outcomes. The aim of this comparison is to determine which combination of energy renovation measures is the most cost-effective solution.

Table 4.6: Comparison of existing and new characteristics of building envelope

	U-value [W/m^{2}K] Existing | New	Area m^2	Costs [HRK/m^2]	Economic efficiency HRK/saved W/m^2
External walls	3.49 | 0.45	2196	280	92.1
Wooden windows	3.6 | 1.8	350	1000	555.5
Basement floor	2.61 | 0.5	350	150	71.1
Basement walls	2.2 | 0.5	170	280	164.7
Basement ceiling	2.55 | 0.35	350	150	68.2
Terrace	2 | 0.35	100	250	151.5
Staircase windows	4 | 2	110	500	250

Firstly, an illustration of results is showed in Figure 4.13 where heat demand after implementation of heat savings measures and achieved heat savings are presented. As it can be seen, the highest heat savings are recorded in Scenario VII in which all parts of the building envelope are improved (455 MWh - 57% of heat demand reduction), while the lowest heat savings are related to Scenario II where old wooden windows are replaced (40 MWh - around 5% of heat demand reduction). Other scenarios which are combination of several individual technologies achieve higher heat savings in comparison to individual energy efficiency measures. However, investment costs of those combined improvements are significantly higher.

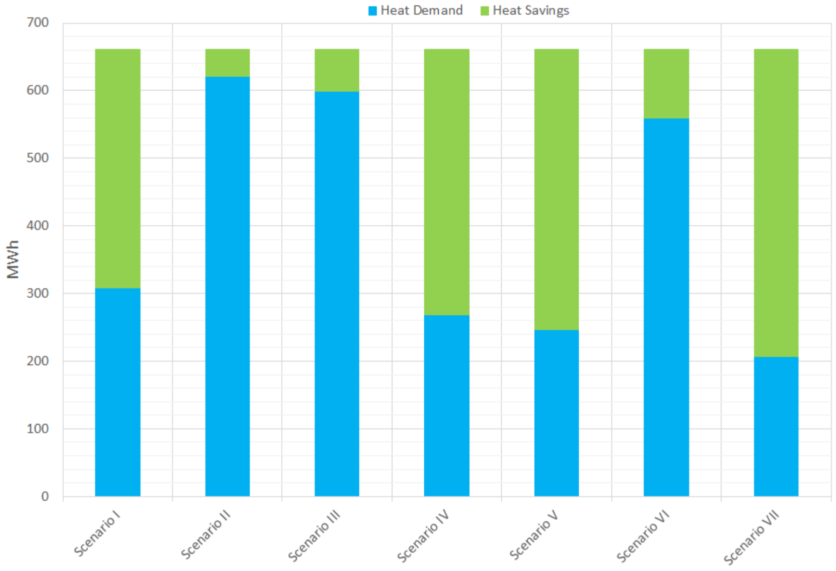
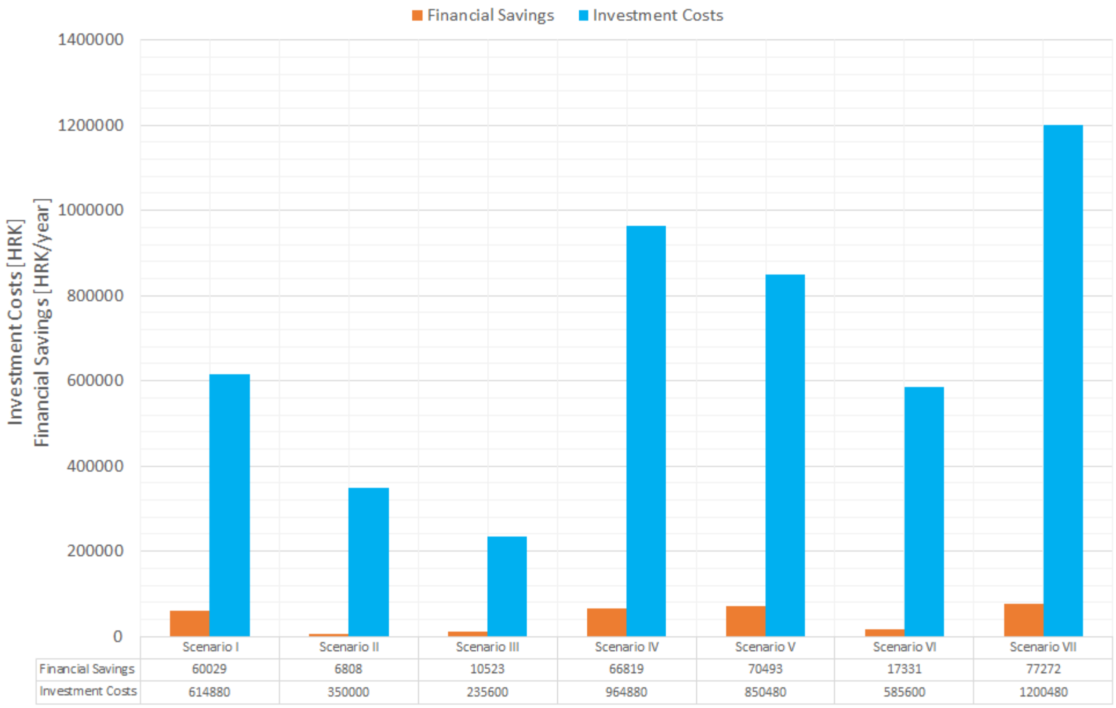


Figure 4.13: Heat demand and heat savings for different energy renovation alternatives

Besides of heat savings, it is important to present a financial aspect of different alternatives, as it is given in Figure 4.14, where investment costs for each scenario can be seen, as well as financial savings per year. Those financial savings are calculated as a difference between the costs before the renovation and after the renovation. As presented in Table 4.6, different alternatives have different investment costs per m^2, while Tables 4.1 and 4.2 show that those alternatives are applied on certain area (for instance, area of external walls is 2,439 m^2, while area of basement walls is 170 m^2). As presented, the highest investment costs are achieved in Scenario VII, while the lowest are accounted for Scenario III where unheated areas only are improved. Regarding financial savings, it is interesting to note that Scenario I has the highest savings in comparison to other individual technology scenarios (Scenario II and III), while the biggest financial savings is recorded, again, in Scenario VII since all technologies are combined. Regarding windows improvements, scenario II has the lowest financial savings, but significantly high investment costs for a single technology improvement. For instance, Scenario I has 10 times higher financial savings, while Scenario III has almost double.



	Scenario I	Scenario II	Scenario III	Scenario IV	Scenario V	Scenario VI	Scenario VII
Financial Savings	60029	6808	10523	66819	70493	17331	77272
Investment Costs	614880	350000	235600	964880	850480	585600	1200480

Figure 4.14: Investment costs and yearly financial savings for different renovation alternatives

It is interesting to present investment costs and heat savings in a single graph, as given in Figure 4.15 to compare different alternatives from that point of view. This combination of results shows a few interesting outcomes of scenarios. For instance, Scenario II has higher investment costs than Scenario III, but achieve lower heat savings which makes it less feasible. Also, Scenario IV and Scenario V have the same relation since, besides of external walls improvement, Scenario IV includes windows improvement, while Scenario V includes unheated areas. Once again, it is seen that Scenario VII has the highest heat savings, but also the highest investment costs. An interesting solution is Scenario I, where a ratio between investment costs and heat savings is much higher than in other scenarios.

Lastly, a payback time should be discussed. As presented in Figure 4.16, different scenarios have a different payback time based on ratio between investment costs and financial savings

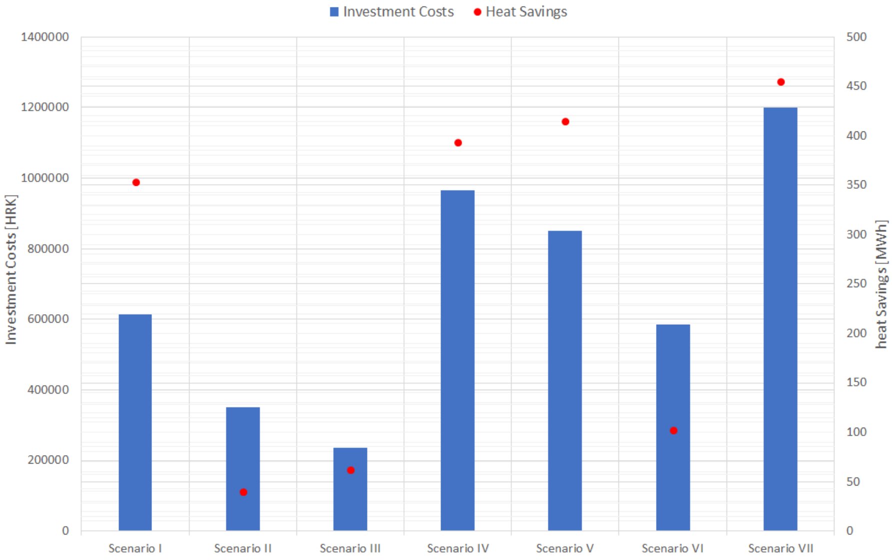


Figure 4.15: Investment costs for different renovation alternatives and related heat savings

(per year). It can be seen that Scenario II has the longest payback time (51 years), as discussed before regarding heat and financial savings and investment costs, while Scenario I appears to have the shortest payback time (10 years). Scenario VI also has a very long payback time (34 years) since it includes the renovation of old windows. Scenario VII has relatively short payback time (15.5 years) although it includes the windows renovation. It can be explained as follows - improvement of windows significantly distort the feasibility of Scenario VII, but due to relatively good feasibility of external walls improvement and unheated areas, this scenario results in an acceptable feasibility. If one excludes windows and focuses on external walls and unheated areas (which is Scenario IV), it can be seen that the payback time would be drastically shorter - 12 years.

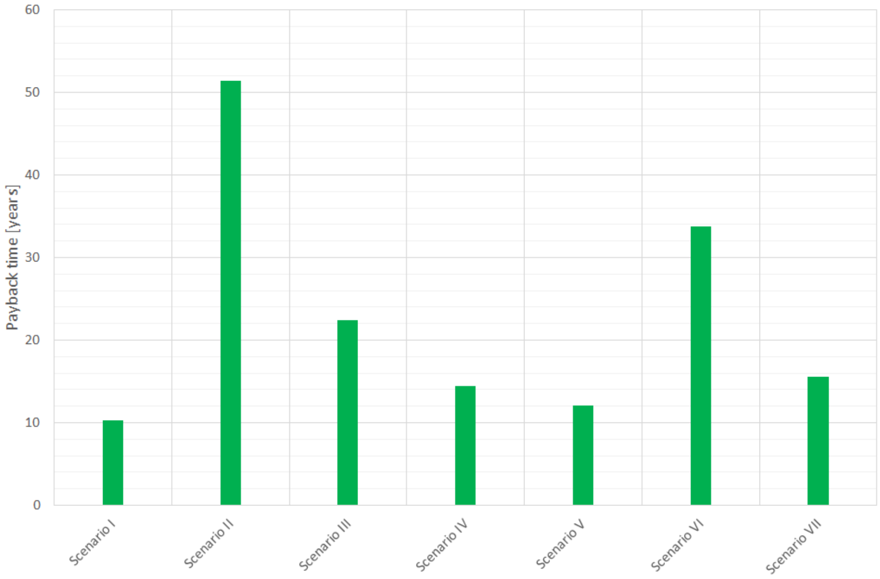


Figure 4.16: Payback time for different renovation alternatives

To summarize all results, Table 4.7 has been made where heat savings, investment costs and a payback time for each of alternative can be seen. Several conclusions can be made as follows. All scenarios which includes windows improvement are significantly less feasible than others since ratio between invested money and heat savings is very unfavourable. On the other hand, Scenario I has the lowest payback time and achieves 53.4% of heat savings. This scenario can be upgraded with investments in unheated areas (Scenario V). This scenario has 2 years longer payback time but ends up with 62 MWh higher heat savings. Lastly, Scenario VII, which presents the ultimate approach ("renovate everything"), saves the most, but also has the highest investment costs. Due to extremely favourable feasibility of other parts of building envelope, this scenario has only 3 years longer payback time than Scenario V.

Table 4.7: Summary of comparison between different energy renovation alternatives

Scenario	Heat Savings [MWh]	Investment Costs [HRK]	Payback time [year]
Scenario I	353	614,880	10.24
Scenario II	40	350,000	51.41
Scenario III	62	235,600	22.39
Scenario IV	393	964,880	14.44
Scenario V	415	850,480	12.06
Scenario VI	102	585,600	33.79
Scenario VII	455	1,200,480	15.54

For the purposes of presenting heat savings per single apartment, energy bills before and after energy renovation (Scenario VII - "renovate all") are compared according to the existing metering and billing methodology for the author's apartment. An annual energy bill for heat consumption before the renovation for the author's apartment (in 2016) is around 4,000 HRK which is calculated by summarizing all monthly energy bills for 2016 (the author has them). If Scenario VII is implemented, investment costs for a single apartment would be around 18,000 HRK. It should be kept in mind that heat consumption for DHW preparation remains the same. Heat savings achieved in Scenario VII are 455 MWh. Therefore, after the renovation, total heat demand for space heating would be 185 MWh for the whole building, which is calculated by subtracting heat demand for space heating before and after energy renovation. In a situation like this, after billing methodology is applied by using ratios as explained in Chapter 5, a single apartment would pay around 2,900 HRK annually, which is 1,100 HRK less than in the current situation. In a situation like this, a payback time for a single apartment is 15.54 years, as presented above. The reason why it is the same lies in the fact that heat savings, just as heat demand are averaged per apartment by using the "area ratio" and the "occupancy ratio" which are explained in Chapter 5. This is a proof that a single apartment cannot benefit more or less than any other apartment while the existing metering and billing technology is applied. Even if half of the apartments are renovated, due to averaging the heat consumption per m^2 and per person, all apartments would have lower energy bills (for the same share).

Possible solutions for metering and billing methodology

5

The purpose of this chapter is to tackle problems related to existing metering and billing of heat consumption, briefly explained in Chapter 2. The current situation is hindering incentives for energy efficiency measures since existing metering and billing methodology greatly reduces the cost-effectiveness of heat savings per apartment and related financial savings - it is based on the "area ratio" and occupancy. If only one apartment performs any energy efficiency measures, it will not experience full benefits since heat consumption is averaged by using ratios. Therefore, main issues should be discovered and analysed to present possible solutions for creating a better investment environment for energy renovations. Not only it reduces the incentives for energy renovation, but incentives for achieving heat savings by changing habits and behaviour of the residents since heat consumption for DHW preparation is averaged per number of people.

Firstly, the existing situation regarding the methodology is described in details for the metering and billing of heat consumption for both space heating and DHW preparation where problems are detected. Moreover, additional information are given for the selected residential building. Afterwards, a technological screening for improvements in metering methodology is presented with the aim of implementing metering devices which would result in charging residents for their actual consumption. Lastly, evaluation of new metering and billing methodology in terms of several created options is given with the aim of finding the best solution regarding fostering incentives for heat savings and achieving as accurate metering and billing as possible.

It is important to mention that both methodologies are closely related and dependant on each other, especially billing methodology - if area ratio is used for determining heat consumption (metering) then the billing methodology is based on the same area ratio, while if any other way of determining heat consumption is implemented or created, the billing will be properly adjusted..

5.1 The existing metering and billing methodology

An initial step in the analysis of possible solutions for metering and billing methodology is to present and evaluate the existing situation (methodology) created by the Croatian Government and HEP - Toplinarstvo and applied on the selected residential building in order to detect issues which are aimed to be solved. Thus, an overview of the current methodology is given. Relevant data and energy bills have been obtained and analysed, while public documents published by HEP - toplinarstvo have been obtained for additional explanation. As it was mentioned earlier, the author did not manage to set up a meeting with the Croatian National Heating Company (HEP - Toplinarstvo) which would be beneficial in terms of obtaining additional data. This would maybe result in new knowledge and insights, as well as technical specifications such as pipes schematics. Also, a lot of technical data is missing due to insufficient published data by HEP - Toplinarstvo. However, a lot of missing additional information are obtained in an interview with the tenant representative. Besides the general methodology, concrete technical information are given and explained for the selected building. It should be mentioned that the tenant representative provided with neither technical nor any other documentation except total energy bills for the whole building and for his own apartment. In a situation like this, there are limited options for solving problems regarding the existing metering and billing technologies. While this section consists of theoretical explanation of metering and billing, a concrete example of calculations for a random month is given in Appendix A.

Before presenting the metering and billing methodology, technical detailed regarding heat production should be presented as well as owners' feedback regarding the fair metering and billing. The local DH plant which supplies the selected residential building are owned by the national heating company (HEP - Toplinarstvo) which owns all pipes and almost all heat generation units in Croatia. Through their organisational scheme, they produce and distribute heat, maintain distribution network (through maintenance companies) and sell produced heat to end-users. In other words, HEP - Toplinarstvo controls the whole process behind heat production, distribution of heat and selling of heat to the end-users. Usually, owners pay around 250 HRK during the summer period and up to 600 HRK during the winter period, based on ambient temperature. On each energy bill, around 50 HRK is accounted for fixed costs, while the rest is variable and depends on the actual consumption which is averaged per apartment by using ratios.

There are separate pipelines for space heating and DHW which are built from the local DH plant to the selected building. The heat carrier in both pipelines is pressurised hot water, preheated for space heating (2nd generation district heating) and preheated at 30 °C for DHW. In case of space heating, the building has countercurrent heat exchangers which are used for re-heating if necessary (for all three buildings). Regarding DHW preparation, all three buildings in the building complex share countercurrent heat exchangers which are re-heating and additionally heating DHW to 40 °C and then storing the hot water in water tanks in each building.

Apart from heat production, pipe schematic inside of the building should be explained. According to the tenant representative (since the author did not manage to set up a meeting with HEP - Toplinarstvo), there is a main inlet pipe which has branches at each floor going through all apartments. In other words, at each floor, a branch was built which delivers heat to all apartments on that floor. Regarding the outlet pipes, they are all connected to the main outlet pipe. No additional information could be obtained.

Also, all apartments have the same number of outer (external) and internal walls except two buildings at the top of the building, two apartments under the terrace and the apartments in the ground floor which has unheated basement beneath them. This information is very important since it should be kept in mind that, by achieving fair metering and billing, those apartments will have higher energy bills due to their position and higher heat consumption. However, the author's goal is to achieve a situation in which all apartments will pay for their actual heat consumption since only then, incentives for heat savings by changing human habits and behaviour can be possible. Same was stated by the tenant representative and by the majority of owners of the flats in the building. During the meeting with owners, the author recognized that the majority of them are very unhappy with the existing metering and billing methodology since it hinders benefits of energy renovations in apartments. Also, owners of above mentioned apartments with higher number of external walls are well aware of ending up with higher energy bills. However, if energy renovation is performed, their energy bills would be lower in comparison with the current situation. Therefore, they expressed readiness and acceptance for changing the existing methodology. It should be mentioned that on the above-mentioned meeting several owners were not present (19 of them) and did not express their opinions regarding the existing methodology and potential for solving relevant problems.

5.1.1 Metering

Regarding the metering of heat consumption for both space heating and DHW preparation, calorimeters are used. A pair of calorimeters for space heating for the selected building solely and and a pair of calorimeters for DHW preparation is shared with other two buildings in the building complex. Calorimeters measure difference between temperatures on the inlet and outlet pipes and calculate heat consumption. DHW is preheated in the local DH plant and additionally re-heated by two countercurrent heat exchangers as explained above which are dimensioned to be able to heat up an hourly demand for DHW which can be stored in a hot water tank (total volume is 15 m^3 which is equivalent of 2 hours demand for DHW in the selected building) [Alfa-inzenjering, 2014b].

After few decades, in November 2016, the tenant representatives managed to get the permission to install two calorimeters on the inlet and outlet pipes on each building together with the countercurrent heat exchangers. Installation of calorimeters in each building resulted in metering heat consumption for space heating separately. Because of that, a more fair division of heat consumption for space heating is created where total heat consumption is not metered for all three buildings together.

However, regarding DHW preparation, all three buildings still share two calorimeters, where heat consumption is then divided per number of people in a single apartment. Whenever DHW is prepared in any of three buildings, two calorimeters are metering the heat consumption. At the end of each month, total heat consumption for DHW preparation (for all three buildings) is divided by using the "occupancy ratio" for each apartment, as explained below. Although the tenant representatives submitted a request for installing calorimeters for each building (as for space heating), HEP - Toplinarstvo (heating company) still has not accepted the proposal due to high investment costs and technical complications. In a situation like this, wasteful neighbours can consume a lot of DHW, but receive a lower energy bill for their consumption than they should get in a situation where every apartment would be charged for its actual consumption. This metering methodology significantly hinders any incentives for heat savings since heat demand for DHW preparation is averaged.

5.1.2 Billing

While the metering methodology is more or less simple to understand, the existing billing methodology is complex with several charging items, several tariff groups and models which creates a lot of confusion among owners of the apartments. Therefore, it should be properly explained and discussed.

As it was mentioned, heat demand for space heating is measured for each building separately, while heat demand for DHW preparation is measured for all three buildings. In the current billing methodology, several models are created and used to divide heat demand among all apartments in a building, based on the metering methodology and accuracy of metering of heat demand per apartment:

- **A basic model for division of capacity supply**

  In order to produce heat for all three buildings, certain blocks in the local DH plant have to be used. Each year, tenant representatives and HEP - Toplinarstvo Ltd. make a contract which defines the amount of blocks used for the production of heat - total capacity used for the selected residential building is 312.73 kW. Since it is accounted for all apartments together, division of costs per apartment for using this capacity has to be made. Currently, there are two sub-models which are used, based on availability of additional information - if there is an information about how much each apartment uses or not.

  Model 1S - applied when there is information about each apartments' share in capacity. If this is the case, this information is used later in estimating costs in energy bill. New buildings usually uses this sub-model since either separated calorimeters or additional metering units are installed.

  Model 2S - applied when there is no such an information. In this case "area ratio" is used to divide usage of capacity per apartment. Firstly, an area of each apartment is divided by total living area of all apartments in a building. Later, a share of each apartment is multiplied by total capacity used (determined in a contract) to calculate how much each apartment uses (its share).

- **A basic model for division of delivered heat for space heating**

  In order to divide heat consumption for space heating per apartment, total delivered heat is divided by using several sub-models, based on available addition information.

  Model 1EG - used when sub-model Model 1S is used (when there is an information about what is the share of capacity used per apartment)

  model 2EG - applied when sub-model Model 1S cannot be used. In this case the "area ratio" is used, as presented above.

  Model 3EG - the newest model created last year where measurement devices (heat allocators) are installed on each radiator in all apartments. Those measurement units counts impulses which present the total heat output of each radiator. The number of impulses per apartment depends on heat consumption per radiator (it is measured by measuring the temperature of radiator and air in the room). A new ratio called "impulse ratio" is used where the total number of impulses per apartment is divided by the total number of impulses in the whole building. This ratio is then used instead of "area ratio" which can be perceived as a better solution for metering heat consumption for space heating since the "impulse ratio" does not have a constant value, but depends on how much heat is used per apartment (and in the whole building).

- **A basic model for division of delivered heat for DHW preparation**

  The last model used is a basic model for division of heat for DHW preparation. In this case, the "area ratio" is not used since consumption of DHW is directly related to habits and behaviour of people in the apartments (it depends on occupancy). Therefore, a new ratio called "occupancy ratio" is used. It should be mentioned that it is used when no additional information per apartment is available such as volume of water used in each apartment, as follows.

  Model 1EV - applied when there is an information about how much hot water is used per apartment (in m^3). This number is then divided by total volume of hot water used in the building.

  Model 2EV - used when there is no information about volume used in each apartment. Instead, "number of people ratio" is used where number of people in each apartment is divided by total number of people in all three buildings. This ratio is then used further in calculations of costs, as it is presented below.

One thing should be mentioned and explained before moving further to the billing methodology. All these distributions (models) are strictly proportional to area of apartments and occupancy. In other words, the "area ratio" is always the same since area of apartments is used (which cannot be changed). Regarding the "occupancy ratio", it is subject to change since number of people in the apartments can change. However, it is clearly defined without any additional fixed elements - number of people in a single apartment is divided by the total number of people (in all three buildings in this case). Furthermore, an overview of costs are given in Table 5.1. Several things should be addressed. Firstly, there are different tariff groups used - based on type of building and its purpose. A Tariff Group Tg1 is used for households, while a Tariff Group Tg2 is used for industry and business buildings (public buildings).

Also, there are several Tariff Models which are based on a heat carrier - a Tariff Model TM1 is used if hot a pressurized water is a heat carrier, while a Tariff Model TM2 is used if steam is used. Also, there are different Tariff Items charged for each apartment - Tariff Item: Capacity and Tariff Item: Energy.

The first one is used for charging for usage of a certain capacity in the local DH plant for production and distribution of heat, while the second one is for usage of energy (fuel) for production and distribution of heat. Also, there are additional costs - a fixed charge for delivery of heat (a constant value per month) and an additional charge for preparation of DHW for each apartment (based on area of each apartment!). For the selected building, costs used for creating an energy bills are presented in Table 5.1. It should be noted that the share of capacity and heat consumption per apartment are calculated by multiplying above-presented sub-models' ratios with total capacity used for the building and with heat consumption (agreed in contract and measured by calorimeters). It should be mentioned that in the selected residential building, there is no any other types of users except the owners who live in their apartments (the building is used as living area only without any business or industry area). Although this may seem very confusing, the author suggest to check Appendix A while reading this chapter to see the actual example of the billing methodology.

Table 5.1: Overview of costs used for estimating energy bills [HEP, 2014]

Cost name	Name of tariff item and charge	Tg1 (TM1) [Unit]
Production of heat	Tariff item: Energy	0.1525 HRK/kWh
Distribution of heat	Tariff item: Energy	0.0175 HRK/kWh
Production of heat	Tariff item: Capacity	2.30 HRK/kW/month
Distribution of heat	Tariff item: Capacity	3.45 HRK/kW/month
Additional costs	Delivery of heat	7.02 HRK/month
Additional costs	Costs of DHW preparation	0.69 HRK/m^2/month

It should be mentioned that energy used for production and distribution of heat for space heating (Model 1EG/2EG/3EG) and for DHW preparation (Model 1EV/2EV) are summarized before applying costs per kWh in the Tariff Item: Energy. Also, these prices are VAT excluded. Therefore, after calculating each energy bill item and summarizing them, Croatian tax should be included (25%) [HEP, 2014]. Regarding the selected residential building, applied models should be mentioned. As explained in Section 5.1.1, there is no specific information about what is the actual heat demand per apartment. Therefore, sub-models 2S for share of capacity, 2EG for space heating and 2EV for DHW preparation are used. In order to divide the costs per apartment, above presented "area ratio" and "occupancy ratio" are used. Variable costs for each apartment consists of metered and billed heat for space heating and DHW preparation (in accordance to above-presented methodology) while fixed costs are charged for maintenance of pipelines and additional fixed costs based on area of the apartment which are presented as costs of DHW preparation in Table 5.1. These costs are one of detected problems in the current methodology, besides of few others, as presented below in Section 5.2.

5.2 General issues in the existing methodology

After presenting the existing metering and billing methodology, one can analyse it to identify general issues which needs to be solved to achieve a fair metering and billing of heat consumption. The following issues can be identified:

- **One pair of calorimeters for metering heat consumption for DHW preparation**

  As it is presented, all three buildings in this building' complex share one pair of calorimeters for metering heat consumption for DHW preparation. The metered value is then divided by using the "occupancy ratio" - in total, 446 people live in the building's complex. There has been several attempts to at least install a pair of calorimeters for each building (just as for metering of heat consumption for space heating), but tenants representatives have not been successful in their intentions yet. There are several reasons for this - according to the tenant representative, high investment costs (30,000 HRK) and the current HEP policy (very indolent to new investments). Although current directives in the heating sector are following European Directives, especially Articles 9-11 which are in charge for metering and billing, HEP - Toplinarstvo Ltd still has not implemented those obligations. Instead, they even demanded that apartments' owners have to cover a certain share of the investment.

- **Usage of "area ratio"**

  Due to the existing metering equipment, HEP - Toplinarstvo is compelled to use "area ratio" for the division of heat consumption per apartment since no other approach is possible. This methodology creates a big issue in achieving a situation where every apartment is charged for its actual consumption. By averaging costs per m^2, an unacceptable environment for any energy efficiency measures is created since a single apartment would experience unfair reduction of costs (almost negligible). A different approach should be taken where abolishment of "area ratio" should be enabled.

- **Usage of "occupancy ratio"**

  Same as for "area ratio", using this ratio is an attempt to divide costs for heat consumption (for DHW preparation) since no adequate metering units exist per apartment (or even per building). This approach is also very unfair in terms of fostering any incentives for heat savings since apartments' owners cannot see it properly on their energy bills (in terms of lowering the costs). Same as for "area ratio", a different approach should be set in order to abolish this methodology.

- **Summarizing of heat demand for space heating and for DHW preparation while using different ratios for division per apartment**

  As it is mentioned above, the methodology for billing of heat consumption for space heating and DHW preparation is different in terms of using different ratios for division of heat demand per apartment. However, these two demands are summarized before total costs are calculated by multiplying the same basic costs. This approach is illogical since each heat demands have different factors which have an impact on total value. While space heating demand is very dependable on the building envelope, DHW preparation demand is very dependable on habits and behaviour of people in the apartments. Therefore, those two demands should not be summarized, but charged separately by applying different prices.

- **Additional costs for preparation of DHW (last item in energy bills in Table 5.1)**

  Maybe the most illogical segment of the energy bills is the last item - additional costs for preparation of DHW, especially the basic unit (m^2). To be more concrete, these additional costs are charged because of using countercurrent heat exchangers on-site. DHW is firstly preheated from 10 °C to 30 °C at the local DH plant and then additionally heated by heat exchangers to 45 °C. However, costs are based on area of each apartment and are always the same (every month). Reasons for implementation of this methodology are unclear, especially because the "occupancy ratio" is used for division of heat demand per apartment, and here, area of apartment is the only relevant information for costs allocation. The author failed to obtain any document from HEP - Toplinarstvo Ltd since they refused to set up a meeting. Also, the tenant representatives have had the same problem for years and still have not managed to set up a meeting to discuss this part of energy bills. Therefore, any additional data regarding this problem is not obtained.

5.3 Technological screening for the metering and billing methodology

Before presenting the actual improvements in the metering and billing methodology, considered technologies have to be presented in terms of investment costs, the reason for implementation and specific characteristics. The reason for such an explanation lies in the fact that there are numerous possible approaches and that different solutions exist for achieving more fair billing and metering. Therefore, it is important to explain which technologies are relevant for the purposes of this project. Regarding metering of heat consumption, two technologies are considered, flux calorimeters and heat (costs) allocators.

Heat meters (Flux calorimeters)

The first reviewed technology for metering of heat consumption are heat meters (flux calorimeters). These meters are devices which measure thermal energy provided by a certain heat source or thermal energy delivered to a certain location (in this case, to the residential building). A heat meter measures the flow rate of the heat transfer fluid and the change in its temperature between the outflow and return legs (pipes) of the system. It is the most common type of meters in the district heating to measure the heat delivered to the consumers. Among the numerous types of heat meters, the author selected a smart heat meter for residential use (MULTICAL 302) developed by Kamstrup [Kamstrup, 2017a], and presented in Figure 5.1. It is mostly used for metering purposes in residential buildings using an ultrasonic measuring principle.

Figure 5.1: MULTICAL 302 [Kamstrup, 2017a]

Ultrasonic meters are velocity meters by nature since they measure the velocity of the fluid within the meter body [Lansing and Measurement, 2003]. By knowing the velocity and the cross-sectional area, a volume can be computed. There are two Transducers which are used for determining the transmit time of an ultrasonic signal which travels with the flow from the Transducer 1 to the Transducer 2. By knowing the transmit time and the technical characteristics of the flow sensor (unit), one can calculate the flow rate which is needed for the purposes of metering heat consumption.

The MULTICAL 302 heat meter consists of a flow sensor, temperature sensors, a calculator and a monitor device. They are applicable in both Option A and Option B described above since several flow sensor cables and temperature sensor cables can be plugged in the same control (monitor) device [Kamstrup, 2017b]. Permissible operating conditions are following: ambient temperature - 5. . . 55 °C (indoor temperature), temperature of medium – 2. . . 130 °C and system pressure – 1. . . 16 bar or 1. . . 25 bar depending on the meter's marking. Those conditions are fulfilled in the selected residential building. A deviation in results for metering are within 1% of the real data for flow sensors, while sensors have a deviation of 0.4% which is considered as sufficient accuracy for the purposes of metering heat flow in the residential building [Kamstrup].

This device calculate energy on the basis of the formula stated in EN 1434-1:2007 (using international temperature scale ITS-90). The energy calculation can be expressed in a simplified form, as presented in Equation 5.1 where V is water volume, T_{inlet} - T_{outlet} is measured difference of temperatures, while k is the heat coefficient of water.

$$E[kWh] = V \cdot (T_{inlet} - T_{outlet}) \cdot k \tag{5.1}$$

According to Kamstrup [2017c], the meter's design ensure the most efficient operational use and brings numerous benefits such as best display readability in all applications and a minimum time for installation, low pressure loss, a possibility of metering both heat and cooling consumption etc. Also, Kamstrup provides with the detailed user guidance and installation procedure which ensures that devices are installed properly. Regarding the price, according to Kamstrup [2017a] a single MULTICAL 302 heat meter with all additional devices, sensors, cables, calibration certificate, extended batteries and installation costs included costs around 2000 HRK for Option A, and 2600 HRK for Option B since larger heat flow sensor is used [Ista Ltd, 2017]. Regarding disadvantages, it should be mentioned that flow sensors are bulky and require a certain space to be mounted on the inlet pipe of radiators. This results in an additional investment costs and small-scale renovation process to mount them. In addition to this, those sensors usually have to be replaced every 6-7 years [Echotermo, 2017].

Heat (costs) allocators

A second technology which needs to be explained is a device called heat (cost) allocator. Heat allocators are devices which are attached on each radiator in an apartment to measure the individual heat consumption per radiator. This methodology enables allocation of costs for heat consumption for space heating per building based on "consumption" in each apartment (each radiator) instead of using "ratios" of area. They can be either electronic or evaporative. Electronic allocators have one/two "thermosensors" which measures the temperatures of radiator and air and transform it by using micro controller into impulses. Evaporative allocators have a special calibrated liquid in a tube which evaporates based heat output of radiators and indoor temperature in the flats. An example of heat cost allocator which uses electronic principle can be seen in Figure 5.2. This device works in a combination with data concentrators and signal repeaters if needed which collect consumer data, store it and solve problems related to distance, obstacles and building materials. For the purposes of this project, electronic heat cost allocators are selected since those allocators are an official suggestion by HEP-Toplinarstvo Ltd in achieving more fair metering and billing of heat consumption in building like this one. The main advantage of this technology is that it does not require any inconvenient work, modifications to the existing heating system or significant expense for the occupants [Echotermo, 2017].

Figure 5.2: An example of heat cost allocator [Zaehlershop, 2017]

Heat cost allocators operate by measuring the surface temperature of the radiator and the ambient air temperature in the room in order to calculate the amount of heat energy delivered to the end user. These data are also sent to the service provider which is used to calculate above mentioned "ratio" of impulses [Texas Instruments, 2017]. A single cost allocator as presented in Figure 5.2 costs around 100 HRK.

In last several years, there has been a lot of problems with heat cost allocators due to many drawbacks. Firstly, the allocator cannot know if there is accumulated air in the radiator or not (especially in winter periods) which cause a change of the thermal properties. Since heat allocators measure indirect physical quantities (the surface temperature of radiators at a specific point and the temperature of the surrounding air), change in thermal properties (temperature of radiator's surface due to accumulated air) causes incorrect measurement by heat allocators. Also, in the heating systems like in the selected building (older than 30-40 years), old radiators are used which often have a layer of lime-scale and tens of centimetres of sand at the bottom which change the thermal characteristics of radiators - temperature and heat output [Echotermo, 2017]. Furthermore, there is a strict requirement regarding positioning of heat allocators which needs to be mounted on a specific position of the surface of the radiator - in the exact middle of radiator's horizontal side and either 1/3 or 1/4 of radiators' upper side. If this requirement is not fulfilled, heat allocators do not track a correct heat consumption - even 5 mm misplacement results in detectable problems (the device do not measure heat consumption correctly) [Echotermo, 2017].

Apart from positioning of heat allocators, the surrounding of radiators and their position in the apartment is also very important. If radiators have a cover of any type (even curtains), a very warm air micro-climate surrounding is created which causes failures in the external temperature sensor. Lastly, it should be mentioned that inlet and outlet pipes positioning influence on the thermal characteristics of a radiator. Therefore, heat allocators do not show the same readings for top-left/ bottom-right, top-right/bottom-left, bottom-left/bottom-left combinations of inlet and outlet pipes since the distribution of temperatures in radiators is not the same. For instance, in a situation where the inlet and outlet pipe are at the bottom, temperatures are lower than in a situation where the inlet pipe is at the top, while the outlet pipe is at the bottom of the radiator [Echotermo, 2017]. However, most of these disadvantages can be mitigated - all radiators are the same in all apartments; a trained technician should be hired for installing heat allocators; curtains and other covers should be removed in front of radiators etc. It can be concluded that this is a viable option for solving problems regarding the existing metering and billing methodology in the selected building.

5.4 Evaluation of chosen alternatives for the metering and billing methodology

After presenting technologies used in the alternatives, an evaluation of these is presented. It should be mentioned that the options are evaluated in terms of investment costs and difficulties regarding the implementation, accuracy and fairness of measuring the heat consumption. The possible solutions in this section do not have any direct beneficial savings which can be translated to a payback, as it is done for energy renovation in Chapter 4, but the fostering of incentives for heat savings by changing human behaviour can be explained. For instance, if individual metering methodology is implemented, owners of the apartments will pay more or less depending on their habits and heat consumption. Certain improvements in the metering and billing methodology can be achieved (problems can be solved), given in the three options as presented below.

Option A: Flux calorimeters for each apartment

The heat consumption of an entire building is metered with heat meters installed per each apartment, separately for space heating and DHW. The entire building is billed according to the heat consumption per apartment (additional costs for O&M are included which covers heat losses in pipes in the building). Each apartment pays for the exact amount of heat consumption for both space heating and DHW preparation. The existing ratios of area and occupancy are abolished and there is no averaging of heat consumption based on any coefficient or ratio. However, the implementation of these devices results in an significantly high investment. The meter's flow rate sensor is bulky and needs a certain space to be mounted which is a difficult requirement since there is often no space between the radiator and the wall from which the inlet pipe comes out. Also, the implementation process of those sensors have relatively high costs (600 HRK per apartment) [Ista Ltd, 2017]. On top of that, flow rate sensors usually have to be replaced every 6-7 years. In a big residential building, it is necessary to replace all of heat meters with the same frequency [Echotermo, 2017]. According to the existing billing methodology, if meters are implemented, the building would not use Models 2S, 2EV and 2EG but 1S, 1EV and 1EG since the exact consumption per apartment could be metered. An overview of this option can be seen in the following bullets:

- **Advantages**
  1. Each apartment has their own heat meters
  2. This is the most accurate method for metering heat consumption
  3. No usage of any ratio
  4. Metering of heat consumption for space heating and DHW preparations separately
  5. Owners are charged for their exact consumption
- **Disadvantages**
  1. High investment costs for calorimeters (two per apartment) (280,000 HRK) and costs of implementation (42,000 HRK) [Ista Ltd, 2017] - 4,600 HRK per apartment
  2. Heat flow sensors are physically large (they need a lot of room to be mounted)
  3. Lifetime of flow sensors is relatively short (6-7 years)

Option B: Flux calorimeters for each floor

The heat consumption of an entire building is metered with heat meters installed for each floor, separately for space heating and DHW. The heat consumption per apartment is billed (allocated) by using existing ratios of area and number of people. While the Option A is created with the aim of achieving a metering and billing methodology where each apartment pays for their real consumption, this solution is a compromise between technical difficulties and investment costs of the flux calorimeters implementation and relatively fair metering and billing of heat consumption. With a significantly lower investment costs than Option A (two times less), this option can be perceived as a reasonable solution in which ratios of area and occupancy are used for four apartments per one flux calorimeter for space heating and one flux calorimeter for DHW preparation. Although this option is presented as a certain improvement in comparison to the existing situation, apartments do not pay for their real heat consumption, but for the modified consumption based on area and occupancy in the apartments (as in the existing methodology). However, it can be recognized as an improvement since the heat consumption for space heating is metered for all 70 apartments by one pair of calorimeters at the moment and for all three buildings for DHW preparation.

However, it should be mentioned that the consumption and division of costs is highly dependant on owners - for instance, if one apartment has a rational heat consumption, while other three apartments waste a lot of energy due to habits and behaviour, that one apartment will receive high energy bills (maybe even higher than before) and will not be charged for its real consumption. This is one of the major drawbacks of this option. However, this situation can be addressed as having a great potential for fostering heat savings since all three other apartments will also have high energy bills. Also, the tenant representative stated that most of owners of the flats are unhappy with their energy bills and would like to have a situation where their habits and behaviour would have bigger influence on the energy bills. If this options is chosen, an impact of their habits on the energy bills is drastically increased (not as in the Option A). Additional costs of implementation are lower than in Option A since bulky flow sensors are not installed in each apartment, but on main pipes in front of branching of pipes to each apartment. In this option, the billing methodology would be modified from the existing 2S, 2EV and 2EG models to improved versions where the "area ratio" and "occupancy ratio" would not be averaged per the whole building, but per four apartments (for each floor).

- **Advantages**
    1. Metering of heat consumption for space heating and DHW separately
    2. Usage of ratio of area and number of people is used per 4 apartments (a significant improvement)
    3. Lower investment costs than the Option A
- **Disadvantages**
    1. Usage of ratios - owners do not pay for the real heat consumption, but for averaged per four apartments
    2. A certain renovation of main pipes is needed in order to mount heat flow sensors and heat meters

3. Relatively high investment costs for calorimeters (two per each floor - 93,600 HRK) and costs of implementation (12,600 HRK) [Ista Ltd, 2017] - 2,000 HRK per apartment

Option C: Heat allocators

Unlike the options A and B, this solution do not consist of any renovation process in the heating system and of changing the existing metering methodology for space heating - two calorimeters for the whole building, while there is an additional investment for two calorimeters which would meter heat consumption for DHW preparation for the whole building. Instead of flux calorimeters, heat allocators are implemented on each radiator in all apartments. The entire building is billed for space heating based on the readings of the allocators instead of using floor area ratio. The billing methodology for the DHW remains the same with a slight modification - the building has its own calorimeters for metering heat consumption for DHW preparation which is the improvement since there are a pair of shared calorimeters for all three buildings at the moment. Therefore, there is a reduction of number of total apartments which are taken into account for billing methodology (from 210 apartments to 70 apartments).

The main advantage of this options is easier installation of heat allocators in comparison to heat meters and lower investment costs. By putting a device on each radiator, a completely new methodology can be developed where instead of using ratios of area for averaging the heat consumption per apartment, readings on the devices are used. This can be recognized as an improvement and a step closer to paying for the actual consumption since the ratio between number of impulses in a single apartment and a total number of impulses in the building is not constant and depends only on usage of space heating in all apartments. However, heat consumption is only metered by using a pair of calorimeters and is divided among apartments by using the "impulse ratio". It can be said that this option is a compromise between high investment costs and somehow fair metering of heat consumption of apartment. Also, this option is an official strategy used by HEP-Toplinarstvo Ltd in achieving more fair metering and billing of heat consumption in the big residential buildings. Drawbacks of this options are presented in details in Section 5.3. In a situation like this, the billing methodology would be changed from 2EG to 3EV (this model is created in the existing methodology just for heat allocators as the implementation in other buildings has already started), while models 1S and 2EV would still be used. Lastly, it should be mentioned that the "occupancy ratio" would be changed since a pair of calorimeters would be installed for each building separately. Therefore, the total number of people would be reduced to 168 people (number of people which live in the selected residential building), as mentioned in Chapter 2.

- **Advantages**
  1. The lowest investment costs and costs of implementation (42,000 HRK) [Ista Ltd, 2017], but additional costs for DHW preparation (30,000 HRK according to the tenant representative) - 1020 HRK per apartment
  2. No modification in the heating system
  3. Easy implementation
  4. An upgrade from ratio of area to impulse ratio which is not a constant value, but changes according to the consumption

- **Disadvantages**
  1. Usage of ratio (impulse ratio) and not metering the real consumption per apartment
  2. No modification (improvements) in metering of heat consumption for DHW preparation (new calorimeter would only reduce the total number of people as explained)
  3. Investment costs for a pair of new calorimeters
  4. Numerous drawbacks of heat allocators as presented in Section 5.3

5.5 Results of evaluation and author's opinion

After presenting three viable options for solving problems regarding the metering and billing methodology and conducting a proper technological screening of those options, results should be presented. Firstly, investment costs are presented for each option in Table 5.2, while later, the author's opinion regarding each option is given after considering all advantages and disadvantages, as well as regarding the impact on the possibility of controlling apartment's own costs, savings and demand (on fostering incentives for heat savings by changing habits and behaviour of residents). Lastly, a comparison between investment costs for each option and an annual energy bill for a single apartment (the author's apartment).

Table 5.2: Overview of investment costs

	Option A	Option B	Option C
Costs for metering devices [HRK]	280,000	93,600	42,000 (+30,000)
Costs of implementation [HRK]	42,000	12,600	0
Total costs [HRK]	322,000	106,200	72,000
Costs per apartment (70 in total) [HRK]	4,600	2,000	1,020

The hardest part of this chapter is to evaluate which out of presented three options is the best in terms of solving problems regarding the existing methodology. Initially, the author's desired outcome was to achieve the fair metering and billing of heat consumption for both space heating and DHW preparation since the existing methodology is relied on the usage of different ratios and on averaging the heat consumption per apartment. In that case, the Option A is the best approach. However, due to its high investment costs, it is uncertain if this option would ever be accepted by owners. Option B can be recognized as the major improvement towards the fair metering and billing - the ratios are still used, but averaging the consumption is reduced to four apartments only. However, in the long term, this option can be perceived as a waste of money if owners will decide to meter the real consumption per apartment. In that case, meters would become useless since additional meters would have to be implemented per apartment. Also, as explained above, there is a problematic situation if one apartment uses energy rationally, while other three on the same floor appears to be very wasteful regarding heat consumption.

Lastly, Option C is the cheapest option with the easiest implementation. Heat allocators are recognized as the best short term option. Because of that, there is already an implemented Law which dictates that all multiple apartment buildings have to install either heat meters or heat allocators (mostly heat allocators). Most of the buildings decide to install heat allocators due to the investment costs. However, there are many uncertainties regarding the existing methodology. Also, there are many recognized problems as stated in Section 5.3 which hinders the implementation. It should be mentioned that this option only partially solves problems regarding to metering of heat consumption for space heating, while charging of DHW preparation remains the same.

All three options should be compared regarding the fostering of incentives for heat savings since heat demand for DHW preparation heavily depends on habits and behaviour of residents in the building. Option A is definitely the best option for fostering of incentives for heat savings due to the fact that each apartment would have an individual heat metering. In a situation like this, habits and behaviour of residents in each apartment would directly reflect on their energy bills, without using any ratio ("area ratio" or "occupancy ratio") for averaging costs. Therefore, the author states it is the best approach.

Regarding Option B, in which each floor has their own heat meters, it can be stated that habits and behaviour would have a bigger impact than in the existing methodology, but less impact in comparison to the Option A. Although the "area ratio" and the "occupancy ratio" are still used for averaging costs, those ratios are significantly reduced from 70 apartments (for "area ratio") and from total number of people in all three buildings to four apartments only. This can be understood as a significant improvement in comparison to the existing situation. However, it is very problematic, as mentioned above, if an apartment on a single floor (or more of them) uses energy in a wasteful way. In a situation like this, other apartments on the same floor would pay more although they use energy in a rational way since total heat demand per floor is divided by using ratios. Therefore, it can be stated that his option is better than the current situation, but worse than Option A in terms of fostering of incentives for heat savings.

In contrast to Options A and B, Option C do not achieve any improvement in the metering and billing of heat consumption for DHW preparation by installing heat allocators. However, an additional pair of calorimeters for metering this consumption is included to separate all three buildings. In that way, it can be said that this option provides more accurate metering and billing of heat consumption for DHW preparation than the existing methodology. Nonetheless, total consumption is divided among apartments by using the "occupancy ratio" which cannot be perceived as a concrete improvement in fostering of incentives for heat savings since there is 168 residents in the selected building. This option cannot compete with options A and B in terms of fostering incentives for heat savings at all. Regarding the metering and billing of heat consumption for space heating, heat allocators provide with a certain improvement by counting impulses on each radiator in all apartments.

By using the "impulse ratio" - a ratio between the number of impulses in a single apartment and the total number of impulses in the whole building, the "area ratio" which is always the same (a constant value) is abolished. Instead of using it, the "impulse ratio" varies on a monthly basis and depends on radiators' heat output in a single apartment and total heat output of all radiators in the building. In other words, it can happen that a single apartment ends up paying more when he has lower number of impulses. For instance, heat allocators can measure 100 impulses in a single apartment and 5,000 impulses in the whole building. In a situation like this, that single apartment's share would be 2%. But, it can happen that heat allocators measure 90 impulses in a single apartment and 4,000 impulses in the whole building. In that case, that single apartment's share would be 2.25%. Also, it can happen that (due to very rational behaviour of all residents) a single apartment has 70 impulses, while the whole building has 2,500 impulses. In other words, the share of that apartment is 2.8%. Therefore, it can be stated that the "impulse ratio" is very dependable on rational usage in all apartments. In that light, it can be said that this option partially foster incentives for heat savings by changing habits and behaviour. However, fostering in this options has a much less impact than in other two options.

Also, it is interesting to compare investment costs for all options with for instance, energy costs per flat on a yearly basis (for 2016). The author's energy bill for 2016 was around 4,000 HRK (energy bills are summarized for each month) which is around 600 HRK less than the investment costs for Option A, two times higher than the investment costs for Option B, while in comparison to Option C, it is around four times higher than the investment costs. Although the total costs for Option A (for the whole building) seems to be high (322,000 HRK), when those costs are divided among all flats (70 in total), it can be concluded that paying "an additional annual energy bill" for achieving individual metering per apartment can be perceived as a reasonable costs. At least, that is the author's opinion. For instance, 4,000 HRK is an average income per month in Croatia (per person).

To conclude, the author opinion is that Option A should be implemented as the ultimate goal and solution for solving the presented metering and billing problems. This option would separate all apartments by installing individual heat meters. In a situation like that, habits and behaviour of residents would have a much larger impact on energy bills which can be perceived as fostering of incentives for heat savings by changing residents' habits, especially for consumption of DHW. Also, this option is described in Articles 9-11 of the EED Directive - those Articles demand that each apartment is billed for its actual consumption, without usage of any ratio for division of costs (especially based on the "area ratio"). Although heat allocators are presented as an official solution for multiple residential buildings like this one, they solve problems only partially. When the Croatian Government implements new strategy (according to Articles 9-11), heat meters (and Option A) will surely become more cost-effective (in case of subsidies or grants) or even obligated to be installed by the Law (with the same or lower costs as presented above).

Discussion 6

The results and suggestions presented throughout Chapters 4 and 5 are derived from a set of data, assumptions and estimations specific to this project. Therefore, it is important to critically reflect on those assumptions and estimations to examine possible consequences of decision made which lead to the thesis' results. Also, it is equally important to discuss additional caveats and limitations not initially accounted for the analyses, as well as initially excluded segments which could influence to some extent on the outcome for both energy renovation and solving problems regarding the existing metering and billing methodology.

This chapter aims at providing such a discussion and a critical view on some of the issues encountered and solved during the writing process of this thesis. In this chapter, usage of different approaches and methodologies is discussed, especially in the process of developing the energy renovation model and solving the mentioned problems regarding the metering and billing methodology in the selected building. Lastly, further work is presented in terms of what should be done in the future to improve the outcome of this study.

6.1 Case study methodology, data collection and a social aspect

When the research questions were initially formed and put as the focus of this study, a general approach was set by using the case study methodology, as explained in Chapter 3. Since the problem is based on a micro level with possibly specific problems, specific data and very detailed documentation had to be obtained and analysed. The author has had significant problems in setting up meetings with relevant governmental bodies and energy renovation companies, as well as with a maintenance company for the selected building which resulted in a lack of data regarding technical specifications. Also, maybe the most important meeting was not possible to be set up with HEP - Toplinarstvo where new insights regarding metering and billing would be obtained which could have resulted in different possible solutions in Chapter 5. Apart from that, new knowledge and different perspectives would be included in this study if the meeting was set up.

On the other hand, when it comes to technical characteristics, a company which conducted an energy audit provided their insights and data used for their research. However, further data gathering should be addressed as a key for proper quantification of benefits of energy renovation. If the author had managed to meet with HEP- Toplinarstvo, the outcome of this study would have been more accurate and realistic in comparison to the existing situation - less assumptions would be made, especially in estimating U-values and in calculation of temperatures in unheated areas in the building. Despite of data limitations, the author believes that the created model (with presented assumptions) and results of scenarios are valid.

It is interesting to discuss other aspects of this study which have been excluded such as public awareness and owners' acceptance (readiness) for any investments. Although all scenarios presented above can be seen as a real improvement in energy performance and as a solution for reduction of energy bills, the author highly doubt that the project would be actually accepted and finalized due financial situation. This assumption is based on previous attempts of solving problems in metering of water consumption and electricity - only 40% of owners decided to install individual meters for water consumption while the others refused to. In a situation like that, those 40% of owners are charged for their actual consumption, while other owners use an old meter. Their consumption is averaged in a similar way as for heat consumption. It is also important to note that the building has a very large debt (to Lindgrad Ltd - a maintenance company) which is a result of poor maintenance and poor financial policy of previous tenant representatives. Thus, this debt has to be covered if any further renovation will take place.

Although the majority of owners are unhappy with the existing energy bills, the metering and billing methodology and the current condition of the building envelope, a lot of them do not want to contribute financially to the building's bank account which is used for paying electricity bills and maintenance, as well as for future energy renovations. In a situation like this, a possibility for any investment is almost non-existent, even with subsidies and grants, especially when owners' awareness and readiness is low - most of them have the opinion that the Croatian Government wants to rob them, as well as an opinion which completely negates any long-term investments.

6.2 Energy renovation model

In a process of creation of the heat demand model, several assumptions had to be made. Therefore, the defined approach and relevant consequences of those assumptions should be discussed.

Firstly, exclusion of DHW preparation and its improvements from the energy renovation model needs to be addressed. As it can be seen in previous chapters, the heat demand for DHW preparation accounts for 20% of total heat demand in the selected building. The same heat company is preparing and supplying DHW for cleaning, showering and other usage - DHW is preheated before the distribution and then re-heated in the heat exchangers on site to 40 °C. The main reason for exclusion of this part lies in the fact that the heat demand model only uses temperatures and physical characteristics of the selected building, while consumption of DHW is directly connected with habits and behaviour of people in the building. In a situation where energy renovation would be performed and better building envelope would exist in the selected building, human behaviour and habits would still be the most dominant factor if one wants to determine consumption of DHW, while this is not the case for the space heating.

Therefore, a decision was made to exclude this part since the increase in rational usage of DHW is not related with the building envelope. The only aspect included in this study is metering and billing of DHW which can be seen as one of possible stimulants for achieving rational consumption - people would pay more in a situation where every owner pays for their actual consumption. This can be perceived as fostering of incentives for heat savings by changing habits and behaviour of residents, as explained in Chapter 5.

Furthermore, the assumptions in energy renovation model as presented in Chapter 3 are the most influencing factor for results of this study. Therefore, this approach should be critically reflected through several highlighted parts.

Hourly heat demand model and Online ambient temperature

An hourly model is selected which requires ambient temperature for each hour since a degree-day approach has been used. In a situation like this, where ambient temperatures were obtained for a nearby satellite-city, there are deviations from the real case which needs to be addressed. There is a possibility that the temperatures on the exact address of the selected building are either higher or lower which would result in either lower or higher heat demand. However, as the heat demand model was validated, it can be stated that the model is a sufficiently reliable presentation for the purposes of this project.

Steady state model

Another interesting approach has been dismissed by using a steady state model instead of a dynamic one. In that way, heat capacity of the flats, walls, things and people are completely neglected. Also, by excluding the dynamic state model, the heat demand model is simplified. If the author used a dynamic state model, outcomes of this thesis would have been different. There would be a significant internal contribution of above presented segments which would either increase or decrease heat demand, according to period of year. For instance, in a dynamic state model, a time lag exists where walls either increase or decrease indoor temperature (if they are warmer or colder) due to walls' heat capacity, while people and things in the apartment reduce the actual heat demand since all appliances and human beings emits energy. In a situation like that, after a certain time, due to the wall capacity and people, apartments would become constant at the different temperature (higher or lower) than in the steady state model.

T_{indoor} is constant and set to 22 °C

For the purposes of this project, T_{indoor} is set as a constant value (22 °C) all the time. This assumption should be elaborated since there is a certain deviation from the reality - indoor temperature is changing constantly based on ventilation rate (and ambient temperature), heating and human behaviour (and preferences). In other words, estimation of indoor temperature is in reality a dynamic process where multiple factors have to be taken into account. However, for the purposes of this study and for establishing the heat model, it is accurate enough to have a steady indoor temperature (a constant value).

Another aspect which needs to be addressed is an assumption that all apartments have the same indoor temperature which directly influences on heat losses since it in theory eliminates heat transfer between floors/ceilings of the apartments. In reality, there is dissipation of heat and heat flow between apartments since indoor conditions are not the same which directly reflects on heat demand per apartment. In order to simplify calculations, this heat flow have been neglected by assuming same indoor conditions while bearing in mind that the model is not as accurate as it could have been. Since heat flow through ceilings/floors of apartments has been excluded (except for the ground floor), a renovation of floors/ceilings is not analysed in scenarios.

Calculated temperature in unheated areas

As for temperatures in the unheated areas in the building (basement, staircase, corridors and elevators), temperatures are calculated by evaluating impact of outdoor and indoor. Equations, presented in Chapter 3 are the author's attempt to take into account ventilation/door losses, as well as thermal properties of relevant parts of the building envelope. It should be mentioned that, for instance, the influence of outdoor temperature is bigger for the staircase area and the basement than for corridor since it is surrounded by indoor walls on three sides. As presented in the validation, the model corresponds well with the real data, therefore, it can be treated as acceptable.

Ventilation losses and solar gains

The last part of discussion regarding the energy renovation model is simplification of ventilation losses and solar gains since those two factors have been presented in a single formula (separately). However, for the purpose of this thesis, a standard formula from EN12831 has been used which is replacement for complex calculation of ventilation losses - a single number (ventilation rate) is used which corresponds to full exchange of all indoor air per hour. The ventilation rate of 0.5/h is used, just as in the energy audit. A problematic part is that the same ventilation rate is used for all apartments, although current conditions of the building envelope per apartment are different. However, since this value was used in the energy audit, it is taken as sufficiently good for the purposes of this study. Due to complexity and lack of time, sensitivity analysis has not been made which would give better solution (approach) for this problem.

To present solar gains, a single formula is used, as explained in Chapter 3. This formula is very dependent on a factor called solar gains (g) which is estimated according to type of windows, area, angle and orientation by looking in a standardized table. However, for the purposes of this project, solar gains factor has been extracted from the energy audit [Alfa-inzenjering, 2014a]. Since the author made an assumption which classified windows as either old wooden or newer PVC windows, two solar gains factors have been taken into account.

6.2.1 Financial indicators - discount rate

When a payback time, financial savings and feasibility of each scenario have been calculated, it is mentioned that discounted cash flow is not considered. It is crucial to explain why the author made this decision since this step results in falling short of reality as it does not include effects of discount rate.

Besides of presenting financial benefit of performing the above-presented energy renovation, there are several social benefits which should be addressed in this section. Those benefits are the reason why a simple payback time is chosen without taking discount rate into account. Before presenting those reasons, it should be said that the inclusion of a discount rate would result in increase of a payback time for all scenarios since the value of money will be different (lower) in the future. However, solving problems of poor energy performance of the selected building in terms of increase of living comfort, reducing mildew and health problems which can be caused by coldness/hotness in the apartment and increase of comfort of people in the building can be presented as a non-profit endeavour. Therefore, regardless when the investment for any scenario is made, these intrinsic benefits (both technical and social) remains the same.

6.3 Solving problems regarding the metering and billing methodology

Apart from energy renovation, this thesis covers solving problems regarding the metering and billing methodology. As it is mentioned in Chapter 5, the author failed to obtain a complete set of data and to set up meeting with HEP - Toplinarstvo Ltd to obtain any additional data. In a situation like that, an interview with the tenant representative (who does not have any documentation to support his statements) and the company "Alfa-inzenjering Ltd", data obtained from the company "Ista Ltd" as well as the only published document regarding the metering and billing methodology by HEP - Toplinarstvo Ltd are the only sources of technical data for this chapter. Despite of sort of data scarcity, three solutions have been presented and well elaborated in terms of advantages and disadvantages in comparison with the existing methodology (and in comparison between those options) and in terms of evaluating the possibility for fostering of incentives for heat savings by changing habits and behaviour of the residents. It can be stated that those options can be treated as rational solutions for the existing methodology. Also, the author managed to compare investment costs of all options and concluded that the option A is the best possible approach for achieving the desired outcome of separating metering and billing of heat consumption per a single apartment. The author is well aware that additional obtained data could change the outcome of this chapter and generate new knowledge and insights. However, considering all limitations and data scarcity, it can be stated that presented options are sufficiently good for the purposes of this thesis.

6.4 Further work

As mentioned so far, several issues arise from data availability, assumptions, and simplifications of otherwise complex calculations and issues. Thus, it is crucial to prompt a discussion about further work that could be the subject of future studies. For this purpose, the following points provide a brief overview on these matters:

Sensitivity analysis

As it has been mentioned, several assumptions have been made which may change the outcome of this study such as ventilation rate, solar gains, U-values of different parts of the building envelope and discount rate. Thus, it is interesting and very beneficial to perform sensitivity analyses on critical parameters like these which can change the outcome of this project, especially in a financial point of view (discount rate). This can give new insights and cause new problems in this case, which, eventually can create new possible outcomes. For instance, the inclusion of discount rate and sensitivity analysis of the same can show the changes in the payback time for the energy renovation which clearly can give different outcomes on cost-effectiveness of implemented technologies.

On the other side, sensitivity analysis of ventilation rate has a direct impact on heat demand. By increasing the ventilation rate (or decreasing), heat demand per apartment is increased or decreased, based on the ambient temperature. If one decides to change solar gains and check its impact, it can be concluded that the increase of solar gain constant will increase the solar gains, while in case of decreasing the constant will result in lower solar gains per apartment.

Further investigation in the metering and billing methodology

The metering and billing methodology and solving problems regarding this methodology should be identified as an area where the further work should be put the most due to complexity of presented problems and desired outcomes. It should be said that the metering technology appears to be a bigger problem than the billing methodology since without a proper metering of heat consumption, the billing methodology cannot be designed properly. For instance, the billing methodology can only give relative solutions for averaging the energy bills and dividing the costs based on ratios, as it is the case in the current situation. If the metering of heat consumption would be designed to meter the exact consumption of each apartment individually, the billing methodology would not be complex, but focused on charging for the actual consumption.

Therefore, a more thorough technological screening should be conducted with the aim of finding new technologies which can improve the existing metering technology. A possibly good approach could be to put an effort in replication of effective methodologies from other countries. In that light, the HEP - Toplinarstvo and the Government of the Republic of Croatia made an agreement with the French energy company called EDF to invest into smart meters which would eventually solve the problems in the metering methodology (or at least improve the current situation). The author failed to gather more information regarding this agreement since the HEP - Toplinarstvo declined to meet and discuss about this investment.

Conclusion 7

This thesis' aim is to analyse possible ways for the energy renovation of the selected residential building in Zagreb to achieve certain heat savings, as well as determine which solution is considered to be the best approach in solving problems regarding the metering and. In this sense, the thesis is created and focused towards answering the following research questions:

What is the most cost-effective combination of end-use heat savings in order to renovate a typical apartment building in Zagreb to achieve a higher energy class?

What is the best approach in solving problems regarding metering and billing of consumed heat while considering technical and economic limitations of a typical apartment building in Zagreb?

A model was created with the aim of simulating heat demand and heat losses of a building in order to be able to assess the effects of investments in energy renovation. This model, however, has some drawbacks due to certain assumptions, simplifications and due to lack of data. Nonetheless, an appropriate representation of the real-life situation has been created (and validated) which has been remodelled in terms of changing the building envelope (with presented technologies) to achieve heat savings.

Several scenarios have been created which are compared in terms of heat savings, investment costs and payback time. The higher the investment costs are, higher heat savings can be achieved with the exception of implementing new windows, as presented. However, the higher the investment costs are, the longer the payback time is needed.

The ultimate approach ("renovate all"), which includes the full-scale energy renovation of external walls, windows, unheated areas (basement, terrace, staircase windows) is identified as the highest heat savings scenarios (455 MWh - 57% of total heat demand) with the highest investment costs (1.2 MHRK). Payback time of this ultimate approach is 15.5 years. This scenario is the best possible approach if the highest heat savings are to be achieved.

On the other side, if the aim is to achieve shorter payback time, Scenario I (external walls) and Scenario V (external walls + unheated areas) can be chosen with 10.2 and 12.04 years in which 353 MWh (44% of total head demand) and 415 MWh (51% of total heat demand) of heat savings can be achieved. Investment costs in those two Scenarios are calculated to 0.615 MHRK and 0.85 MHRK, respectively. To conclude, replacement of windows (both the glass and the frame of old wooden windows) in the apartments is classified as the least cost-effective option in terms of heat savings due to long payback time.

The other part of the thesis is dedicated to solve problems regarding the metering and billing methodology in which several issues have been detected. Firstly, the existing metering and billing methodology is relied on the "area ratio" and the "occupancy ratio" which are used to divide costs for space heating and DHW preparation. The building has its own calorimeters for space heating, but uses calorimeters for DHW preparation together with other two buildings in the building complex. In a situation like this, several problems have been detected and tried to be solved. In that light, three options have been chosen and evaluated in terms of advantages and disadvantages in comparison to the existing methodology and in terms of investment and implementation costs.

The Option A is the best possible approach to achieve a fair metering and billing where every apartment pays for its real consumption. However, it is the most expensive option (322,000 HRK in total - 4,600 HRK per apartment) since a lot of heat meters have to be installed. Also, by implementing this option, incentives for heat savings by changing habits and behaviour of residents can be fostered the most in comparison to other options since every apartment has an individual metering.

An alternative is given by the Option B where heat meters are also installed, but per floor (not per apartment). This option has lower expenses (106,200 HRK in total - 2,000 HRK per apartment), but needs the "area ratio" of the "occupancy ratio" to divide costs among apartments on the same floor. Although total number of people for those ratios are reduced to four apartments, there is a possibility of sharing the floor with owners who consume energy in a wasteful way. In a situation like this, owners would pay more than they consume. However, this option presents an improvement, in both metering/billing of heat consumption and in fostering of incentives for heat savings by changing habits and behaviour which would have a bigger impact on energy bills than in the existing methodology.

A last option (Option C) has the lowest investment and implementation costs (42,000 HRK in total). However, this option is just an upgrade from one ratio to the another (from the "area ratio" to the "impulse ratio"), while an additional pair of calorimeters is installed to separate this building from other two buildings in terms of metering heat consumption for DHW preparation. In total, the investment costs of this option are 72,000 HRK - 1,020 HRK per apartment. On the other hand, in support of this option, the current Croatian Law promotes this option as the relatively easy solution for multiple apartment buildings. In contrast to the "area ratio", the "impulse ratio" does not have a constant value all the time, but changes depending on heat consumption in all apartments. This option has the lowest possibility for fostering of incentives for heat savings among all options. However, it can be perceived as a certain improvement in comparison to the existing methodology since the "impulse ratio" varies. Regarding DHW preparation, the "occupancy ratio" is used, but the total number of people is reduced to 168 residents (number of people in the selected buildings).

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Appendix A

A.1 Calculations: Examples and explanation of estimating heat demand

An example of the heat demand estimation in a single apartment is presented to provide a better understanding of the calculation. The selected apartment at the 12th floor has following characteristics:

- Area = 56 m^2
- Height = 2.5 m
- $U_{\text{external walls}}$ = 3.49 W/m^{2}K
- U_{ceiling} = 2.55 W/m^{2}K
- U_{floor} = 2.55 W/m^{2}K
- $U_{[}$windows] = 1.8 W/m^{2}K
- U_{doors} = 2 W/m^{2}K
- $A_{\text{external walls}}$ = 24.3775 m^2
- A_{ceiling} = A_{floor} = 56 m^2
- $A_{\text{big windows}}$ = 3 windows * 3.625 m^2
- $A_{\text{small windows}}$ = 2.2475 m^2
- A_{doors} = 2 m^2
- solar gains (g) = 0.25
- Ventilation rate = 0.5 1/h

A random day of 12th January at 12 pm is selected with the following weather conditions:

- T_a = 12.76 °C
- Solar radiation = 273 W/m^2

As presented in Chapter 3, the calculation of the heat demand is established by summing energy entering and leaving the apartment. The main losses are through the apartment envelope (floor, wall and roof) and by the air ventilation (ventilation losses), while the main input is the solar radiation. It should be mentioned that due to assumptions made in the model, losses through floor and roof of the selected apartment are zero. The following formula is used for calculation of yearly heat demand:

$$Heatdemand = \sum_{n=8760} q_{vent} + \sum_{n=8760} q_{bldg} - \sum_{n=8760} q_{solar} if T_{amb} \geq T_{ref} \tag{A.1}$$

As for the selected hour, calculations are conducted as follows:

Heat losses for the apartment depends on the building envelope characteristics and the difference of the temperature between inside and outside (degree day). The degree day for the following day is calculated by using Equation A.2 - heating is not needed if T_a is higher than the T_{ref} (10°C). In this case, T_{indoor} is 22 °C.

$$DD = \begin{cases} 0, & \text{if } T_{amb} \geq T_{ref} \\ T_{indoor} - T_{amb}, & \text{otherwise} \end{cases} = 22 - 12.76 = 9.24°C \tag{A.2}$$

As presented, heat demand through each part of the building envelope is calculated separately:

$$q_{walls} = \frac{U_{externalwalls} \cdot A_{externalwalls} \cdot DD}{1000} = \frac{3.49 \cdot 24.3775 \cdot 9.24}{1000} = 0.786kW \tag{A.3}$$

$$q_{windows} = \frac{U_{windows} \cdot A_{bigwindows} \cdot DD}{1000} + \frac{U_{windows} \cdot A_{smallwindows} \cdot DD}{1000} \tag{A.4}$$

$$q_{windows} = \frac{1.8 \cdot 3 \cdot 3.625 \cdot 9.24}{1000} + \frac{1.8 \cdot 2.2475 \cdot 9.24}{1000} = 0.218kW \tag{A.5}$$

$$q_{doors} = \frac{U_{doors} \cdot A_{doors} \cdot DD}{1000} = \frac{2 \cdot 2 \cdot 9.24}{1000} = 0.037kW \tag{A.6}$$

For heat losses through floor and ceiling, degree day is calculated between temperatures in the selected apartment and apartments above and under, which means that degree day in this case is zero. Therefore, heat losses though these parts of the building envelope are zero.

$$q_{floor} = \frac{U_{floor} \cdot A_{floor} \cdot DD}{1000} = \frac{2.55 \cdot 56 \cdot 0}{1000} = 0kW \tag{A.7}$$

$$q_{ceiling} = \frac{U_{ceiling} \cdot A_{ceiling} \cdot DD}{1000} = \frac{2.55 \cdot 56 \cdot 0}{1000} = 0kW \tag{A.8}$$

Finally, summarized heat flow through the apartment envelope can be calculated:

$$q_{envelope} = q_{walls} + q_{windows} + q_{doors} + q_{floor} + q_{ceiling} = 1.04kW \tag{A.9}$$

Regarding ventilation losses and solar gains, following formula are used:

$$q_{vent} = \frac{0.33 \cdot A_{apartment} \cdot h_{apartment} \cdot v_r \cdot DD}{1000} = \frac{0.33 \cdot 56 \cdot 2.5 \cdot 0.5 \cdot 9.24}{1000} = 0.213kW \tag{A.10}$$

$$q_{solar} = \frac{g_s \cdot A_{windows} \cdot I}{1000} = \frac{0.25 * (3 * 3.625 + 2.2475) * 273}{1000} = 0.896kW \tag{A.11}$$

The total hourly heat demand for the apartment is then calculated by adding losses and inputs as shown in equation A.12 :

$$q_{apartment} = \begin{cases} q_{envelope} + q_{vent} - q_{solar}, & \text{if } q_{envelope} + q_{vent} > 0 \\ 0, & \text{otherwise} \end{cases} = 1.04 + 0.213 - 0.896 = 0.357kW \tag{A.12}$$

A heat demand for the selected apartment in the selected hour is 0.357 kW. These calculations should be done for every hour throughout the year and then added to calculate the annual heat demand (kWh/year). Once it is done for a single apartment, the process should be repeated for every apartment in order to obtain the total heat demand for the whole building.

A.2 Calculations: Examples and explanation of the billing methodology

Same as for calculations for heat demand, explanation of billing of heat consumption should be presented in order to provide a better understanding. As it is presented in Chapter 5, there are three different models for billing of heat consumption, based on area ratio and number of people in the selected apartment. Relevant data for estimating costs are following:

- Tariff group - Tg1 (households)
- Tariff model - TM1 (hot pressurized water as heat carrier)
- Area of the selected apartment - A = 56 m^2
- Total area of all apartments - A_{total} = 4,104 m^2
- Number of people in the apartment - N = 2
- Total number of people in all three buildings - N_{total} = 446
- Model for division of power supply - model 2S
- Model for division of delivered heat for space heating - 2EG
- Model for division of delivered heat for DHW preparation - 2EV

Before presenting the billing methodology, few segments of energy bill should be mentioned once again. Regarding metering of heat consumption for space heating, each building has their own calorimeters which measures consumed heat, while for DHW preparation, all three buildings share the same calorimeters. Because of that, total number of people is 446 which corresponds to number of people in all three buildings, while total living area of all apartments is 4,104 m^2 and corresponds to the living area of one building only (selected in the case study). Furthermore, models for division of capacity used and delivered heat should be properly addressed:

- Model 2S - capacity share for each living area is determined in relation to area ratio (ratio between a single apartment's area and total living area in the building)
- Model 2EG - using area ratio once again where total delivered heat is divided among all apartments in a single building based on area ratio
- Model 2EV - total delivered heat for DHW preparation is divided among apartments by using ratio of occupancy (ratio between number of people in a single apartment and total number of people in all three buildings)

For the purpose of this calculation part, an energy bill for May 2017 is chosen. Following additional data is needed to complete calculations:

- Total capacity used for heat production - 312.73 kW
- Total delivered heat for space heating in the selected building - 26.000 kWh
- Total delivered heat for DHW production for all three buildings - 56.000 kWh

It should be mentioned that since this is the energy bill for May, ratio between heat used for space heating and DHW preparation is not a realistic presentation of overall ratio since space heating demand is significantly lower than in winter periods. Ratio of living area and occupancy is calculated according to Equations A.13 and A.14.

$$A_{ratio} = \frac{A}{A_{total}} = \frac{56}{4,104} = 0.01365 \tag{A.13}$$

$$N_{ratio} = \frac{N}{N_{total}} = \frac{}{446} = 0.00448 \tag{A.14}$$

Lastly, costs should be presented for each model, as well as additional costs, as it can be seen in Table A.1. Each month, a tenant representative makes a contract with a local DH plant and agrees about capacity used for production of heat which is needed to meet the heat demand in the selected building ($\mathrm{P}_{\mathrm{total})}$. Total produced and delivered heat for space heating ($\mathrm{E}_{\text{total-2EV}}$) and for preparation of DHW ($\mathrm{E}_{\text{total-2EG}}$) are metered on calorimeters, as explained in Chapter 5.

Table A.1: Overview of costs used for estimating energy bills [HEP, 2014]

Cost name	Name of tariff item and charge	Tg1 (TM1) [Unit]
Production of heat	Tariff item: Energy	0.1525 HRK/kWh
Distribution of heat	Tariff item: Energy	0.0175 HRK/kWh
Production of heat	Tariff item: Capacity	2.30 HRK/kW/month
Distribution of heat	Tariff item: Capacity	3.45 HRK/kW/month
Additional costs for delivery of heat		7.02 HRK/month
Costs of DHW preparation	Charge for preparation of DHW	0.69 HRK/m^2/month

It is convenient to divide calculations into four steps, as follows:

1. Model 2S

   Share of used capacity for heat production and heat (for a single apartment)

$$P_{apartment} = A_{ratio} \cdot P_{total} = 0.01365 \cdot 312.73 = 4.267kW \tag{A.15}$$

   According to Table A.1, following costs are calculated:

   - Capacity used for heat production:

$$Costs_{2S-1} = P_{apartment} \cdot Productionofheat(tariffitem : Power) = 4.267kW \cdot 2.30 = 9.81HRK \tag{A.16}$$

   - Capacity used for heat distribution:

$$Costs_{2S-2} = P_{apartment} \cdot Distributionofheat(tariffitem : Power) = 4.267kW \cdot 3.45 = 14.72HRK \tag{A.17}$$

2. Models 2EG and 2EV

   Share of heat production and distribution for space heating of a single apartment:

   - Energy used for heat production and distribution for space heating:

$$E_{2EG} = A_{ratio} \cdot E_{total-2EG} = 0.01365 \cdot 26,000 = 355kW \tag{A.18}$$

- Energy used for DHW preparation (production and distribution):

$$E_{2EV} = N_{ratio} \cdot E_{total-2EG} = 0.00448 \cdot 56,000 = 251kW \tag{A.19}$$

Before applying costs, those two figures have to be summarized:

$$E = E_{2EG} + E_{2EV} = 355 + 251 = 606kW \tag{A.20}$$

Finally, according to Table A.1, costs for energy usage is:

- Energy for heat production

$$Costs_{E1} = E \cdot Productionofheat(tariffitem : Energy) = 606 \cdot 0.1525 = 92.42HRK \tag{A.21}$$

- Energy for heat distribution

$$Costs_{E2} = E \cdot Distributionofheat(tariffitem : Energy) = 606 \cdot 0.0175 = 10.61HRK \tag{A.22}$$

3. Additional costs for delivery of heat

$$Costs_{additional} = 7.02HRK \tag{A.23}$$

4. Costs of DHW preparation

$$Costs_{DHWpreparation} = A \cdot ChargeforpreparationofDHW = 56 \cdot 0.69 = 38.64HRK \tag{A.24}$$

Table A.2: Calculated costs

Name of costs	[HRK]
$\text{Costs}_{\text{2S-1}}$	9.81
$\text{Costs}_{\text{2S-2}}$	14.72
Costs_{E1}	92.42
Costs_{E2}	10.61
$\text{Costs}_{\text{additional}}$	7.02
$\text{Costs}_{\text{DHW preparation}}$	38.64

Once all costs are calculated, as presented in Table A.2, they can be taxed and summarized for presenting total costs on a monthly basis for a single apartment. After applying taxes (25%) which is 43.31 HRK, total costs for May, 2017 is **216.53** HRK.