Impact of building renovation on the decarbonized European energy system

MSc Thesis

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Impact of building renovation on the decarbonized European energy system

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Preface

Writing this thesis was a very interesting experience. I improved many skills especially programming, where even the installing the model forced me to deepen my knowledge and use tools whose existence was unknown to me at that time.

This thesis would not be made without help of many people. Therefore, I would like to thank my daily supervisor Francesco Sanvito, who on weekly basis was guiding me and giving constructive and valuable feedback about my work. A huge impact on this thesis had my main supervisor Stefan Pfenninger, who gave a very useful feedback, which resulted in adding a completely new structure to the whole report. Moreover, I would also like to thank Prof. Kamel Hooman, who agreed to be a committee member. Lastly my gratitude goas to my friends Javi and Harrie who showed me several programming tricks and made the whole process of making a model smoother and enjoyable.

Summary

Energy system modeling is used by governments to set goals and directions for energy system policy. Currently, there are optimization models that are able of modeling building renovation, but their scope is limited only to the heating system. There are also models that consider interactions between different energy subsystems, but they lack the ability to simulate building renovation. Having those two things combined would be beneficial as the impact of renovation on the power system might be significant.

The residential sector is the second biggest sector after transportation when it comes to final energy consumption. Whereas most of this energy is in the form of thermal energy. This demand can be significantly reduced by undertaking renovation measures such as increasing the thickness of insulation, replacing windows, or installing heat recovery ventilation. Moreover, intelligent control of air temperature can be employed in order to alter the heat demand profile.

The goal of this thesis is to assess the impact of building renovation on the energy system. It was done with the use of Euro-calliope model. The energy system in Euro-calliope model is defined as a set of constraints including the energy demand of different energy carriers and technologies that can create or convert those carriers to other carriers. As each technology has a cost assigned to it, the model is capable of optimizing (minimizing) the cost of the system which fulfills all defined constraints. In the current state, Euro-calliope model does not offer the chance to renovate the building stock. Therefore, the aim of this work is to introduce the building renovation option subject to the software objective function and reshape, when necessary, the heating sector.

To quantify the impact of renovation on the energy generation, transmission, and storage technologies, there were nine scenarios created and run. Those scenarios were based on three different weather years (varying in renewable energy supply and heat demand) and on the penetration of renovation strategies, which directly impacts the renovation level of buildings. The study leads to three main outputs which are listed below.

Firstly, the heating system is tightly related to the power system as most of the heat is generated by using heat pumps (80% to 90%). Therefore, the impact on power generation technologies is very visible. The penetration of renovation increases the fraction of energy generated by photovoltaics in the energy mix. However, when it comes to absolute values, in all scenarios wind farms are dominating. Building renovation only decreases the demand, but it has no impact on the spatial distribution. On the other hand, the weather year has a huge impact on the generated electrical energy (for Portugal it decreased 8 times).

Secondly, there are only three significant storage technologies. For long-term energy storage, methane storage is used. Hydro storage stores energy both for the long and short term. For the short term, the storage in construction elements is used, where the excess of energy that cannot be stored in hydro storage is accommodated.

Lastly, the optimal renovation always results in a higher renovation level than the currently present renovation levels. However, those levels are usually (85% of cases) lower than the currently imposed local renovation standards. Regarding heat recovery ventilation, it is not present in any optimal scenario, therefore is not interesting from the energy system perspective. The renovation has a positive impact on decreasing the variability of the system costs for scenarios with low renewable supply. However, the over-renovation of buildings is very expensive compared to small gains in the stability of a system cost.

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1 Introduction

1.1 Background

Energy consumption is inevitably related to human activity. It is supplied via energy systems that are crucial for sustaining the quality of life and the existence of modern society. Therefore, the design and operation of an energy system is an important aspect that indirectly affects everyone's lives. Energy systems can be mathematically modeled, which is used to analyze the impact of different technical and economic factors on the behavior of those systems.

In this way, it can be assessed how the energy system should be built to provide the cheapest energy and as a result, maximize the total welfare allowing people to enjoy low energy costs and companies to produce more competitive products. As the first one impacts the re-electability of the policymakers and the second one increases the investments and export, an incentive to use energy models by policymakers is visible. Many countries like the UK (Li & Strachan, 2021), Denmark (Danish Energy Agency, 2013), and Poland (Ministry of Climate and Environment, 2021) already use energy models to create long-term plans regarding the energy sector. Therefore, having models that accurately resemble the behavior of real energy systems is a necessity.

According to (Pye & Bataille, 2016), the complete energy model should model phenomena like the operation of a system, technology innovation and stock, behavior of companies and residents, capital investment, and infrastructure deployment of every sector. It seems that the technological innovations and dynamic operation of the residential sector, particularly heating, are not correctly assessed in current large-scale energy models. Therefore, in the next paragraphs, it was explained why this should be changed.

Firstly, the residential sector is one of the most impactful sectors in energy models. As visible in Figure 1, it is the second biggest sector in the EU, in terms of final consumption, just behind the transportation sector.

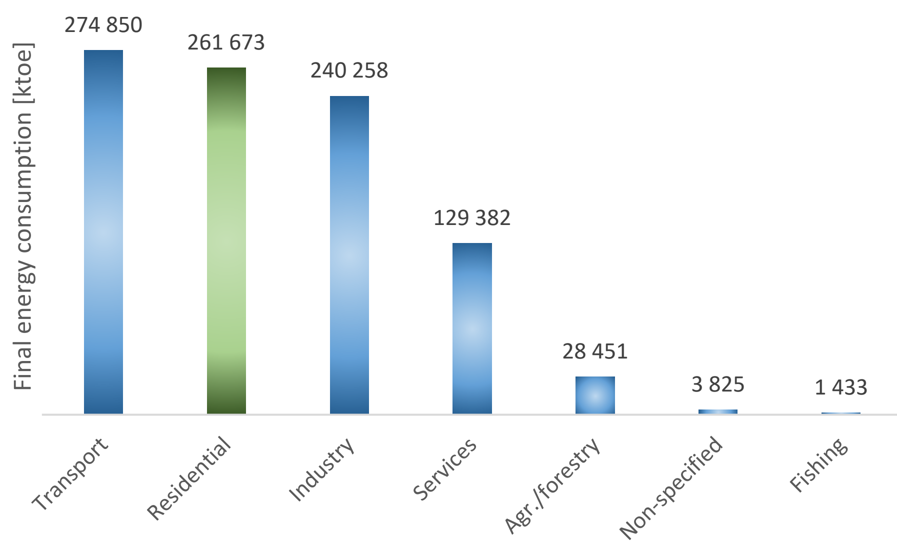

Figure 1. Final energy consumption in European Union- comparison between sectors (Eurostat, 2022)

As shown in Figure 2, everywhere except the US, the heat demand is responsible for more than 50% of the total final demand of the residential sector. Moreover, there are many ways of decreasing this heat demand via building renovation, like increasing the buildings' insulation properties and installing a heat recovery system for ventilation. In addition, a shift in heat generation sources is predicted, including a tenfold increase in the number of heat pumps and solar thermal collectors at the cost of coal, natural gas, and traditional biomass boilers (IRENA, 2018).

Therefore, it is important to know what the impact of building renovations on the energy system is, as it might have a significant effect on the power and other energy systems. This question is very relevant in modern times, as the expectations from the energy system are high reliability, carbon neutrality, and low environmental impact (European Commission, 2022).

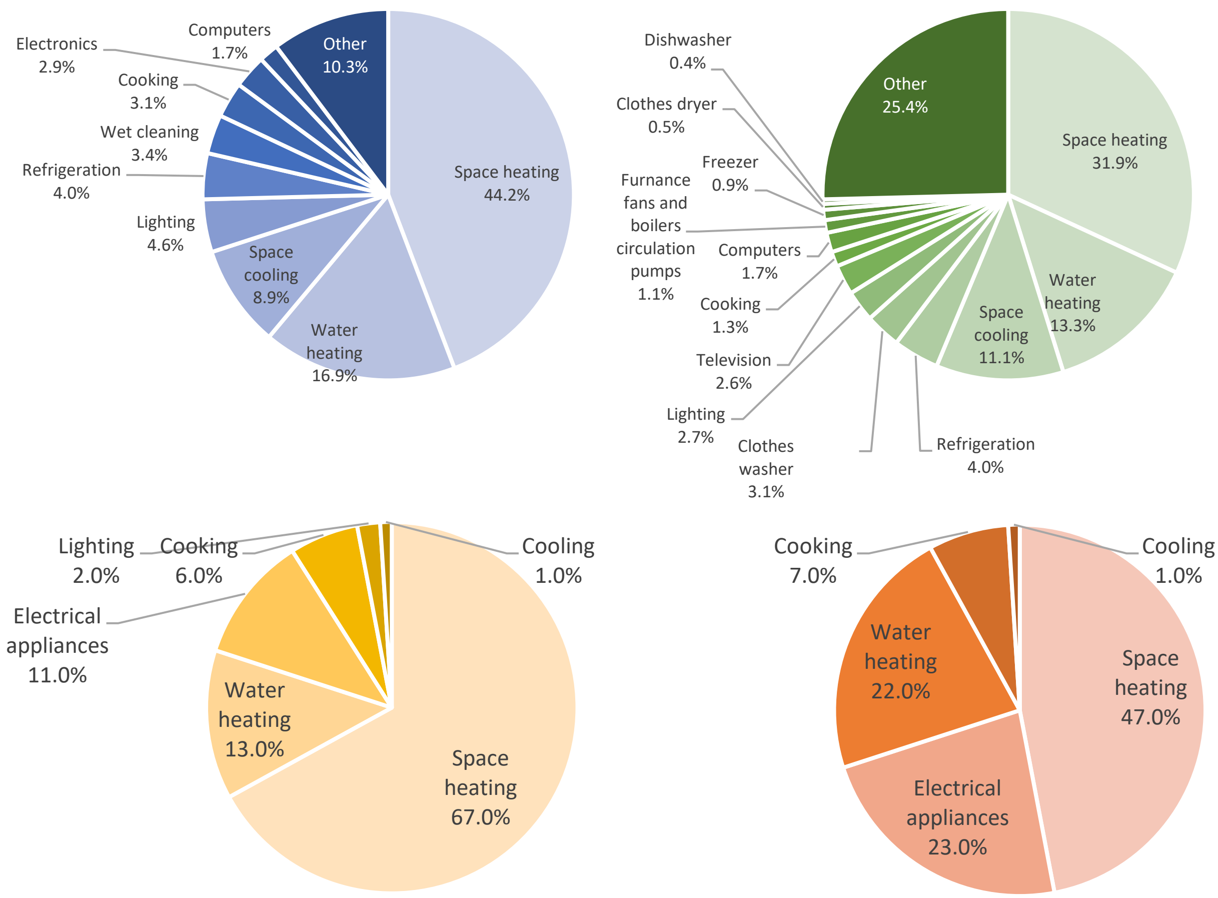

Figure 2. The breakdown of the final energy consumption of residential buildings:

top left corner	*in Australia (Maasoumy & Sangiovanni-Vincentelli, 2016)*
top right corner	*in the US* (Center for Sustainable Systems, 2021)
bottom left corner	*in European Union (Tod & Thomson, 2016)*
bottom right corner	*in Spain. (Trotta & Lorek, 2015)*

1.2 Research objective

The question asked in the last paragraph of Chapter 1.1 summarizes the main goal of this thesis. To add more context to it, the main research question is presented below:

How does building renovation impact on the cost-optimal spatial distribution and behavior of energy generation, transmission, and storage technologies in European decarbonization scenario?

The objective of this work is articulated by those three subquestions:

1. How are existing energy system models assessing the building renovation and how modelling can be improved?
2. What is the current state of buildings' heat insulation among countries in Europe?
3. What is the impact of different weather conditions on the adoption of renovation strategies?

Questions 1 and 2 are answered as a part of a literature review that was focused on the research papers where building renovation was performed. Researchers used different methods, spatial scales, and time scales, made many simplifications, and got different results. By analyzing those factors, the knowledge gap was identified which was addressed further in the modeling part.

Subquestion 3 and the main research question can be answered only based on the mathematical modeling of energy systems, which was performed by adding a building renovation feature to the existing model Calliope and analyzing the difference between different renovation scenarios. The description of Calliope is given in Chapter 3.1.

1.3 Thesis report structure

The structure of this thesis is presented in Figure 3. Firstly, in Chapter 2, there is a literature review described, where different approaches to modeling a building renovation in energy systems were analyzed. Next, in Chapter 3 there is a description of heating system modeling that adds renovation measures to the existing energy system model – Calliope. For an interested reader, the details regarding the modeling are presented in Appendix A to D. In Chapter 4, there is a description of scenarios and assumptions that were used to run a model in order to answer research questions. In Chapter 5 the results of simulations are presented, where the additional information proving statements in this chapter is available in Appendix E. Lastly, Chapter 6 discusses results and gives ideas for future research.

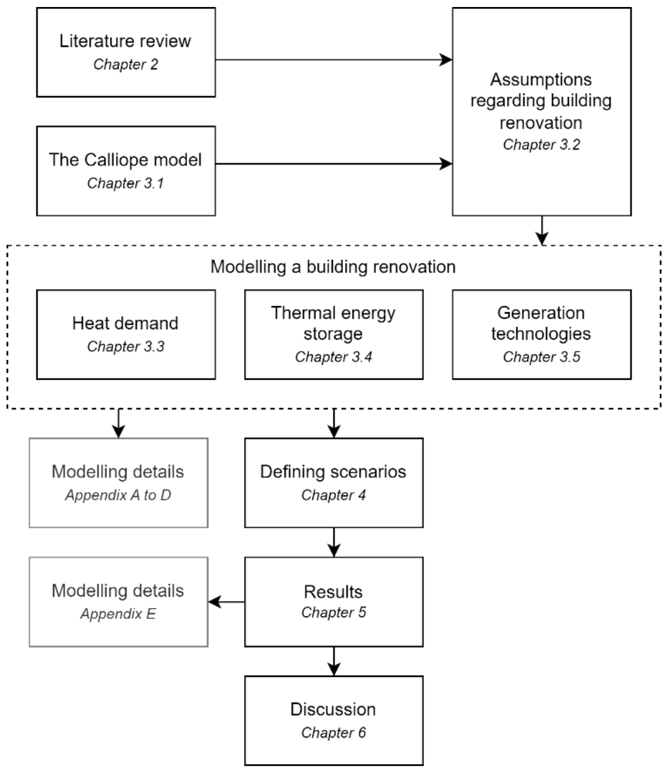

Figure 3. Thesis structure including chapters and logical dependency.

2 Literature review

This chapter contains the literature review of the research papers that analyze the modeling of a building renovation. This step was important to know what bottlenecks are in currently used methods, what are their strengths and to see where improvements are needed and can be done. Thanks to that the knowledge gap was identified. In total, there were 55 papers checked, out of which 24 were accounted as relevant to the topic. The list of relevant papers is shown in Table 1. Nevertheless, many interesting findings also were present in non-relevant papers and therefore those interesting findings were discussed with the main findings in Chapter 2.7.

Table 1. Research papers directly studying the building renovation.

No.	**Title of the paper**	**Reference**
1	Mixed integer linear programming and building retrofits	(S. I. Gustafsson, 1998)
2	Optimizing Distributed Energy Resources and building retrofits with the strategic DER-CAModel	(Stadler et al., 2014)
3	Optimal design of energy conversion units and envelopes for residential building retrofits using a comprehensive MILP model	(Schütz et al., 2017)
4	Multiobjective optimisation of energy systems and building envelope retrofit in a residential community	(Wu et al., 2017)
5	The feasibility and importance of considering climate change impacts in building retrofit analysis	(Shen et al., 2019)
6	Multi-objective optimization of building retrofit in the Mediterranean climate by means of genetic algorithm application	(Rosso et al., 2020)
7	Possibilities for Deep Renovation in Multi-Apartment Buildings in Different Economic Conditions in Europe	(Končalović et al., 2022)
8	Optimal renovation of buildings towards the nearly Zero Energy Building standard	(Iturriaga et al., 2018)
9	MANGOret: An optimization framework for the long-term investment planning of building multi-energy system and envelope retrofits	(Petkov et al., 2022)
10	Evaluation of energy renovation strategies for 12 historic building types using LCC optimization	(Milić et al., 2019)
11	Dynamic building stock modeling: General algorithm and exemplification for Norway	(Sartori et al., 2016)
12	Dynamic building stock modeling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU	(Sandberg et al., 2016)
13	Development of an energy atlas for renovation of the multifamily building stock in Sweden	(Johansson et al., 2017)
14	Modeling and optimization of retrofitting residential energy systems at the urban scale	(Jennings et al., 2014)
15	A new methodology for investigating the cost-optimality of energy retrofitting a building category	(Mauro et al., 2015)
16	Using a dynamic segmented model to examine future renovation activities in the Norwegian dwelling stock	(Sandberg et al., 2014)
17	Modeling opportunities and costs associated with energy conservation in the Spanish building stock	(Mata et al., 2015)
18	Reaching the climate protection targets for the heat supply of the German residential building stock: How and how fast?	(Diefenbach et al., 2016)
19	A bottom-up harmonized energy-environmental models for europe (BOHEEME): A case study on the thermal insulation of the EU-28 building stock	(Gulotta et al., 2021)
20	Using urban building energy modeling (UBEM) to support the new European Union's Green Deal: Case study of Dublin Ireland	(Buckley et al., 2021)
21	An Integer Linear Programming approach to minimize the cost of the refurbishment of a façade to improve the energy efficiency of a building	(Salandin et al., 2020)
22	A spatio-temporal life cycle assessment framework for building renovation scenarios at the urban scale	(Mastrucci et al., 2020)
23	Identifying practical sustainable retrofit measures for existing high-rise residential buildings in various climate zones through an integrated energy-cost model	(He et al., 2021)
24	Energy Efficiency in Buildings	(Streicher et al., 2020)

2.1 Analysis of methods

Different researchers used different methods to assess the same problem. Those methods can be divided to:

- mathematical programming methods (linear programming, mixed integer linear programming, mixed integer non-linear programming),
- life cycle assessment,
- material flow analysis,
- optimization using neural networks and
- simulation-based sensitivity analysis.

The frequency of used methods was presented in Figure 1.

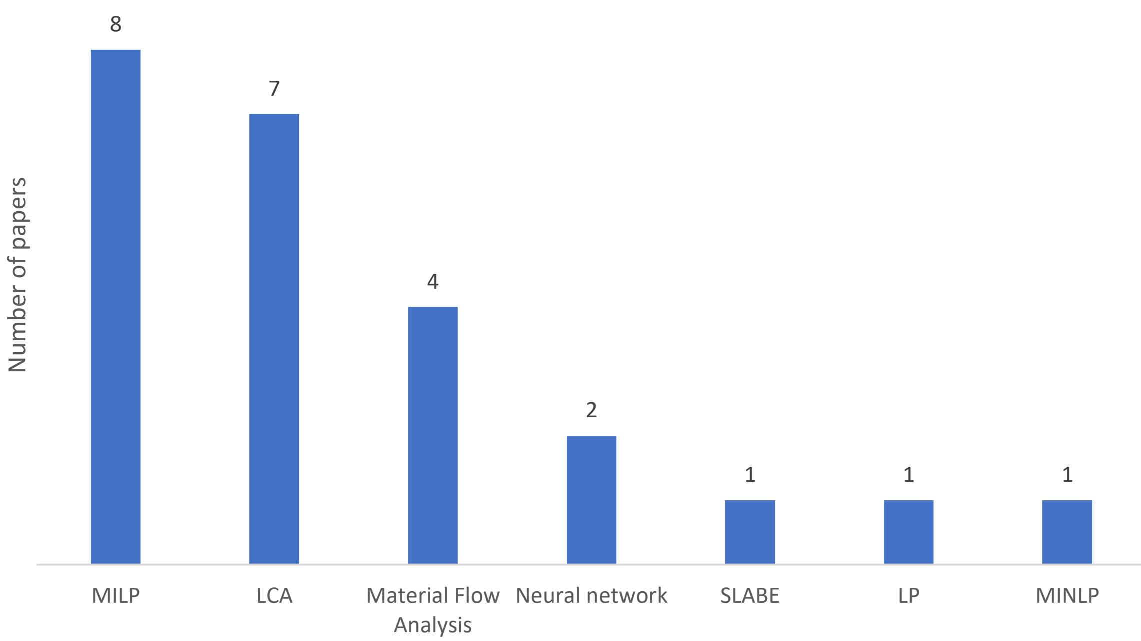

Figure 4. The method used in analyzed papers. The most frequently applied method was MILP, followed by LCA and Material Flow Analysis.

The most popular method among analyzed papers is linear mathematical programming (MILP, LP) which enables the optimization of the renovation measures within complex systems. However, its disadvantage is that it lacks the capability of solving non-linear problems, which enforces using simplifications. The second most popular method was LCA (Life-cycle Cost Analysis or Life Cycle Assessment) which is good at comparing different predefined solutions. Unlike mathematical programming, LCA cannot model optimized dispatching which is a huge drawback and limits the functionality of dispatchable generation units. Material Flow Analysis analyzes the dynamics of the building stock when the building is built, renovated, and demolished. When it comes to details of the renovation process, they are ignored. Similar capabilities to mathematical programming have neural networks. The advantage of them is that they are easier to create and that they are not computationally intensive, however, those methods work as a black box, so the optimization process is unknown, and results are limited. One research paper used the SLABE model, which claims that current models use only one reference design and do not model the behavior of the building users, which can be significantly different.

2.2 Analysis of a spatial scale

Analyzed papers focused on many varying spatial scales as shown in Figure 5. The smallest scale that was analyzed consisted of two facades of a building (Salandin et al., 2020). On the other hand, the larger scale models were consisting of up to multiple countries of the European continent, 11 countries (Sandberg et al., 2016) and 28 countries (Gulotta et al., 2021).

It can be visible that optimization methods (mathematical programming and neural networks) were used up to the city scale. For a larger scale, only LCA and Material Flow Analysis methods were used. This is related to a plethora of challenges that need to be overcome to apply optimization methods for a large scale. Researchers struggled with gathering data regarding building features that would be suitable for a larger area. Also, then the climatic conditions and consumption profiles are different. This increases the computational complexity of a problem. Moreover, the heat can be transferred on a much smaller scale than electricity. So, there is no point in analyzing the whole country at once if the simulation of separate cities would give the same results when it comes. It is true only if the heating system is treated on its own.

In reality, district heating systems and even local heat sources are intertwined with other energy systems like natural gas systems and power systems. Hence, the analysis of the impact of the building renovation on the power system shall be made on a larger scale. The city scale would ignore the transmission of energy carriers between urban and rural areas.

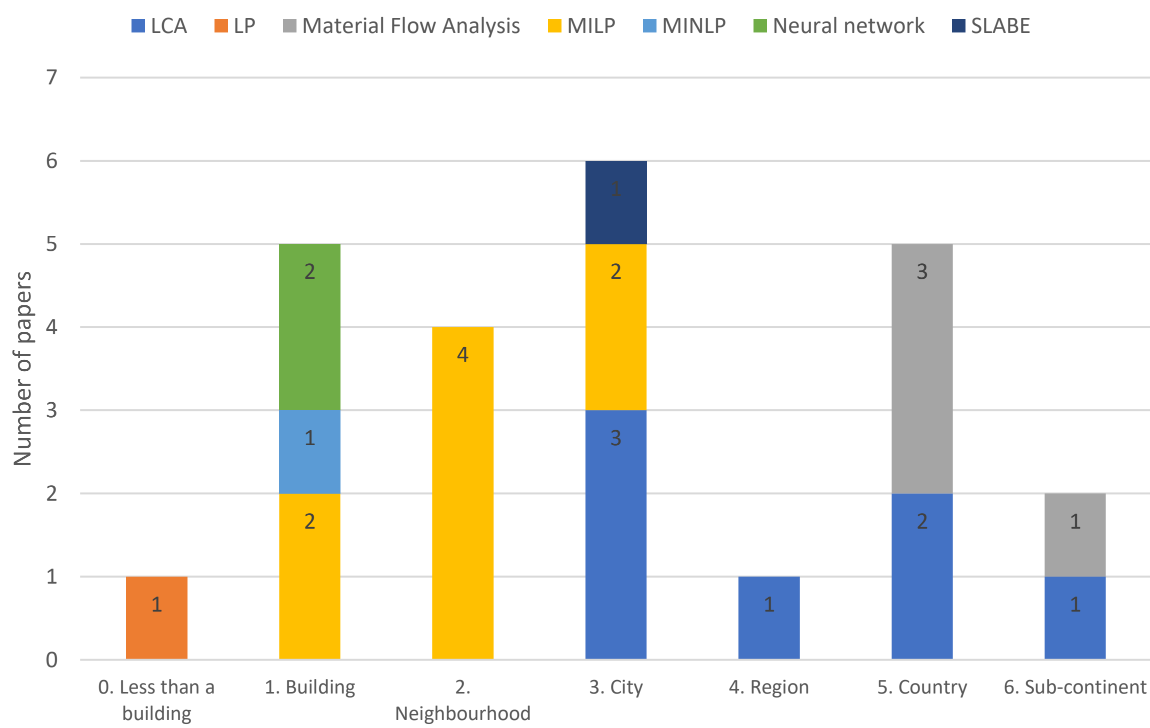

Figure 5. Spatial scale of analyzed papers grouped by methods. Optimization methods are limited to spatial scale of city or lower.

2.3 Analysis of a time scale

For optimization methods, the parameter which is a time scale is important and therefore it was decided to analyze what time scales are used in the literature. All papers analyzed at least the whole year to assess the seasonal weather changes. Among the analyzed papers, there were 4 methods of dealing with the changes in atmospheric conditions:

- analysis on an hourly basis, where all 8760 hours in a year were characterized by separate weather conditions,
- representative days, where the hourly time scale was used for several days of a year where those days were further scaled to give the whole year,
- segments, where the year was divided into several segments with constant weather conditions,
- degree-days, where the one (or two) number was used to represent the typical weather for the whole year.

As can be seen, the first method is the most detailed one and computationally complex. Researchers claimed that the reason for decreasing the timescale was the computational complexity. Based on the abundance of papers, where the simpler methods were used, it can be deduced that the lower time scale, does not negatively affect the results. If the time scale was not given directly in the paper, it was assumed to be 8760 hours in a year.

An overview of the used methods is given in Figure 6.

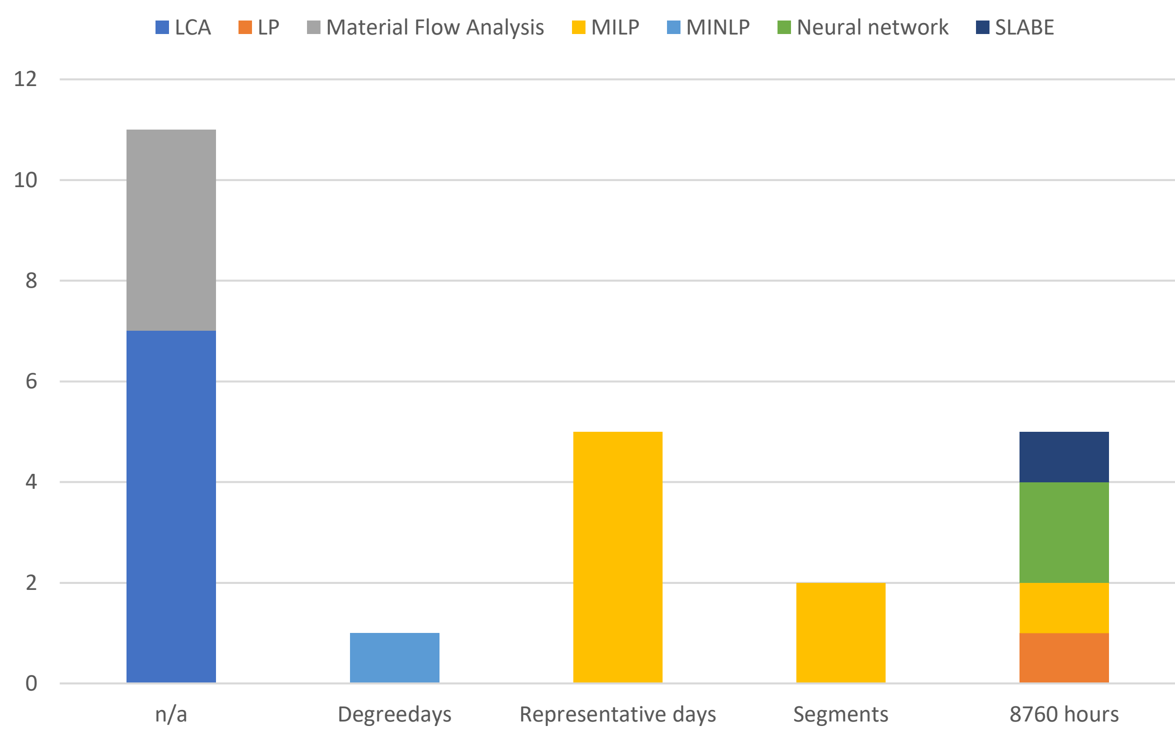

Figure 6. The time scale of analyzed papers grouped by methods.

2.4 Analysis of renovation measures

Different papers also analyzed different renovation measures as can be seen in Figure 7. Material Flow Analysis only decides if the building is renovated or not so no detail of the renovation is known. In all other papers, the outside wall renovation was included. Moreover, 11 papers also included other means of renovation than only improvement of envelope insulation like:

- PV installation,
- solar thermal collector installation,
- improvement of an existing heat generation source,
- replacement of an existing heat generation source,
- ventilation improvements,
- adding energy-efficient lighting,
- door replacement,
- and other.

It is visible that half of the papers analyzed the improvement of thermal performance of outside walls (OW), windows (WIN), roofs (ROOF), and floors (FLOOR).

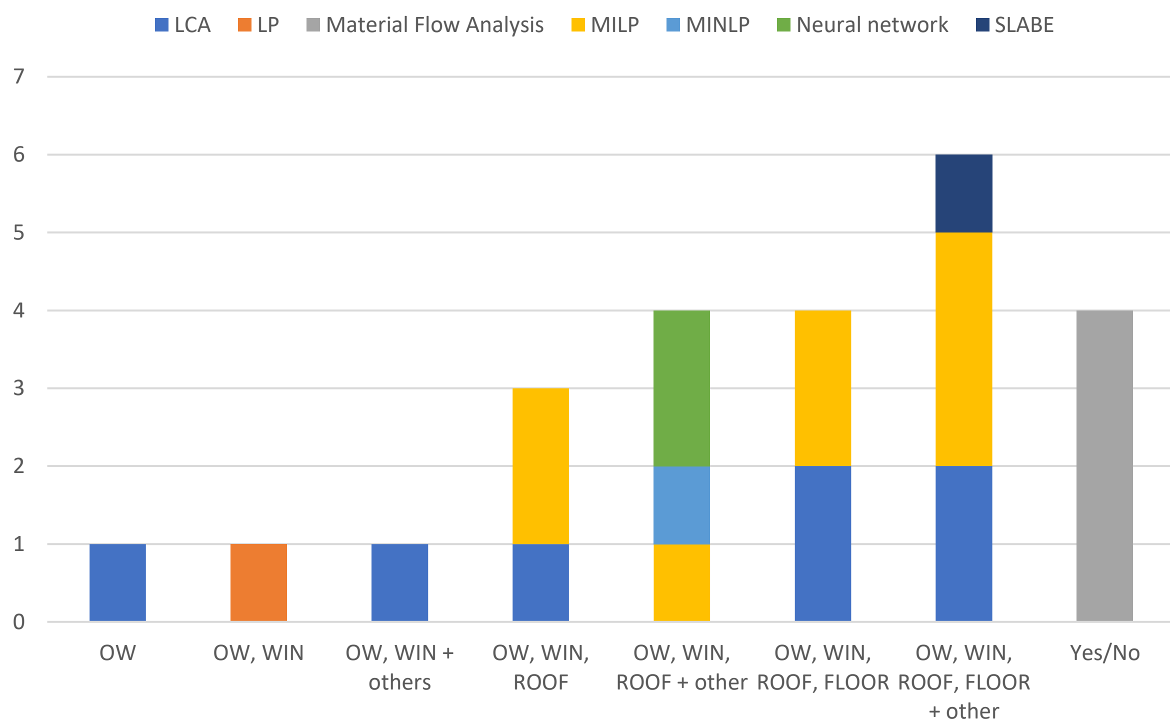

Figure 7. Renovation measures of analyzed papers grouped by methods.

2.5 Analysis of archetypes

Another feature that differs from research papers, is the way of calculation of building's heat demand, which can be used as an input to the optimization algorithm. A significant number (42%) of papers was focused on analyzing of single building archetype for which the construction details (as exact dimensions, construction materials, their thicknesses, and heat conductivities) were known or assumed. For those buildings usually special software was used to create the heat demand profile of a building. It may seem that using special software increases the accuracy of a simulation, but this is not true in all cases. Often there were used significant simplifications regarding heat transfer phenomena and heat gains. The abundance of those simplifications shows that simplified models are not much less accurate than those complex ones and are well-established in the research community.

When it comes to papers where more buildings were analyzed, they were clustered in forms of archetypes. This was made due to the inability of accessing the exact parameters of the building except for the most superficial ones like the construction year and the floor area. There were many different ways of defining archetypes like construction year, function (residential, non-residential), typology (single-family house, multi-family house, construction material (concrete, wood, brick), climate conditions, and location.

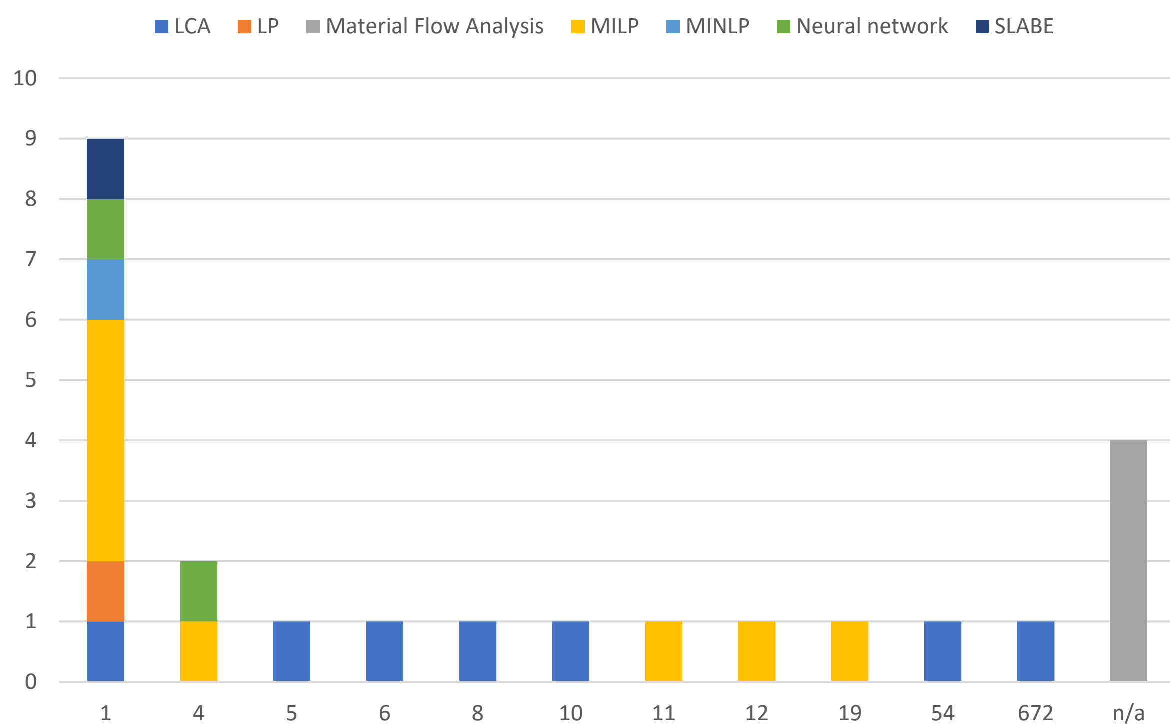

Figure 8. Number of buildings archetypes of analyzed papers grouped by methods. Most papers were analyzing only one archetype.

2.6 Analysis of renovation results

Lastly, different papers stated different renovation measures as profitable. The conditions of profitability were different and ranged from low payback time to the lowest environmental impact. The recommendation of insulation was analyzed separately for outside walls (OW), windows (WIN), roof (ROOF), and floor (FLOOR) renovation. If there was an objective statement that something is profitable the 1 was assigned to the renovation. If it was stated as not profitable, then 0 was assigned. If there were no objective statements, the renovation means were compared with the most profitable mean. The results of the analysis are shown in Figure 9. It can be seen that everything except floors was profitable to be renovated in a similar number of cases (between 31.5% and 36.7%). It is worth adding that, it was common that only one renovation measure was profitable to do, and others were not profitable at all. The only exception was paper (Stadler et al., 2014), where none of the renovations were profitable. In addition, different papers showed that different renovation measures were the most profitable. This difference is probably caused by different climate conditions and spatial scales of analyzed cases. Moreover, different assumptions regarding costs also have an impact on the final result.

Some papers analyzed several scenarios. In that case, the results of the most basic scenario were taken into account. Other papers do not analyze monetary costs at all. A good example is (Diefenbach et al., 2016), where the thickness of insulation was chosen so that the emissions are reduced to the accepted level. In (Gulotta et al., 2021) instead of the monetary payback time, the environmental payback time was the only important thing. Therefore, instead of costs there was an environmental impact taken into account and instead of savings, the reduction of the environmental impact of the building was used. In (Buckley et al., 2021), the best investment was defined as the one that reduces carbon dioxide emissions for the least amount of money (EUR/kg_{CO2}). If there were several different scenarios analyzed, the monetary costs were taken as relevant.

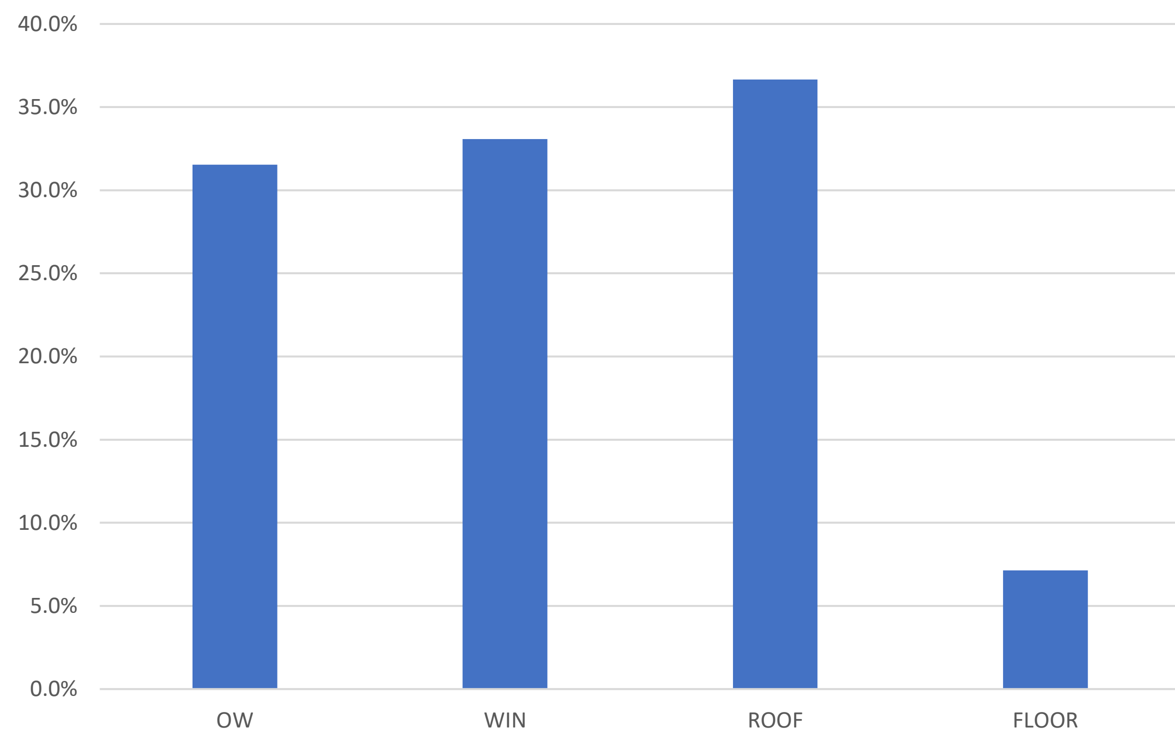

Figure 9. Percentage of times when the renovation of outside walls, windows, roofs and floors was profitable in analyzed articles.

2.7 Discussion of findings

In this section, the discussion of interesting findings from the literature review was done. The diversity of findings is very broad, so the discussion is organized in a way that for each finding there was prepared a separate paragraph. Therefore, the following paragraphs are not interconnected in any way. Paragraphs were sorted in the importance order so that the first paragraph touches on the most important finding.

It is known that when analyzing an improvement of the insulation, the profitability of an investment is defined as the quotient of the investment cost divided by the possible savings due to the investment. The paper (Stadler et al., 2014), analyzed the case study of improving the thermal performance of a building built in 1970. It resulted in the optimal U-value of 0.53 $\frac{W}{m^2K}$. The author compared it with 2014 standards which are equal to 0.42 $\frac{W}{m^2K}$. As it can be seen, the new standards are forcing construction companies to build buildings that are more expensive than they should be. This problem was not raised in any other paper. However, similar results were visible for example in (Iturriaga et al., 2018), wherein none of the three analyzed cases of renovation, it was possible to renovate windows. Knowing that energy prices might drop in the future, the problem of too strict standards might be even more apparent. Therefore, the research should not only analyze, if it is profitable to increase the insulation but also the possibility of decreasing the thermal performance of a building.

A known fact is that buildings have a thermal capacity. Therefore, by dynamically changing the inside air temperature, it is possible to heat up and cool down walls in order to store the heat. Checking how it would be possible to implement in mathematical programming and what the result would be was suggested in a very old paper (S. I. Gustafsson, 2000). Since then, the control schemes of building climate were significantly developed as described in (Barber & Krarti, 2022). However, none of the analyzed papers was modeling such behavior. Hence, the heat energy storage in construction elements will be addressed in this thesis.

The (Iturriaga et al., 2018), differentiates between different heat potentials. The author divided heat into high temperature, medium temperature, low temperature, and cooling. Also, the conversion pathways between them were defined. As a result, different generation sources were assumed to produce a heat of different potentials. Thanks to this, a more realistic analysis can be performed because some processes require a higher heat temperature, and therefore some generation sources cannot be used to provide the required potential.

A very interesting approach was made in (Petkov et al., 2022), where the researcher also analyzed the schedule of renovations. They divided the 2020-2060 period into 5 different time steps to which they assigned different renovation measures based on the techno-economic decisions. This is a very interesting approach, that can be used to simulate the existing system and its pathway into the future. However, it does not give any information about how new buildings should be built.

It is also worth mentioning that similar optimization problems are also present for different demands of buildings like water demand. In (Emami Javanmard et al., 2020) the optimization of water usage is made. There are systems of collecting and cleaning waste and rainwater analyzed. Those measures result in energy and carbon dioxide consumption.

In order to improve the accuracy of large spatial scaled problems, the GIS software can be used to extract the building's dimensions. This also helps with defining the effects of shading, and roof orientation and enables to introduce of intra-building interactions. However, the problem of uncertain construction materials would still exist. Moreover, additional series of assumptions need to be made for the data that is unknown like window/wall ratio or floor's height. The simplest use of GIS software was done in (Mastrucci et al., 2020), where the geometry of buildings in Luxemburg and their height was gathered that way. As (Buffat et al., 2017) and (Carnieletto et al., 2021a) proves that this gives a significant advantage regarding accurate heat demand calculations. The accuracy of this solution can be significantly improved if the GIS database can be coupled with another information source containing the energy consumption data of each building. This was done in Sweden (Johansson et al., 2017), where the national database contains information about the energy consumption of over 80% of existing buildings.

The very important result presented in (Sandberg et al., 2016) is that between 70% and 80% of building stock will be deeply renovated. This suggests that the façade would need to be renovated either way. Therefore, if thermal insulation is added when the deep renovation would take place, the labor costs related to adding insulation should be included, in the costs of any renovation and for no-renovation cases.

An interesting method of analyzing the building sector was shown in (Mastrucci et al., 2017), where the mass of materials used to build buildings was analyzed. Researchers kept the building renovation out of the scope of this research paper.

An interesting representation of results is investment curves (Streicher et al., 2020). They show the indication that building archetypes should be first renovated. It seems that results from such an analysis might be very useful to create a renovation plan. On the other hand, the order of urgency of renovation measures and building archetypes can be also calculated outside of optimization models by calculating a payback time of such an investment.

2.8 Knowledge gap

As the heat and electricity price depends on many different variables including the energy consumption of residential buildings, it would be expected also to check the impact of the renovation on the power and heat systems. It was only taken into account in one paper (Diefenbach et al., 2016). Moreover, the heat and power systems were assumed and not optimized (due to using an LCA method). It seems that huge improvements can and should be made in this field. There was also one research paper (Johansson et al., 2017), which analyzed the district heating network together with heat generation units and their dispatch. However, the building renovation was out of the scope of researchers.

It is visible that there are examples of papers focused on optimizing energy systems and other papers focused on optimizing building renovation. However, there is no research paper that coupled those two things. This knowledge gap needs to be addressed in this thesis, as it is necessary to answer the main research question.

3 Modeling a building renovation

To answer the main research question, the mathematical model of the energy system needs to be used. The Calliope model is capable of cost-optimizing multiple energy systems and interactions between them. Moreover, after modification, it is also capable of modelling building renovation. Therefore, the Calliope model is the right tool to use. To be specific, the Euro-calliope model was used, as it contains predefined locations and most of required inputs to simulate European continent.

Firstly, in Chapter 3.1, the description of the Calliope was given, which is followed by an overview of the existing heating system modelled in the Calliope. Secondly, in Chapter 3.2, the reader can find assumptions which are a base to build a new heating system model. Then in Chapter 3.3, Chapter 3.4, and Chapter 0 the three main components of the heating system are described which are heat demand, thermal energy storage, and heat supply respectively.

3.1 Calliope – energy systems model

3.1.1 Working principle

The Calliope model works by manipulating energy carriers with different technologies that are assigned to specific locations. Based on that there are constraints created, which are used in the optimization algorithm. The optimization is made by minimizing the cost (also other factors can be minimized like CO_2 emissions) of the system.

The type of technology defines the role and is related to its constraints that will be further used in the optimization algorithm. There are 5 main types of technologies in Calliope:

- supply technology – this technology uses a resource from the outside of the system and converts it into an energy carrier.
- conversion technology – this technology converts an energy carrier to another energy carrier
- storage technology– this technology can store an energy carrier so that it can be used in a different moment
- demand technology – this technology works as a sink for an energy carrier.
- transmission technology – This technology enables the transmission of an energy carrier to a different location.

All those technologies have costs assigned. There are costs related to the capacity of a technology [EUR/kW] and to the energy that flows through the technology [EUR/kWh]. Moreover, there is a lifetime of the technology defined as the interest rate, to correctly assess the value of the system in the future. In addition, those technologies are assigned to specific locations (Pfenninger & Pickering, 2018).

This particular model was chosen as it is best known to the research community of TU Delft, it is already complete in other aspects of the energy system and is malleable to such an extent that new features as building renovation can be added.

3.1.2 Spatial resolution

Euro-calliope is the existing model with predefined locations and all necessary inputs to simulate Europe. There are three special levels available:

- continental scale, where Europe is treated as one location,

- national scale, where 35 countries are treated as separate locations, connected with neighboring nodes,
- euro-spores, where bigger countries are divided into smaller locations (96 locations in total) based on the realistic power transmission connections (Tröndle et al., 2020).

In this thesis, only the national special resolution was applied, which is a compromise between continental and euro-spores special scales. This is aligned with the undertaken approach of having a high quality of the output without unnecessary computational complexity. Moreover, the input data regarding current building stock is not available for separate regions. Furthermore, those regions are not divided by climate zones that are the prevailing force in changes in the building stock. A good example is (Carnieletto et al., 2021b), where the data of a building stock in Italy, is available only for one of the climate zones. A similar situation is when it comes to heat demand for different regions.

3.1.3 Temporal resolution

The default temporal resolution is equal to one hour. Any other larger time step is possible within the Calliope. To include the seasonal difference in heat demand, the whole year needs to be simulated, moreover, some parts of Euro-calliope (ex. CHP) require the simulation of the whole year (Tröndle et al., 2020). It was decided that a 2-hour resolution is enough to obtain a reliable result and simultaneously reduce the computational time and file size compared a to 1-hour time resolution.

3.1.4 Existing model

Currently, in the Calliope, the heat is modeled as one carrier that is consumed in each location. The heat demand is calculated by the workflow for each of the countries for each hour of the year. This demand needs to be satisfied by technologies that convert other energy carriers to heat. There were already attempts to divide the heat demand to heat demand for cooking, heat demand for space heating, and other heat demands but they were not successful. Therefore, the basic model has only one heat demand technology that accounts for low-temperature heat (residential and services sector). The high-temperature heat for the industry is obtained by introducing fuels demand but this is out of the scope of this thesis (Tröndle et al., 2020). The overview of the heat sector of the current model is shown in Figure 10.

As can be seen, there are 11 conversion technologies that convert electricity, methane, biomass, solar energy, waste, and hydrogen to the intermediate heat carrier which is specific for each of those 11 technologies. Then each of those heat carriers can be stored in small or big storage technology. These intermediate heat carriers are then converted to heat, which is consumed by the demand technology.

Those 11 technologies are as follows:

- electric heaters,
- air source and ground source heat pumps (including the technology that is the average of air and ground source),
- solar thermal collectors,
- methane and biofuel boilers,
- biofuel, methane, waste, and hydrogen combined heat and power (CHPs).

It is worth mentioning that the air source and ground source heat pumps are by default not used in the model and they are replaced by the heat pump technology. Moreover, solar thermal collectors have undefined irradiation, therefore they are also by default not used in the model. As the solar thermal collectors are missing, it was decided to add them to the model.

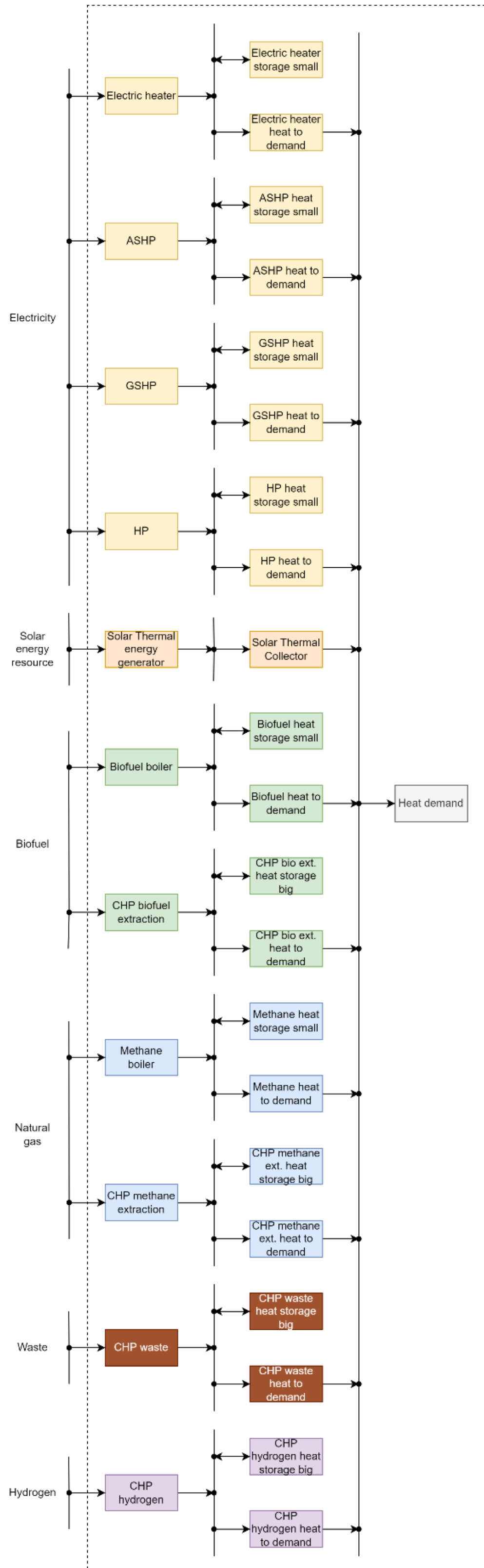

Figure 10. Block diagram of currently modeled heat sector. The boundaries of the heat sector are marked with a dashed line. Based on (Tröndle et al., 2020).

3.2 Assumptions regarding the new heating system model

As it was mentioned before, the new heating system model needs to be presented in order to add a building renovation. Therefore, a set of assumptions was created, that served as a base of the model. Those assumptions are presented below.

- First, the renovation shall only be implemented for residential buildings. The main reason is that residential buildings are more similar when it comes to parameters that are describing them. The goal of a residential building is one – to provide a living space (Johansson et al., 2017; Sandberg et al., 2016). On the contrary, service buildings' goals vary from being an office to being a shop or a diner. This variety affects the way how the heat is consumed, and how and when the heat is needed which impacts the possible renovation methods and their costs (Carnieletto et al., 2021). It is worth mentioning that the residential sector is more than twice as big as the services sector, as described in Chapter 1.1. Therefore, changes in energy system behavior will still be meaningful after ignoring the services sector.
- The second assumption is that the impact of building renovation can be modeled in two different areas, impact on the heat demand and impact on the flexibility of the heat demand due to demand side management. Those two phenomena are described in Chapter 3.3 and Chapter 3.4 respectively.
- Lastly, only the heat sector of Euro-Calliope was completely made out of scratch. Other sectors shall be kept intact so that the results obtained from the renovation simulation can be compared to other Euro-Calliope models.

Based on this, the overview of the new heating system was prepared (visible in Figure 11). It consists of:

- heat generation technologies (first column of technologies on a flowchart), which are responsible for supplying heat to the system. There are no major changes except for adding one new technology, which is a solar thermal collector.
- conversion technologies (green and blue technologies in the second column) whose role is to model the process of renovation including the costs of renovation and the impact of renovation on heat consumption. This part is completely new as before, there were no renovation technologies available.
- storage technologies (violet), that model the ability of a building and water tank to store the heat and overcome the intermittency of renewable energy sources. The storage in potable hot water was apparent in the original heat model but storage in construction elements is completely new.
- demand technologies (third row of technologies), which defines different types of heat demand. In the original model, there was only one heat demand, whereas now there is a separation into four different ones.

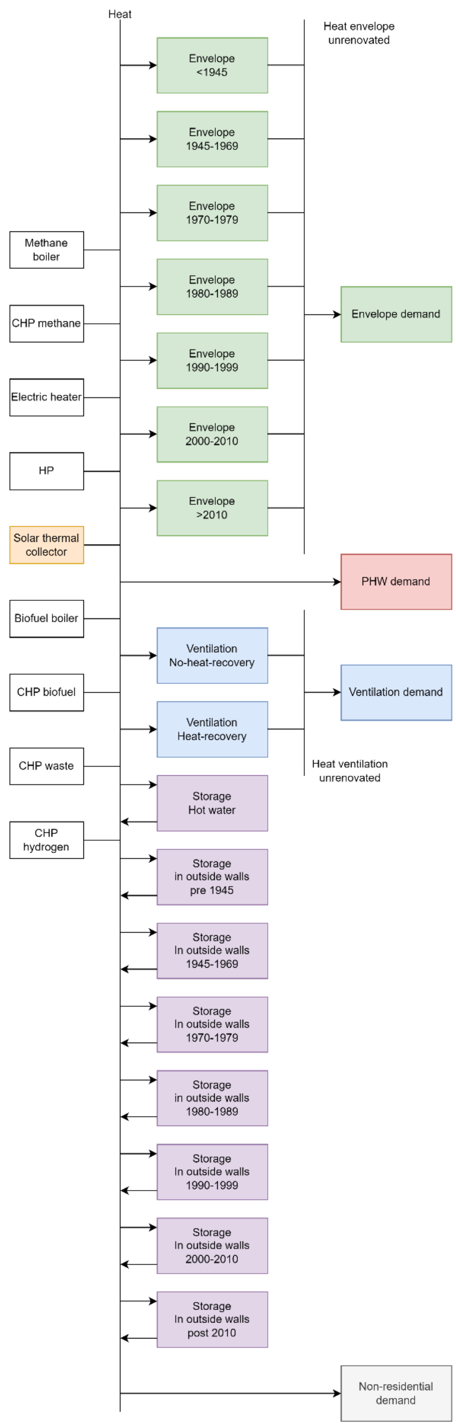

Figure 11. The new model of heating system showing generation technologies in the first column, conversion and storage technologies in the second column and demand technologies in the third column..

3.3 Heat demand

In Calliope, the heat demand profile is a predefined input to the model. It is calculated by the complex workflow in which details are unknown (Tröndle et al., 2020). As only the residential sector is interesting for this thesis, it needs to be split from the rest of the demand. Moreover, there are different renovation measures that can be applied to decrease the heat demand and store thermal energy.

Hence, the existing heat demand profile needs to be divided into the following four categories of heat consumption in order to correctly assess the features and building renovation measures available for each category.

- The first category is **heat loss through buildings' envelope**, where the insulation of walls, roofs, floors, and windows can be improved by renovation, which would result in decreased heat demand.
- The second one is **heat loss due to ventilation**, where heat recovery can be implemented to decrease the heat demand.
- The third one is the **preparation of potable hot water**, where any building renovation cannot decrease the heat demand. However, there is an interesting solution regarding the storage of potable hot water.
- The fourth one is the **non-residential heat demand**. As the current heat demand profile consists of the demand of both the residential and the services sectors, the services sector needs to be separated to keep the model complete.

3.3.1 Heat loss through the building's envelope

Heat losses through the building's envelope happen when there is a temperature difference between the inside and the outside of a building. The heat that is needed to cover those losses and keep the right temperature inside the building is one of the components of the building's heat demand. It depends on the thermal insulation quality.

The thermal insulation quality is usually given by the parameter called thermal transmittance (U-value), which describes the heat losses of the construction element per area, per temperature difference. The current building stock significantly (up to 20 times) varies when it comes to the building's thermal insulation quality. In general, the construction year of the building is a good predictor of the quality of heat insulation due to available construction materials and insulation standards in those times. The Eurostat organizes the building stock into seven different groups based on the construction year (Eurostat, 2023) as below:

- pre-1945
- 1945-1969
- 1970-1979
- 1980-1989
- 1990-1999
- 2000-2010
- post 2010

Another dimension of this problem is different types of construction elements that are characterized by different heat transmittance and areas of heat transfer. The Eurostat collects data about the quality of insulation (U-values) of outside walls, windows, roofs, and floors (Eurostat, 2023) for each of the buildings' archetypes. The assumed modeling approach consists of renovation from one archetype to the other one and no separate renovation of each of the construction elements is possible. The same approach was used in the literature (Jennings et al., 2014).

Perfectly it would be good to simulate the renovation from each group to different groups, but then it would require having 49 different paths (including decreasing the renovation level). This would result in information about the optimal renovation paths. As a result, this would increase the computational complexity of the model significantly.

This problem can be also modeled in a different way, where instead of modeling renovation paths, the 8 groups of buildings are modeled. Such a model would result in the optimal composition of buildings based on their construction year. As a result, there will not be any information about paths. However, by comparing the current state with the optimal state, those paths can be to a certain degree recreated. Because of this, the second method will be implemented.

From Calliope's perspective, each building group will be modeled as a separate "conversion technology", which converts "heat" to "unrenovated heat", with given efficiency and costs, as shown in Figure 12. By unrenovated heat, it is understood the average (within a country) heat that needs to be supplied if no renovation is implemented. Thanks to this approach, by setting different compositions of archetypes, many different scenarios can be set with ease, including the scenario which simulates the system without the renovation. The calculation of efficiency and the estimation of costs is described in Appendix A.

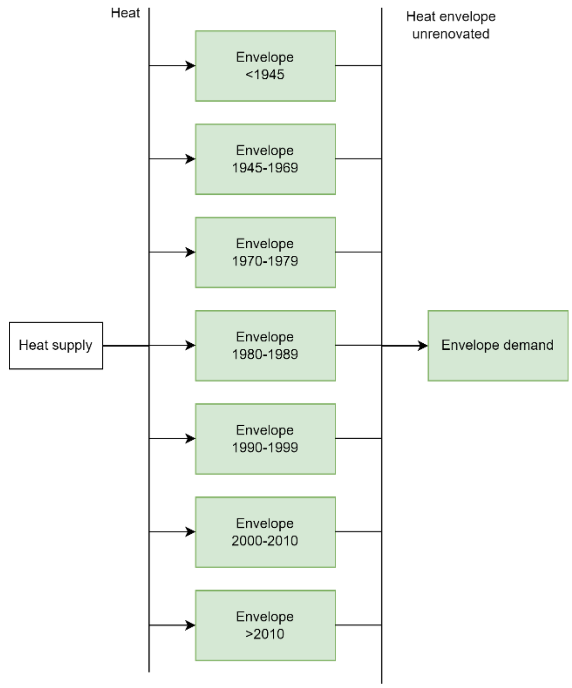

Figure 12. Envelope conversion technologies that represent different building archetypes.

It is worth mentioning that under normal conditions, Calliope would treat different archetypes as different technologies, that would be dispatched accordingly (approximately) to the variable cost. This means that the more efficient envelope archetype would be always dispatched before the more expensive one. It is known that all buildings regardless of the archetype would have their own heat demand at any moment.

In Calliope, there is an existing group constraint called "demand_share_per_timestep_decision", which defines the new optimization parameter which is a fraction of the heat demand of each building archetype in total residential heat demand in each time step. Therefore, it solves the problem of an unrealistic dispatch.

The visualization of how this constraint is working is given in Appendix A.

3.3.2 Heat loss due to ventilation

In general, the ventilation can be categorized as natural or mechanical. Where in buildings with natural ventilation, the air circulation is maintained by the free convection caused by changes in air density due to temperature difference between indoor and outdoor air. In the case of mechanical ventilation, the intake or exhaust air fan is supporting the natural convection. If the exhaust and intake fans are installed at the same time, the air supplied can transfer heat to the extracted air (or vice versa), therefore heat recovery is possible (Cuce & Riffat, 2015). This phenomenon is visualized in Figure 13.

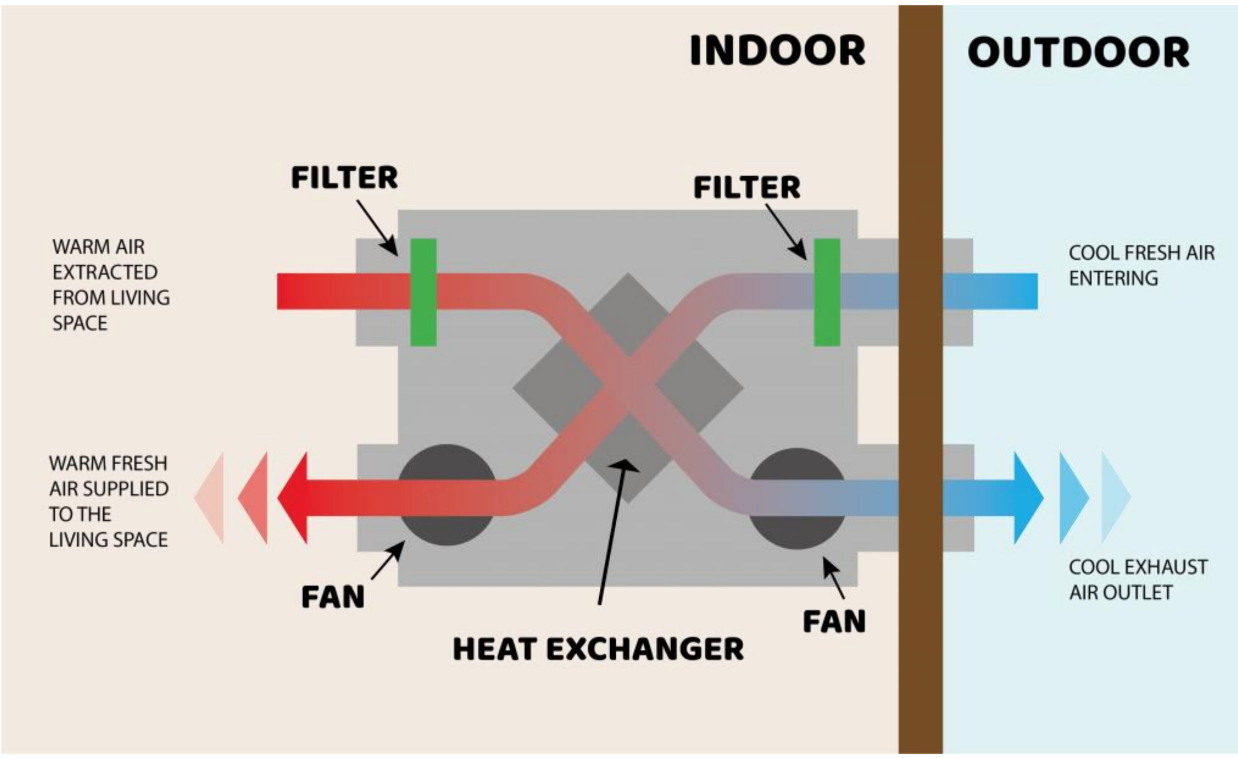

Figure 13. Fundamentals of heat recovery ventilation (Pure Ventilation, n.d.)

As was already mentioned, the supply and exhaust fans are needed. Moreover, they need to be more powerful in order to overcome the pressure drop over the heat exchanger. Therefore, the decrease in the heat demand will create an additional electricity demand, which needs to be modeled in Calliope as a “conversion plus technology” that would convert heat and electricity to the heat demand of unrenovated ventilation. The heat demand of unrenovated ventilation is the value that is the result of the demand splitting, describing the current composition of ventilation types. For the purpose of this thesis, the ventilation types were divided into “no heat recovery” and “with heat recovery”.

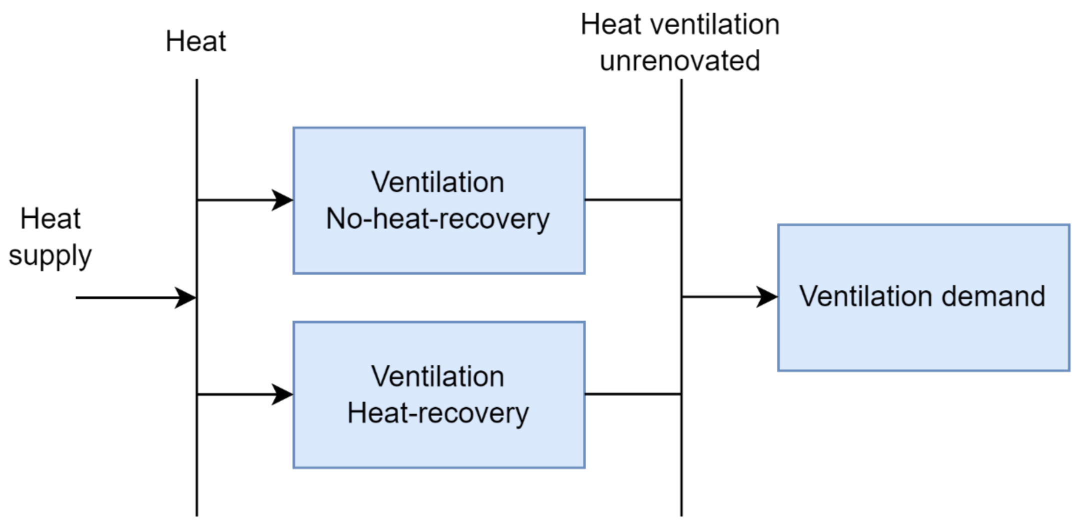

Figure 14. Implementation of ventilation demand in Calliope.

The literature is very limited when it comes to publishing shares of different ventilation types. The only numbers are given in (Concannon, 2002) and (Litiu, 2012), where data was gathered in 1994 and 2012. According to (Concannon, 2002), it can be seen that heat recovery ventilation is certainly not present at all except countries like Sweden, Norway, France, and Denmark. The exact number of heat recovery ventilation in those countries is also not known because the paper sums together heat recovery and non-heat recovery systems. In (Litiu, 2012), heat recovery ventilation is combined with non-heat recovery ventilation, in most graphs. The general outcome from this research is that in many countries heat recovery is non-existing, and the newer buildings have a higher share of “balance mechanical ventilation”, which includes also heat-recovery ventilation. The only country in which heat recovery ventilation was not coupled with other types of vntilation is Greece, where for buildings before 1978 it was installed in 1% of dwellings and after 1978 in 5% of buildings.

Another factor is the additional power consumption to force air movement. The power consumption is constant throughout the year because of the increased air tightness of the building which makes natural ventilation ineffective. However, electricity consumption-related costs do not need to be added manually, as they are modeled by Calliope.

Due to a lack of data, it will be assumed that currently 0% of buildings are equipped with heat-recovery ventilation. As for the envelope technologies, the efficiency and the costs were calculated. The detailed calculations can be found in Appendix B. When it comes to the power consumption, the simplification was made and constant efficiency was assumed instead of constant consumption, as it should not have any significant impact on the model. The result regarding this assumption was discussed in Chapter 6.

Lastly, a similar dispatch problem that was described for envelope technologies is present for ventilation technologies. Therefore the ‘demand_share_per_timestep_decision’ constraint needs to be added for those technologies.

3.3.3 Preparation of potable hot water and cooking demand

The heat demand for the preparation of potable hot water will not change with the building renovation since there is no meaningful way of decreasing its consumption via the renovation. The final heat demand for the hot potable water is already modeled in the workflow and will be used (after separation from the rest of the heat demand) as the input to the “demand technology” that describes the hot potable water.

Cooking demand will be neglected in this thesis for several reasons. First of all, cooking heat demand is very small compared to the total energy demand in residential buildings. As can be seen in Figure 2 in Chapter 0, cooking consumes between 1.3% and 7% of total residential energy demand.

Moreover, the realistic representation of cooking demand in the calliope will be computationally consuming because it requires adding a separate set of technologies that can be used as cooking stoves, and due to the low impact on energy consumption, it will not affect the system significantly.

3.3.4 Splitting the heat demand

The Calliope model has a one heat demand profile that describes the demand created both by the residential sector and the services sector. It is characterized by the hourly resolution and covers all hours since 2010 to the end of 2018. To assess the impact of renovation strategies, this demand needs to be further divided into:

- heat demand caused by losses through residential buildings’ envelope (envelope heat demand),
- heat demand caused by ventilation losses in residential buildings (ventilation heat demand),
- heat demand for heating potable hot water in residential buildings (PHW heat demand),
- heat demand of services buildings (non-residential heat demand).

Details showing how the initial demand was calculated are unknown and therefore in order to split this demand, the general profile needs to be recreated. The Calliope files also contain average yearly heat demands (for 2050) of the following 4 characteristics for 35 countries:

- space heating demand of the residential sector,
- potable hot water demand of the residential sector,
- space heating demand of the services sector,
- potable hot water demand of the services sector.

Those yearly demands shall and were used to recreate the demand profile in the following way.

First of all, the profile of potable water consumption for the Netherlands from a different energy model (Quintel, 2013) was found. Originally it describes one year with an hourly resolution (8760 hours). Then it was adjusted to the correct time zone (UTC+0), leap years were filled in with data, and the values were normalized so that the area under the yearly demand curve is equal to one. Next, the normalized hourly values were multiplied by the yearly demand values for each country, and the final yearly profile of heat demand for potable hot water was created.

it is known that the envelope heat demand and ventilation demand are proportional to the temperature difference between the inside and the outside as described in Chapter 0 and Chapter 0. Therefore, if one knows the temperature profile, the heat demand profile for envelope and ventilation is also known. In this thesis, the population-weighted temperature profile for each country was used (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016). Based on the results of calculations made in 3.3.1 it is possible to calculate the envelope heat demand of each archetype for any temperature. Moreover, from the analysis made in 3.3.2, it is possible to calculate the heat demand for ventilation for one building for any outside temperature. As was mentioned in this paragraph, envelope and ventilation heat demand depends on the temperature in a similar way, so the proportion between them will be always the same.

This proportion combined with the yearly space heating demand of the residential sector, is used to create the yearly envelope heat demand and yearly ventilation heat demand. They, together with temperature profiles give the envelope heat demand profile and the ventilation heat demand profile. In addition, at this stage, it is possible to calculate the number of archetypical buildings in a country's stock by dividing the building's space heating demand by the county's space heating demand. This value was used for calculations in Chapter.

It is worth mentioning that the residential heat demand for Iceland is equal to 0 (Tröndle et al., 2020), as most of the heat comes from the geothermal heat plants, which are currently not a part of Calliope. After analyzing the local scale, limited availability (in Europe), and uncertainties regarding costs (IEA, 2010, 2011) it was decided to keep geothermal plants out of the scope of this thesis as it is in the Euro-calliope.

3.4 Thermal energy storage

In Calliope, the impact of renovation on the flexibility of demand can be modeled with the “storage technology”. However, there are many parameters that need to be set, so that the model reflects the real behavior of the storage device. One of the most important parameters is the loss rate, which describes how much capacity is self-discharged within one hour. Another parameter that needs to be taken into consideration is the storage and energy capacity of the storage technology. Based on those differentiated properties there was made a distinction between the following technologies, as shown in Figure 15

- the thermal energy storage in the sensible heat of hot potable water and,
- the thermal energy storage in the sensible heat of buildings’ construction elements.

The first one consists of a well-insulated tank that is filled in with hot water and then the water is discharged when there is a demand. This means that the user has full control over the dynamics of the process (heating and usage). On the contrary, the thermal energy storage in the building’s structure is much different. The charging process is much slower because the heat is transferred via the radiator to the inside air, which needs to be heated to the temperature over 20°C, to heat up outside walls. The discharging process is even slower and there is no control over it except modifying the inside air temperature. Hotter walls spontaneously transfer heat to the inside air (and to the environment).

The process of adding those two storage technologies was described in Chapter 3.4.2 and Chapter 3.4.1.

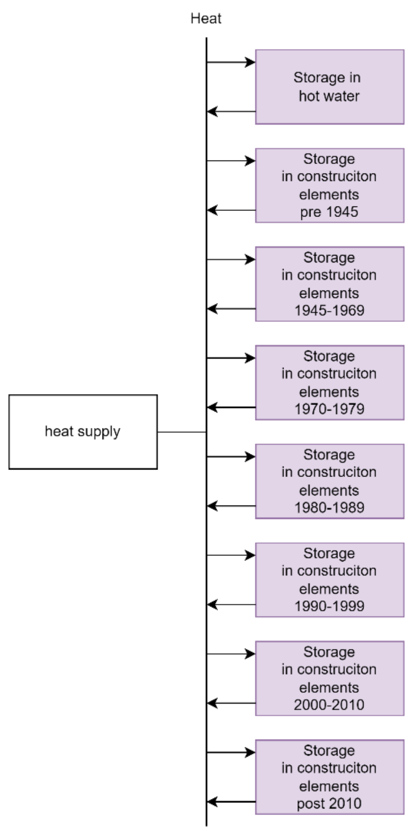

Figure 15. Overview of thermal energy storage technologies, one for each building archetype.

3.4.1 Heat storage in construction elements

In order to model the heat storage in construction elements in Calliope, several parameters need to be used to describe it as presented in Figure 16.

The first one is the storage capacity, which depends on the building's archetype and the total wall area in the location, therefore seven separate technologies need to be defined in each country. However, the differences might not be very significant for some countries (up to 68% difference). Moreover, the storage technology might be limited by the charging/discharging power and not by the storage capacity.

The second parameter is the charging/discharging rate. For this purpose, the dynamic model of an outside wall was created. The charging and discharging are non-linear processes but after linearization, they can be applied in Calliope. With accurate control of the air temperature, it is possible to charge the whole storage in 10 hours. The example (depending on the archetype) profile of wall and air temperature is shown in Figure 31 in Appendix C.

The same dynamic model gives information about the self-discharge rate, which is fairly high compared to charging time and equal to 3.76% of stored energy per hour.

The next parameter is cost, which is equal to zero as it is an intrinsic property of the building.

As this is thermal energy storage, all losses were included in the self-discharge property, so the efficiency is equal to one.

An important assumption that was made when modeling the thermal energy storage, is that there is no need to prevent using heat storage in construction elements from storing heat for the potable hot water demand. This simplifies the model making it computationally less complex. However, it might result in an unphysical result as the heat stored in walls cannot be used for heating the PHW. The validity of this assumption was checked in the results.

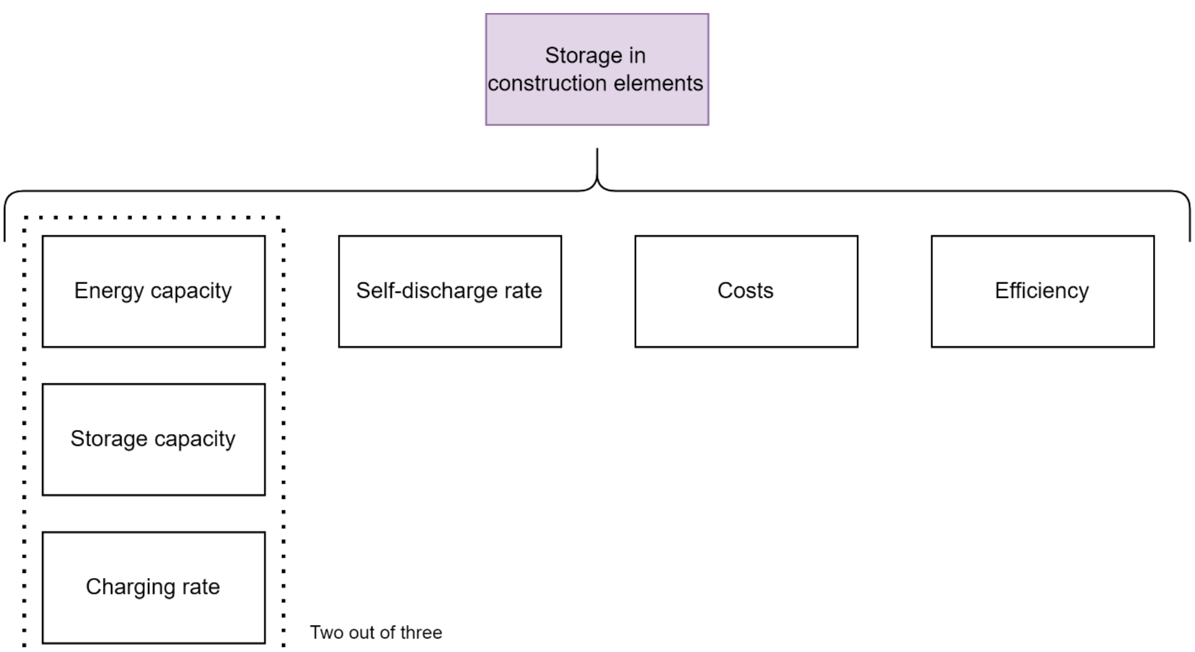

Figure 16. Storage in construction elements - Calliope inputs.

3.4.2 Storage in hot water

Energy storage in hot water was already implemented in the existing Calliope model. There were 11 different storages in each location defined, one for each generation technology. The idea of creating separate heat storage for each technology was taken away as it does implement anything except division to small- and large-scale heat storage, which played an insignificant role in the original model. As a result, only one storage in hot water was introduced to the new model. All numbers related to it were applied without modifications from the existing Euro-calliope model.

3.5 Heat supply

The heating system cannot exist without technologies that would supply it with heat. As heat generation technologies are present in the current model, not many changes were made. The biggest change was to add solar thermal collectors as they can be installed on rooftops of residential houses. So far in the model, solar thermal collectors were implemented but turned off as they were not working.

Other technologies were without significant modification implemented into the new heating system model. Only small adjustments were made when it comes to the output carriers to heat. In the original model, each heat generation technology had a separate output carrier to feed separate storage technologies and further be converted to heat. As described in Chapter 3.4, the idea of separate storage was abandoned.

The overview of heat generation technologies is presented in Figure 17.

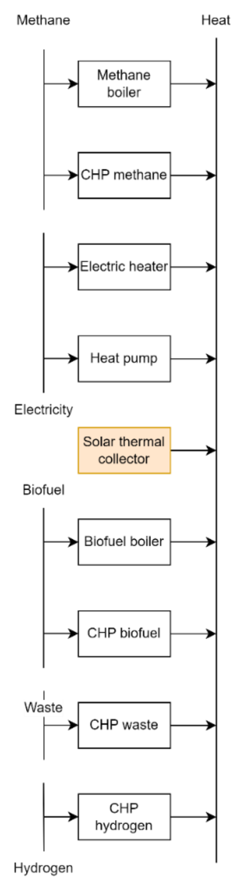

Figure 17. Overview of generation technologies

The first thing that needs to be addressed when analyzing thermal collectors is that they compete for an area with another technology which is rooftop PV, as the area of rooftops is limited. To solve this problem, the rooftop area for each country was calculated based on the existing information about rooftop PV. Next, this area was added to the land area available in a given location, which is used for land PV and onshore wind farms. Further, group constraints were given that limited the land area to technologies dispatched on land and roof area to technologies dispatched on roofs. Thanks to this the maximum installed power of solar thermal collectors is constrained in each location.

The second thing is to mathematically model the position of the sun relative to the position and orientation of the solar thermal collector, which is necessary to calculate the heat generation of the device in each location for every hour of the day per square meter of a roof area. In Calliope itself, this parameter is defined as a capacity factor.

Lastly, all cost-related assumptions of this technology were taken from the existing model.

This gives all the required inputs to Calliope and results in a fully functional generation technology. The details of the mathematical modeling of the solar thermal collector step are given

4 Scenarios

4.1 Renovation measures

As it was mentioned in Chapter 3.1, the goal of the simulation is to minimize the cost of the energy system. As a result, the optimal composition of building archetypes will be chosen for each country. However, to assess the impact of renovation on power and heat generation sources, storage technologies, and transmission, more scenarios characterized by a different renovation penetration are needed. As a result, additional two non-optimal scenarios were run.

The first assumed that no renovation would occur, so the composition of building archetypes is constrained to reflect the current state. This is a hypothetical scenario with low penetration of renovation. Hypothetically it is possible to create a scenario with even less penetration of renovation by assuming that the only archetype present in the system is buildings built before 1945. However, this scenario would be very unrealistic, thus it was not considered.

The second scenario that would explore the impact of high penetration of renovation on the energy system, is a scenario where the only present archetype is the post-2010 archetype. This means that all buildings would be maximally renovated. It can be interpreted as a world where building renovation is mandatorily enforced by governments. It would be also possible to create an archetype with a better insulation property than the Eurostat states for the post-2010 archetype, however, this idea was not explored further as it was not considered very relevant.

The summary of differences between renovation penetration is presented in Table 2.

Table 2. Summary of renovation scenarios

	No renovation	**Optimal renovation**	**Full renovation**
Details	Composition of archetypes as now	Composition of archetypes optimized	Only the post-2010 archetype is present in the system

4.2 Sensitivity analysis

The most important factor of the future energy system is the availability of renewable energy, on which this system relies. Therefore, it is beneficial to check if the renovation can positively affect the energy system for different renewable energy supply. As a result, in addition to 3 different renovation penetrations, there was also a sensitivity analysis performed on each of them. Moreover, having data for 3 different weather years gives an opportunity to check if the relation between renovation and another parameter is preserved in all three of them, reducing the chance of wrongly attributing some relations to the renovation penetration.

All the input data to Calliope, together with the one created for the purpose of the thesis, describes a time period of 9 years from 2010 to 2018. Those years are characterized by a different supply of renewable energy. Therefore, those years can be sorted from the ones with the lowest to those with the highest renewable energy availability in order to do the sensitivity analysis. The description and conclusion of the calculation of renewable energy potential are given in Chapter 4.4. As a result, three different weather years were used, 2010 for the lowest availability of renewables, 2018 as a typical year, and 2015 as the year with the highest renewables potential. The summary is presented in Table 3

Table 3. Summary of renovation measures

	Low availability	Typical availability	High availability
Year	2010	2018	2015

4.3 Scenario matrix

The result of having 3 different renovation penetration scenarios together with a sensitivity analysis results in 9 separate scenarios that require the definition of separate constraints and running a simulation 9 times. All scenarios can be shown in the form of a matrix as in Table 4, where the names of scenarios are stated. Those names are used in the rest of the report, especially when presenting and discussing results.

Table 4. Scenario matrix. The vertical axis describes difference in the availability of renewable energy supply and the horizontal axis describes different renovation levels.

	No renovation	Optimal renovation	Full renovation
Low renewables availability	no renovation 2010	optimal renovation 2010	full renovation 2010
Typical renewables availability	no renovation 2018	optimal renovation 2018	full renovation 2018
High renewables availability	no renovation 2015	optimal renovation 2015	full renovation 2015

4.4 Renewable potential

The calculation of availability started from the definition, which is how much electricity can be produced in a year from the most impactful renewable energy sources. Technologies that were considered to have a significant impact on the renewables supply are hydro run of rivers, open field PV, wind onshore competing, wind onshore monopoly, wind offshore, rooftop PV, and solar thermal collectors.

The maximum feasible capacity installed of given sources is given directly or indirectly (as the capacity per area), therefore knowing the capacity factor for each timestep it would be known what the maximum possible energy produced in a year from a given energy source is. By summing the yearly energy production potential for each technology and each country it is possible to get a total renewable energy potential in a given year. As a result, different years can be compared and then used to choose the right weather year with low, typical, and high renewables availability.

The reader may notice that for the same area, there are several technologies competing, in particular wind farms and PV that compete for the ground area or PV and solar thermal collectors, which compete for the rooftop area. In order not to favor any technology the fractions of the available area were assumed to be 50% for both competing technologies.

5 Results

The goal of this section is to present and discuss the results received from the model. There were almost 2 GB of data created for all 9 scenarios, that was used to analyze the outcome.

To answer research questions, firstly the **heat generation technologies** were analyzed. Figure 18 presents the yearly heat generated in each scenario with differentiation to technologies. It can be seen that heat generation is dominated by heat pumps with a small fraction of solar thermal collectors, biomass boilers, and methane boilers. It can be seen that the renovation has a significant impact on the heat demand. The heat generation can drop by over 25% between the not renovated and fully renovated scenarios but it does not change the dominant generation technology. This decrease is visible in each of the meaningful technologies except the solar thermal collector, where it stays on the same level (around 6 TWh of production per year). The biggest decrease (in absolute terms) of around 50 TWh is visible for the heat pump technology. The renewables availability has a much smaller impact on the total heat generated in the system than the renovation penetration.

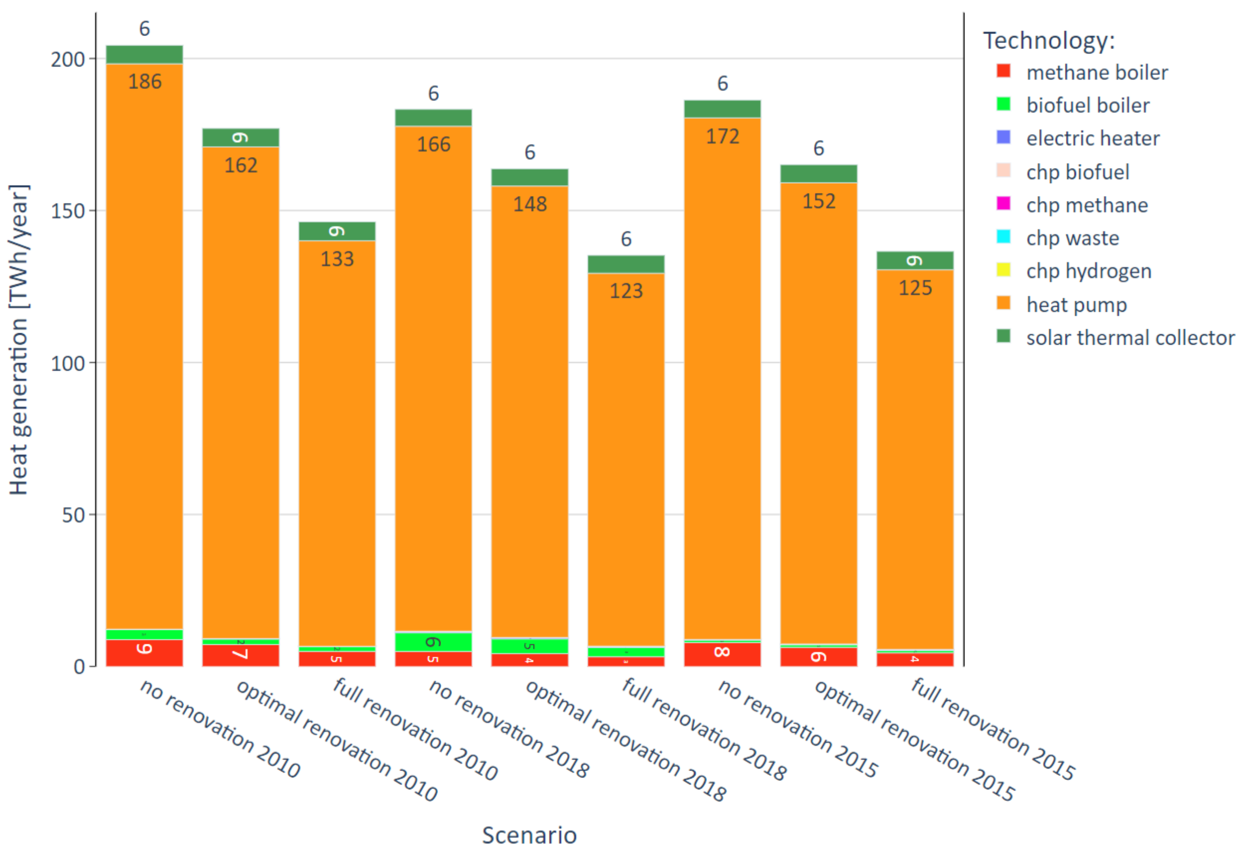

Figure 18. Heat generation mix for the whole system in nine different scenarios. Colors represent different heat generation technologies.

Interesting facts are also visible on the national scale. As expected, the heat generation mix is different in every country. However, those changes are not that significant as the heat pump dominates in almost all countries. The main result is that the renovation has a very small impact on the heat generation mix. On the other hand, the weather year has a more visible impact on the generation mix. A good example is Lithuania, where between weather years the fraction of biomass boilers changed by 12% whereas due to renovation it changed only by less than 1%. More insight (including graphs) about it is presented in Appendix E, as it is not relevant for answering research questions but helps in understanding the system.

As it was mentioned, the heat in each scenario is predominantly supplied by using heat pumps that are powered by electricity as a result, the heating system surely impacts the **power generation technologies**.

Looking at the Figure 19, it is visible that there are three main power generation sources wind onshore monopoly, wind onshore competing, and open field PVs. There are also four technologies that are significantly less, but still significant for the system (hydro reservoir, hydro run of river, nuclear and offshore wind). The rest of the technologies can be neglected when analyzing from the systemwide perspective. As the changes are really small between scenarios, the comparison tables were prepared.

Moreover, it is worth noticing that the increase in building renovation decreases the heat electricity generation. Similar behavior is present with the increase of renewables potential.

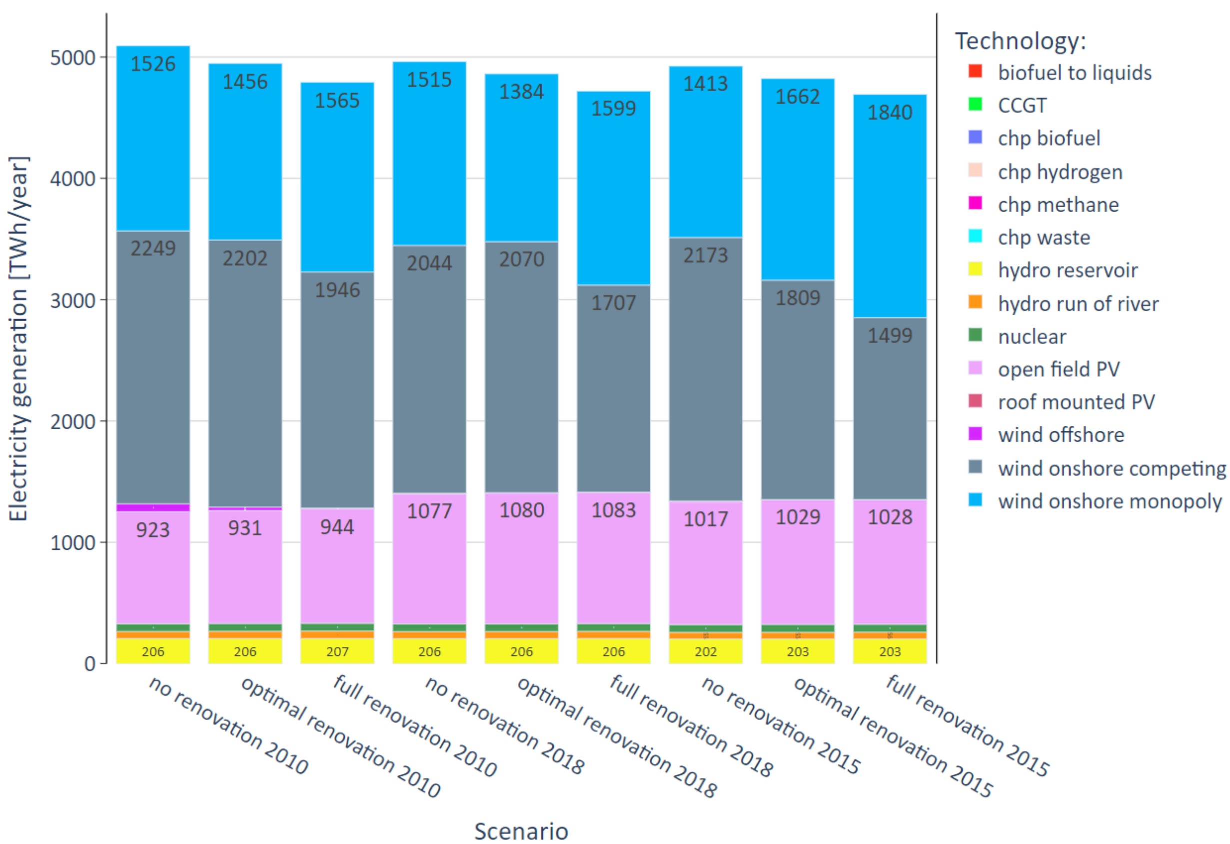

Figure 19. Power generation mix for the whole system in nine different scenarios. Colors represent different power generation technologies.

Another interesting result is that solar thermal collectors always outcompete the rooftop PVs as the LCOE of heat is similar to the LCOE of electricity and the efficiency of thermal collectors is approximately 3 times higher.

In Table 5, there is an overview of electricity generated for the four most meaningful technologies in TWh/year. To notice slight changes between scenarios, all values are calculated relatively to the basic scenario. In addition, the color gradient was added, so that the changes are visible at first glance. In Table 6, the energy mix is presented.

Table 5. An overview of electrical energy generated, as a fraction of the optimal_renovation_2018 scenario.

	open field PV	wind offshore	wind onshore competing	wind onshore monopoly	sum
no_renovation_2010	85.4%	n/a	108.7%	110.3%	104.8%
optimal_renovation_2010	86.2%	n/a	106.4%	105.3%	101.8%
full_renovation_2010	87.3%	n/a	94.0%	113.1%	98.6%
no_renovation_2018	99.6%	n/a	98.7%	109.5%	102.1%
optimal_renovation_2018	100.0%	n/a	100.0%	100.0%	100.0%
full_renovation_2018	100.2%	n/a	82.5%	115.6%	97.1%
no_renovation_2015	94.1%	n/a	105.0%	102.1%	101.3%
optimal_renovation_2015	95.2%	n/a	87.4%	120.1%	99.2%
full_renovation_2015	95.1%	n/a	72.4%	133.0%	96.5%

Table 6. An overview of electrical energy generated as a fraction of the total electricity produced in a given scenario.

	open field PV	wind offshore	wind onshore competing	wind onshore monopoly	sum
no_renovation_2010	18.1%	1.3%	44.2%	30.0%	100.0%
optimal_renovation_2010	18.8%	0.6%	44.5%	29.4%	100.0%
full_renovation_2010	19.7%	0.1%	40.6%	32.6%	100.0%
no_renovation_2018	21.7%	0.0%	41.2%	30.5%	100.0%
optimal_renovation_2018	22.2%	0.0%	42.6%	28.5%	100.0%
full_renovation_2018	23.0%	0.0%	36.2%	33.9%	100.0%
no_renovation_2015	20.7%	0.0%	44.1%	28.7%	100.0%
optimal_renovation_2015	21.3%	0.0%	37.5%	34.5%	100.0%
full_renovation_2015	21.9%	0.0%	32.0%	39.2%	100.0%

The offshore wind technology shows very interesting behavior. It is almost not present in scenarios with typical and high availability of renewables, in addition, the renovation has also a negative impact on the generated electricity by this technology. This is due to the fact that offshore wind farms are only competitive when the yearly electricity demand is high.

When it comes to the most important technologies which are solar and wind (competing and non-compering), their behavior is very complex, and it cannot be explained without further analysis. In general, there is 3x more electricity produced by wind turbines than by PVs. Moreover, the PVs are favored in scenarios with higher renovation when it comes to the share in the energy mix, however, the absolute values are similar. It is also visible that the wind competing is decreasing with the market penetration of the PVs, and it is being replaced by the wind monopoly. The reasoning standing behind this behavior is presented in Appendix E.

When it comes to the **spatial distribution of the power generation sources**, the generation is highly centralized in a few locations with the best conditions (explained in Appendix E) as presented in Table 7 and Table 8. The main outcomes are that the renovation has no impact on the spatial distribution in the same weather conditions as it only slightly decreases the production in each country. However, the renewables supply has an enormous impact (in the case of Portugal, an 8x decrease in production) on the spatial distribution of power generation. A more detailed analysis including nine graphs showing generation among all countries can be found in Appendix E.

Table 7. Open field PV – comparison of energy generation between scenarios.

Location	no renovation 2010	optimal renovation 2010	full renovation 2010	no renovation 2018	optimal renovation 2018	full renovation 2018	no renovation 2015	optimal renovation 2015	full renovation 2015
DEU	1 490	1 641	1 790	2 340	2 346	2 330	1 562	1 632	1 564
DNK	0	0	0	0	0	0	0	0	0
ESP	1 446	1 428	1 416	1 544	1 556	1 587	1 498	1 503	1 466
FRA	1 085	1 099	1 117	2 165	2 199	2 274	2 686	2 779	2 925
GBR	0	0	1	35	79	129	0	0	0
HUN	0	0	0	0	0	0	0	0	0
IRL	0	1	27	228	215	176	0	0	0
ISL	0	0	0	0	0	0	0	0	0
ITA	2 574	2 503	2 432	2 539	2 496	2 433	2 574	2 499	2 401
PRT	1 775	1 788	1 810	381	340	264	0	0	0

Table 8. Onshore wind – comparison of energy generation between scenarios.

Location	no renovation 2010	optimal renovation 2010	full renovation 2010	no renovation 2018	optimal renovation 2018	full renovation 2018	no renovation 2015	optimal renovation 2015	full renovation 2015
DEU	0	1	2	0	0	1	0	0	2
DNK	2 876	2 875	2 873	2 903	2 899	2 895	3 315	3 314	3 320
ESP	2 892	2 783	2 388	792	760	727	609	578	461
FRA	3 963	3 630	3 318	1 980	1 860	1 536	564	303	23
GBR	8 346	8 087	7 942	14 063	13 629	13 103	16 268	15 936	15 676
HUN	2 679	2 512	2 357	2 065	1 970	1 849	1 439	1 384	1 281
IRL	1 638	1 497	1 273	3 182	3 118	2 989	2 175	2 155	2 137
ISL	2 046	2 036	2 051	2 164	2 152	2 176	2 298	2 291	2 317
ITA	0	0	1	0	0	0	0	0	0
PRT	5 667	5 687	5 693	2 455	2 372	2 228	1 242	1 221	1 154

To quantify the impact of building renovation and the weather, on the **transmission system,** Table 9 is presented. The table is preferred over the graph as it enables one to quickly compare differences between scenarios, while it would not be possible to compare the thickness of lines between nine graphs. For the visualization purpose, the capacity of transmission lines for the optimal scenario with a typical renewables supply is presented in Figure 20.

Figure 20. Map of transmission capacity

Table 9. Impact of renovation and renewables supply on the capacity of power transmission.

	no renovation 2010	optimal renovation 2010	full renovation 2010	no renovation 2018	optimal renovation 2018	full renovation 2018	no renovation 2015	optimal renovation 2015	full renovation 2015
Total	930.5	903.5	847.5	915.5	876.5	827.5	910.5	883.5	846

The complete table with the capacity of all connections can be found in Appendix E. Analyzing how the current flows in the transmission lines for different scenarios are out of the scope of this thesis and would enable us to spot cases like the connection FRA-ITA, where the capacity in one scenario was 41 higher than in the second one. Another insight is that there are different types of connections present in the system. Some of them are almost exclusively one-directional, for others the flows one way and the other are almost balanced. There is also the connection that is almost constantly used and other connections that are used rarely when high overproduction of electricity is in one of the connected locations.

However, the high-level overview can already give an important insight into the impact of renovation on the transmission system. The most important result is that the renovation always decreases the capacity of transmission lines. Therefore, over-renovating residential buildings would be one of the solutions if one aims for reducing the capacity of transmission lines (up to 10%).

Moreover, the capacity of transmission lines does not depend on the global renewable supply, but on the differences between local renewables supply. As can be seen in the scenario of low supply, the capacity was only slightly higher than for the high renewables supply. Moreover, the lowest capacity was installed in the typical renewables supply scenario.

The renovation has a positive impact on decreasing the **variability of the system costs** for scenarios with low renewable supply As is visible in Table 10, the impact of renewables supply on the cost of the system is more significant for non-renovated buildings (9.0%). It decreases to 8.5% for optimally renovated buildings and further decrease to 8.2% for fully renovated buildings. It is visible that renovation helps to offset the impact of different renewable supply on the cost of the system, making it more resilient to extreme weather conditions.

However, this value is very low (0.8% of a relative difference of costs) and it is wise to check the increase of costs related to the over-renovation of buildings to achieve this additional resiliency.

Table 10. Impact of weather on the cost of the system.

Scenario	BEUR	vs typical weather year	The difference in cost between weather years
no_renovation_2010	719.3	105.1%	9.0%
no_renovation_2018	684.3	100.0%	
no_renovation_2015	657.6	96.1%	
optimal_renovation_2010	700.2	104.6%	8.5%
optimal_renovation_2018	669.7	100.0%	
optimal_renovation_2015	643.5	96.1%	
full_renovation_2010	739.5	103.7%	8.2%
full_renovation_2018	713.2	100.0%	
full_renovation_2015	681.0	95.5%	

In Table 11, it can be seen that the unrenovated system is around 2.3% more expensive than the optimally renovated one. A very intriguing thing is that this additional cost is similar for all weather years. A similar property is visible for over-renovated systems, where it is on average 6% more expensive for all weather years. This suggests a very surprising finding that the impact of optimal renovation on the costs of the system is independent from the renewable energy supply.

Table 11. Impact of renovation on the cost of the system.

Scenario	BEUR	vs optimal	Additional costs of over renovation
no_renovation_2010	719.3	102.7%	5.6%
optimal_renovation_2010	700.2	100.0%	
full_renovation_2010	739.5	105.6%	
no_renovation_2018	684.3	102.2%	6.5%
optimal_renovation_2018	669.7	100.0%	
full_renovation_2018	713.2	106.5%	
no_renovation_2015	657.6	102.2%	5.8%
optimal_renovation_2015	643.5	100.0%	
full_renovation_2015	681.0	105.8%	

Transmission is very important when it comes to balancing the system, but it is not enough so energy storage technologies need to be used to further decrease the mismatch between production and demand.

Methane storage and hydro plants are exclusively used for seasonal storage, even though they are charged during peak in power generation. PHS is used for day-night storage so as for storing energy for time periods of several weeks. The last significant storage technology is the storage in construction elements that exclusively store the energy for short-term storage. It is charged during peaks of electricity production, and it is discharged during peaks in heat demand. It is being used extensively despite high losses because of the high intermittency of the demand profile (especially in the summer). For daily balancing also synthetic fuel plants are significantly used, they produce carriers only during peak in electricity production. Therefore, the synthetic fuel plants can be (depending on the country) significantly oversized so that they can produce enough carrier for when the methane for heat production is needed.

It is worth mentioning that other storage technologies including storage in the hot water tank are not significant in the model. Their capacity is almost zero, therefore they have no impact on the system. It directly competes with the energy storage in the construction elements whose costs are equal to zero.

The spatial distribution of storage technologies is presented in Figure 21. There is no difference between scenarios as the storage capacity of the majority of storage technologies is predefined and not optimized. It is visible that there are 5 dominant countries when it comes to storage capacity. The biggest one is Italy and the second one is Germany, both with over 250 TWh of available storage. France and the Netherlands have more than 100 TWh of methane storage and Austria has almost 100 TWh. For hydro run of river, there are 4 countries that are characterized by a notably higher capacity, those are Norway (45 TWh), Sweden (11 TWh), France (9 TWh), and Spain (8 TWh). Regarding pumped hydro storage the majority of storage capacity is concentrated in Norway (5 TWh) and France (4 TWh).

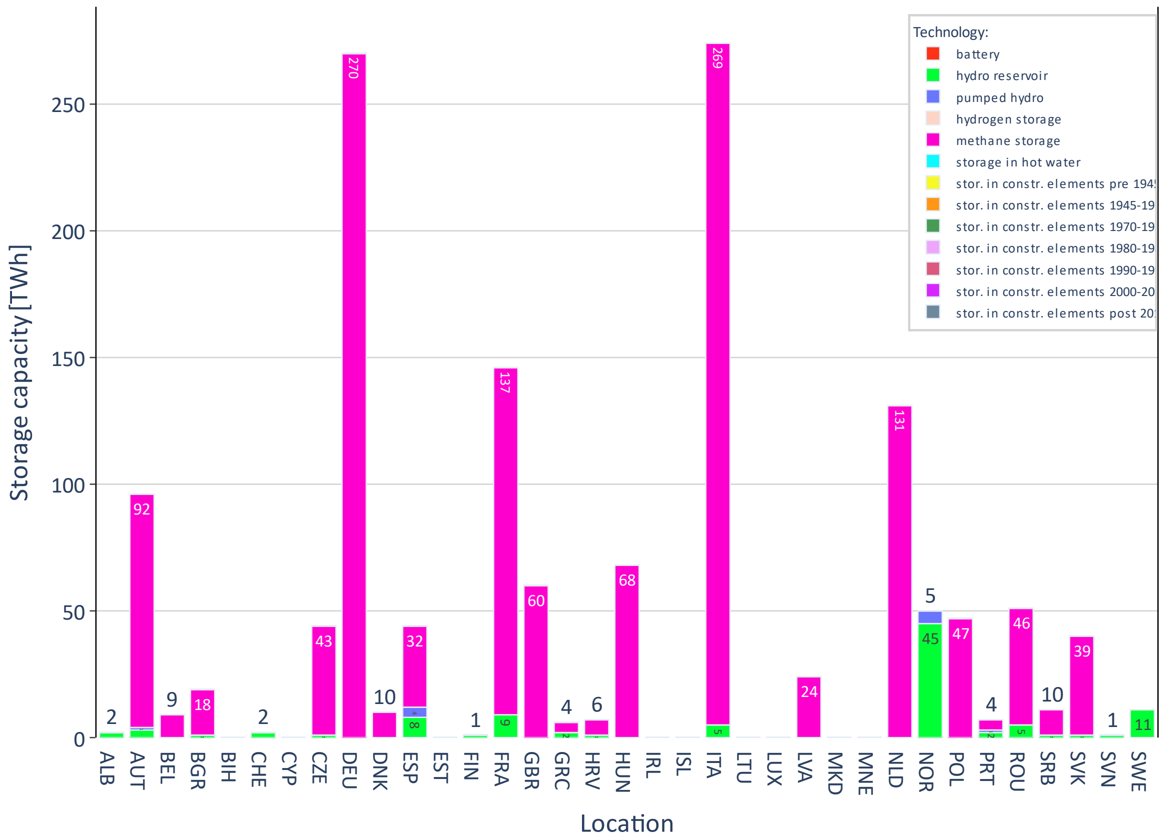

Figure 21. Spatial distribution of storage technologies in optimal renovation scenario for 2018 weather years.

To assess the impact of renewable supply on **renovation penetration**, fractions of archetypes in each country for an optimal scenario were shown in Figure 22. It can be seen that there is no general rule describing this impact. It is very country dependent and there are several countries where non-monotonic relation was discovered. The summary of countries and their behavior is shown in Table 12.

Table 12. Impact of an increase in renewables supply on the renovation penetration.

Impact of increase in renewables supply	Countries
Negative	ESP, EST, FIN, FRA, GBR, ITA, LTU, NOR, SVK, SVN, SWE
Neutral	ALB, BEL, BIH, CZE, DNK, HRV, HUN, LUX, NLD, POL, ROU, SRB
Positive	CYP, MKD, MNE, PRT
Non-monotonic	AUT, BGR, CHE, DEU, GRC, IRL, LVA

The next interesting result is that for smaller countries like Estonia, Albania, and Latvia, the composition of archetypes became more homogenous for scenarios with more renewable availability. The reason for that behavior might be the effect of constraints slacking, however further research shall be done to check this numberical issue.

Another interesting finding is that Greece, Montenegro, Macedonia, Portugal, and Romania were countries, where the post-2010 archetype was the only archetype present after optimization. Hence, there is a high probability that buildings shall be renovated to even higher standards, which are currently not enforced in those countries. This suggests, that adding another archetype for the future buildings would benefit the model. Fortunately, those countries would not impact the whole system significantly, but if one is interested in researching a local scale, no correct results can be achieved without adding such an archetype.

Finally, it is worth noticing that usually there are only one or two archetypes present in one country in the optimal scenario. In most cases, those archetypes are below the post-2010 standards. This means that there can be identified two extreme pathways ways to achieve the optimal solution. The first one would assume no renovation of old buildings but building new buildings in new stricter standards so that the average insulation level is equal to the insulation level of an optimal archetype. The second way is to decrease the standards to the optimal level and simultaneously renovate old buildings to such a level. In reality, the solution would be probably somewhere between two scenarios.

The reason for a low renovation penetration can be explained by a lower levelized cost of electricity for renewable energy sources that are responsible for the significant majority of the energy supply in the model. Therefore, the capital costs of adding insulation exceed the benefit related to the lower energy consumption and slightly higher storage capacity of a building.

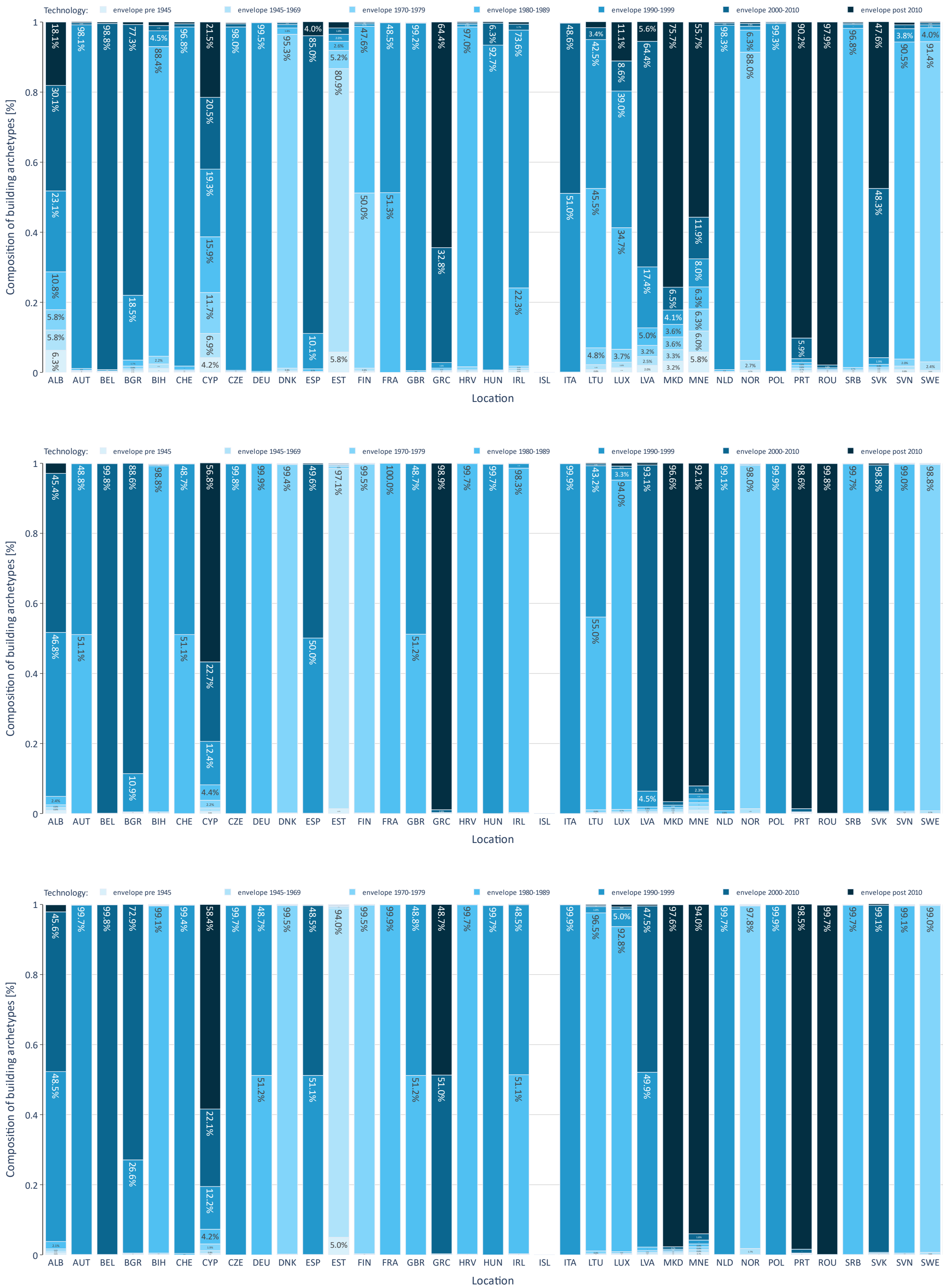

Figure 22. Composition of archetypes in an optimal renovation scenario for 2010 (top), 2018 (middle) and 2015 (bottom) weather year.

The impact of renewables supply on the renovation of **ventilation** is presented in Figure 23. The results are surprising as it turns out that in any case, the heat recovery ventilation is not optimal from the system perspective. As for the envelope archetypes, this is related to the low price of heat compared to the investment that needs to be done to install a heat recovery system.

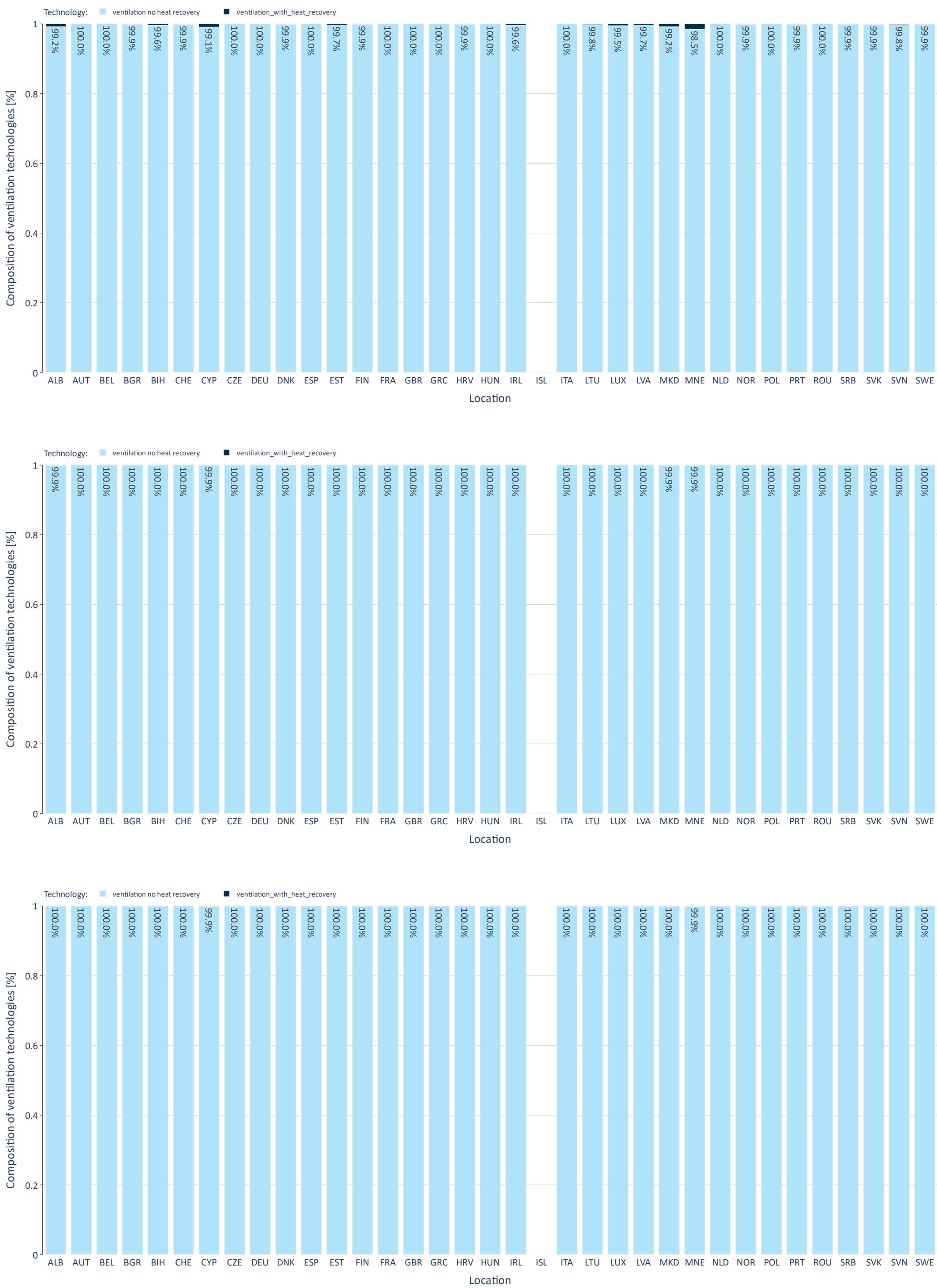

Figure 23. Penetration of ventilation technologies in optimal scenarios for 2010 (top), 2018 (middle) and 2015 (bottom) years.

6 Discussion

6.1 Reference to the literature

As it was mentioned, the literature review showed that no existing paper discuss the model that optimize building renovation and energy systems different than heating at the same time. Therefore, the comparison of results is very limited.

As was visible in the literature review, the penetration of renovation was different in each paper. It was though that it was caused by the different costs' assumptions and different climate zone. The differences in the penetration of renovation were also visible between countries. Southern countries required more renovation and northern countries less renovation.

Furthermore, the results of this model are support a finding of (Stadler et al., 2014), where it was stated that the optimal thickness of insulation is lower than the thickness required by current (2014) standards. In case on the Calliope, the currently required insulation is thicker than optimal for 29 out of 34 countries. This shows that nowadays standards are very strict and not cost beneficial for the whole system. As a result, the mandatory over-insulation, unnecessarily increase the price of houses. It is worth noticing, that the simulation was made for the year of 2050, where costs of energy are different, and the optimal thickness of insulation is different for 2023. Moreover, it was proved that the over-renovation has a little sense as the costs of over-renovating buildings is significant compared to benefits.

The idea of using the mathematical programming to optimally use the thermal capacity was suggested by (S. I. Gustafsson, 2000). The results show that thermal energy storage in construction elements plays a role in a short-term storage as it stores surprises of energy when they are available and discharge when the power generation is lower. By modeling the whole multiple energy carriers, this proves that storage in construction elements is a viable option for a short-term energy storage.

The (Iturriaga et al., 2018), differentiates between different heat potentials. This was not implemented in the model, but from the results it is visible that it is necessary to avoid using the storage in construction elements for storing heat that can be used for preparation of potable hot water. Thanks to the separation of heat potentials, the differentiation to two different heat pumps would also make sense, as heat pumps for preparing low-temperature heat are much more effective than used in the current model.

Assumptions based on the literature were discussed in the section below.

6.2 Weaknesses of the model

Many ways of improving the model can be defined. Some of them can be done straight away as they require only an additional amount of time. Other would require more significant changes in the model.

The biggest weakness of the model is that the storage in construction elements can store water used to cover potable water heating. This effect appears during the hottest periods of time in the evening when there is a peak in demand for potable hot water. At this moment for 2 hours, the storage in construction elements is being discharged to cover the PHW. The heat pump still covers most of the demand but not 100%. This is an unphysical situation and should be avoided. As it presents for around 1 month depending on the country for 2 hours per day. It can be corrected by adding the heat of different potential as in (Iturriaga et al., 2018). Then the low-temperature heat would be separated from the medium temperature hear, which is a PHW.

Despite the cooling demand being outside of the scope of the thesis, it would improve the accuracy of the model. It was analyzed in a few papers, and it can give a significant impact on the costs related to cooling equipment, it is especially interesting because there are technologies that can cool and heat at the same time, hence they would probably be favored by the model. Moreover, better insulation would mean that less energy is needed to cool down the building.

The second biggest weakness of the model is the national scale. Many countries are located in different climate zones, so the optimal insulation thickness is expected to be different as the savings differ on the temperature and costs are constant. As discussed, the data of a regional scale is not available. In addition, it would significantly increase the computational time required to optimize the system.

When it comes to heat generation technologies, the idea of using different heat pumps and different types of solar thermal collectors can be used. It would be certainly interesting to explore which types are best in which countries. Moreover, the efficiency of solar thermal collectors should be calculated dynamically but here it was assumed constant. This change should further increase the penetration of this technology in hot countries and decrease it in cold ones (Suciu et al., 2018). It is interesting to evaluate to which extent this change in the model affects results.

Another weakness is the lack of sensitivity analysis of renovation costs. This is very simple to do and might result in a very important outcome as in the literature used prices were very different from each other. The effects of decreasing the price by a small factor might have a very big impact on the penetration of renovation, as those effects might be very non-linear.

Another weakness of the model is that the archetype with the highest insulation quality is defined as one of the buildings built after 2010. There should be added archetypes that would represent more strict quality standards as in five countries the most optimal archetype was chosen as optimal, and it is probable that it should be the even better-insulated archetype.

6.3 Future research

There are multiple ways that this research can be continued. The most important thing to do would be to do the sensitivity analysis that would check the impact of renovation cost on the renovation penetration as it is one of the weaknesses of the model. It might give a good insight into how the renovation penetration would change if the new, better insulating, and cheaper materials are developed and commercialized.

Moreover, similar system modeling could be made on the city scale, to see if the results are similar as for the sub-continental scale. In this case, the availability of data is much higher, and the GIS software could be used to further improve the quality of data. Furthermore, the district heating generation and distribution can also be checked.

Another idea for the research would be preparing an optimal method of controlling the storage in construction elements as it is impactful when dealing with demand peaks. This research should check the technical possibilities of coupling an individual resident preference with the system balance.

In order to improve the quality of mathematical modeling, more primary research is needed. The most important is to fulfill the lack of information about the current system on a smaller spatial scale than countrywide. Many countries are spread across multiple climate zones and therefore it is expected to have multiple different renovation levels in different regions. The lack of this data is a significant obstacle to using the full potential of models like Calliope, where very complex systems with multiple locations can be simulated.

If all of the above's research would result in very reliable models, the countries would be able to revise their thermal insulation standards and implement financial mechanisms to achieve the optimal level of renovation.

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Appendix A

Heat loss through buildings' envelope – dispatch problem

The Calliope by default, would treat different archetypes as different technologies, that would be dispatched approximately accordingly to the variable cost. This means that the more efficient archetype would be always dispatched before the less efficient one. It is known that all buildings regardless of the archetype would be responsible to a fraction of heat demand at any moment. Below there is an example describing the solution to this problem.

For simplicity, it will be assumed that there are only two building archetypes, old and new buildings, where the efficiency of old buildings is lower than that of newer buildings. The software without any modification will always prefer the building archetype with lower variable costs (new buildings as they are more efficient). This behavior is shown in Figure 24.

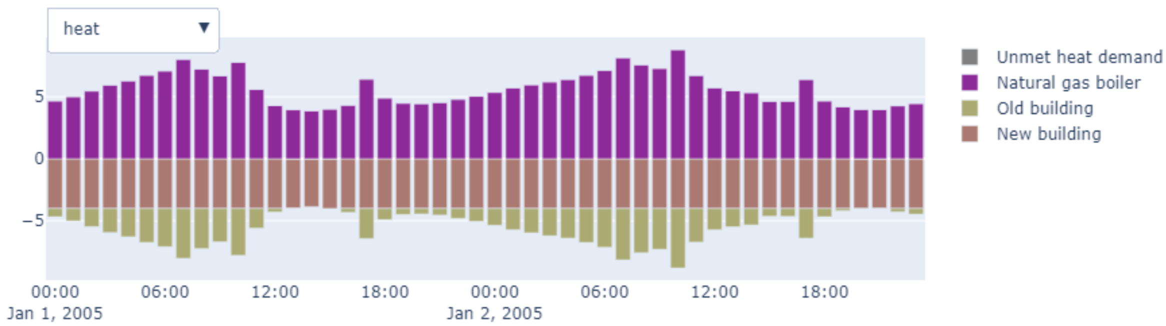

Figure 24. The unrealistic flow of heat between old and new buildings due to the lack of necessary constraints.

It is unrealistic behavior because the heat cannot be diverged between those two technologies. After all, old buildings and new buildings consume the heat simultaneously and only a fraction of old/new buildings in building stock should be optimized. In Calliope, there is an existing group constraint called "demand_share_per_timestep_decision", which defines the new optimization parameter which is a fraction of the heat demand of each building group in total residential heat demand. The results of adding those constraints are presented in Figure 25. As visible, adding this group constraint solves a problem of an unrealistic dispatch.

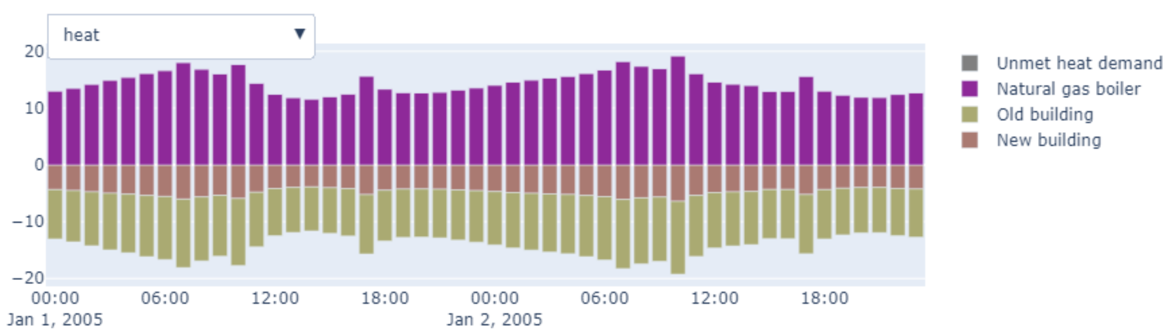

Figure 25. The realistic flow of heat between old and new buildings, which are in constant proportion to the total building stock.

Heat loss through buildings' envelope – efficiency calculation

To calculate the efficiency of the conversion technology, heat losses through the envelope of all seven building categories will be compared to the heat losses of the 'average' building for each country. This means that old buildings (worse insulated than the average of the country) will have this efficiency lower than 1 and new buildings (better insulated than the average of the country) higher than 1.

In order to determine the exact number, the comparison of heat losses through the building's envelope needs to be constructed. The most general equation is given in (Medved, 2022).

$$H = \frac{\sum_{i=1}^{n} b_i \cdot U_i \cdot A_i + \sum_{j=1}^{m} \psi_j \cdot l_j + \sum_{k=1}^{p} \chi_k \cdot n_k}{\sum_{i=1}^{n} A_i} \tag{1}$$

where:

H – building's heat transmittance [$\frac{W}{K}$]

b_i – correction factor, assumed to be equal 1 for surfaces in contact with the outside air/ground and 0 for internal walls [-]

U_i – U-value of i-th element [$\frac{W}{m^2K}$]

A_i – Area of i-th element [m^2]

ψ_j – Linear thermal resistance of the j-th 2D thermal bridge [$\frac{W}{mK}$]

l_j – Length of the j-th 2D thermal bridge [m]

χ_k – Point thermal transmittance of the k-th 3D thermal bridge [W]

n_k – Number of the k-th 3D thermal bridges [-]

To solve this equation knowledge about thermal bridges, which is unknown for most buildings, needs to be available. Therefore, there is also a simplified version of this equation, where those terms are replaced by the term derived empirically (Medved, 2022).

$$H = \frac{\sum_{i=1}^{n} b_i \cdot U_i \cdot A_i}{\sum_{i=1}^{n} A_i} + \Delta\psi \tag{2}$$

where:

$\Delta\psi$ – thermal bridge factor [$\frac{W}{K}$]

Typical values of the thermal bride factor can be found in (Medved, 2022). For the purpose of further calculations, the average of the values found in the literature was assumed.

Table 13. Typical thermal bridges factor based on the (Medved, 2022).

Building archetype	Range [W/m2K]	Assumed value [W/m2K]
Poorly insulated buildings (built before 1990)	0.10 to 0.14	0.12
Well insulated buildings (built after 1990)	0.03 to 0.04	0.035

It can be seen that two things are needed to solve this equation, U-values, and areas of construction elements. The source of U-values for each country and each archetype were taken from the database (Eurostat, 2023). The areas of construction elements of residential buildings vary significantly based on the type of building; single-family buildings would have much less area than multi-family buildings. The typical dimensions of single- and multi-family buildings so as the fraction of each building type in the building stock were taken from (Lechtenböhmer & Schüring, 2011). For some countries, the data was not available, therefore it was created based on the other countries.

If areas and U-values and element's areas are known, then the building's heat transmittance can be calculated for each country and building archetype.

The next step is to calculate the building's heat transmittance for the "average" building, the archetype's heat transmittance will be weighted by the fraction of the building archetypes in the national building stock.

Finally, to calculate the efficiency, the building's heat transmittance (for each archetype) can be divided by the building's heat transmittance of the "representative" building, as shown below.

$$\eta_A = \frac{H_A}{H_R} \tag{3}$$

Where,

η_A – efficiency of an archetype [-]

H_A – Heat transmittance of an archetype $[\frac{W}{K}]$

H_A – heat transmittance of a representative building $[\frac{W}{K}]$

As a result, efficiencies for all archetypes and countries were calculated.

The block diagram that summarizes those calculations is presented in Figure 26.

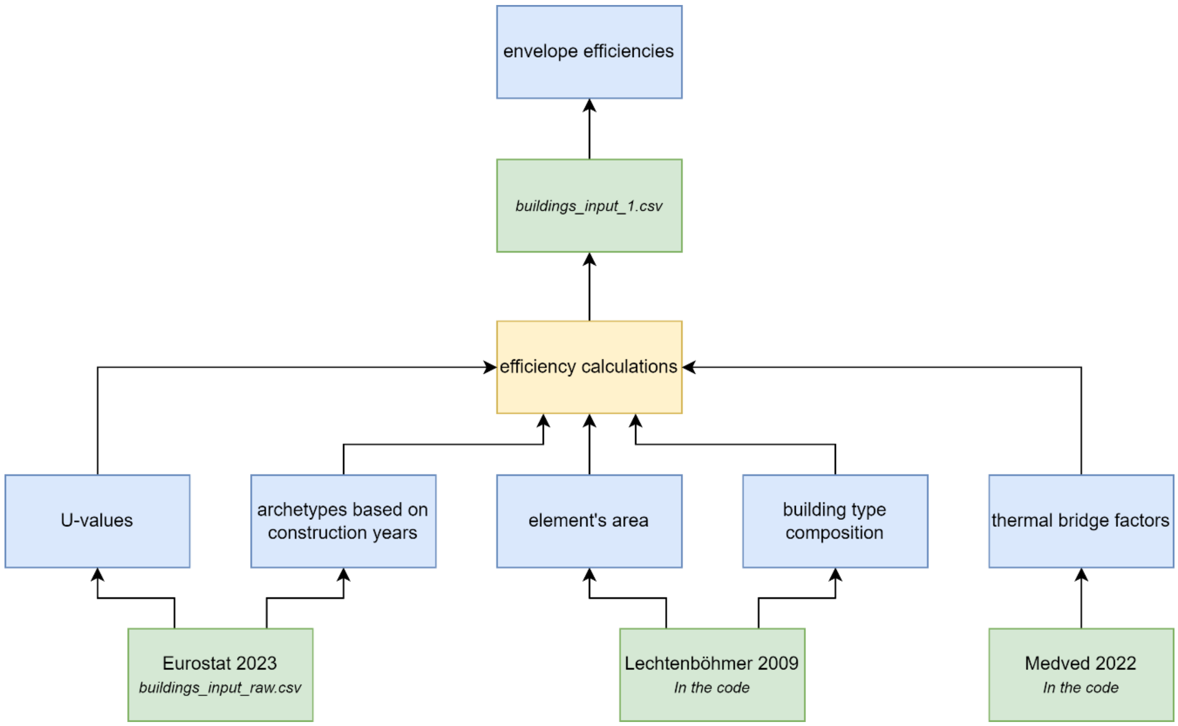

Figure 26. Block diagram of archetype efficiency calculation.

Heat loss through buildings' envelope – cost

When it comes to increasing the insulation of the building's envelope, the only cost related to it is the investment cost. There are no additional operational costs connected to the usage of better-insulated buildings. The investment cost consists of material and labor costs. In order to compare buildings characterized by different archetypes, the way of construction needs to be analyzed. The number of layers and their thickness.

The typical wall consists of an inside layer of plaster, a layer of concrete, a layer of insulation, and an outside layer of plaster (Nallaval & Monto, 2013). The overview can be seen in Figure 27.

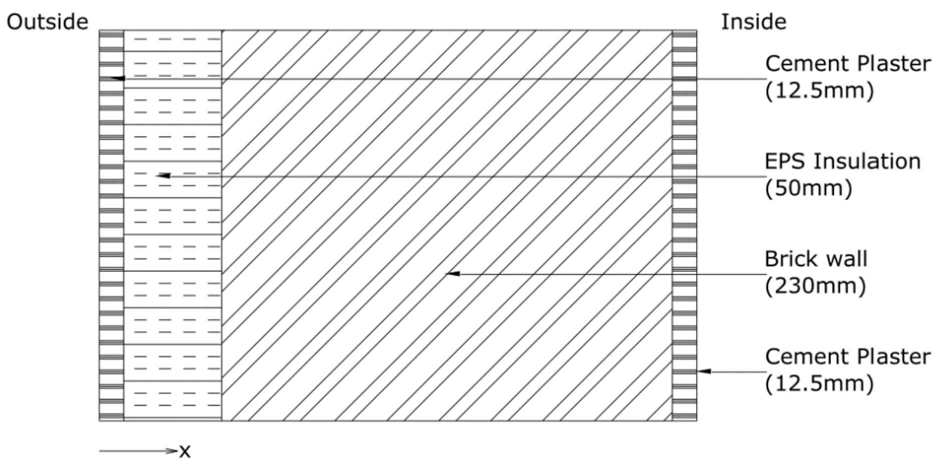

Figure 27. Wall components (Nallaval & Monto, 2013)

According to (Medved, 2022) and (Mauro et al., 2015), layers like tiles, paint, and plasters can be neglected due to negligible thickness and low thermal resistance. Therefore, the wall can be treated as a layer of concrete and an insulation.

Insulation was not common in pre-2nd world war buildings (Perez, 2014). Therefore, for a model purpose, it was assumed that every archetype of buildings builds before 1945, is not insulated. As a result, the equation for U-value is equal to

$$\frac{1}{U_U} = \frac{1}{\alpha_{in}} + \frac{th_{wall}}{k_{wall}} + \frac{1}{\alpha_{out}} \tag{4}$$

Where,

U_U – U-value of an uninsulated archetype $\left[\frac{W}{m^2K}\right]$

α_{in} – heat transfer coefficient for an internal convection $\left[\frac{W}{m^2K}\right]$

th_{wall} – thickness of a wall $[m]$

k_{wall} – conductivity of a wall $\left[\frac{W}{m \cdot K}\right]$

α_{out} – heat transfer coefficient for an external convection $\left[\frac{W}{m^2K}\right]$

For buildings with insulation (build later than 1945), it will be equal to.

$$\frac{1}{U_R} = \frac{1}{\alpha_{in}} + \frac{th_{wall}}{k_{wall}} + \frac{th_{ins}}{k_{ins}} + \frac{1}{\alpha_{out}} \tag{5}$$

Where,

U_R – U-value of an insulated archetype $\left[\frac{W}{m^2K}\right]$

th_{ins} – thickness of an insulation $[m]$

k_{ins} – conductivity of an insulation $\left[\frac{W}{m \cdot K}\right]$

The thickness of insulation can be computed for newer building archetypes, by using the U-value for an uninsulated building, which gives the following result.

$$th_{ins} = k_{ins} \cdot \left(\frac{1}{U_R} - \frac{1}{U_U}\right) \tag{6}$$

It turns out that in some countries, buildings build before 1945 have higher U-value than buildings built between 1945 and 1969 or even between 1970-1979. Therefore, the resulting thickness is negative. This result was treated as an unphysical result and therefore the thickness of insulation is treated as zero for those several cases.

Furthermore, the costs of insulation are in line with the costs given in the literature (Aggerholm, 2018). They were given for a specific thickness of insulation material, so generalization was needed. The literature data can be intra/extrapolated by a linear function, which can be used to obtain the labor cost and the material cost per millimeter of insulation. Those values are equal to $59.8\,\frac{EUR}{m^2}$ and $0.416\,\frac{EUR}{m^2 \cdot mm}$, respectively.

Knowing the area of insulated surfaces (outside walls, roofs, and floors), and the thickness of the insulation material. The volume of insulation can be easily calculated. This and the costs of insulation allow to calculate the cost of changing an insulation. The input data for insulation and windows replacement is given in Table 14

Table 14. Cost of insulation

Thickness [mm]	Cost [EUR/m²]
30	72
80	93
100	101
125	112
150	122
200	143
220	151
250	164

Besides insulation improvement, the thermal properties of windows should be also increased. It can be done in a similar way as for insulation. The biggest difference is in the cost function for windows can be inter/extrapolated as a power function depending on the U-values of the installed window. The cost of changing windows can be found in Table 15 (Bonakdar et al., 2014).

Table 15. Cost of windows' replacement (Bonakdar et al., 2014)

U-value of a window [W/m²K]	Cost [EUR/m²]
1.21	115
1.21	126
0.64	138
0.63	149
0.61	161
0.55	172
0.53	184
0.53	195

The total costs of improving envelope thermal properties are given by the following formula.

$$TC = (A_{OW} + A_R + A_F) \cdot (L + th_{ins} \cdot M) + W_1 \cdot U_{WIN}{}^{W_2} \tag{7}$$

Where,

TC – total cost $[EUR]$

A_{OW} – area of outside walls $[m]$

A_R – area of the rooftop $[m]$

A_F – area of the floor $[m]$

L – labor cost per square meter of insulation $\left[\frac{EUR}{m^2}\right]$

th_{ins} – thickness of insulation $[m]$

M – material cost per volume of insulations $\left[\frac{EUR}{m^3}\right]$

W_1 – window cost constant 1 $\left[\frac{EUR \cdot m^2 \cdot K}{W}\right]$

W_2 – window cost constant 2 $[-]$

U_{WIN} – U-value of a window $\left[\frac{W}{m^2K}\right]$

The last step is expressing those costs per capacity of the renovation technology. This can be done by using the heat transfer equation for a flat wall.

$$Q = U \cdot A \cdot \Delta T \tag{8}$$

Where,

Q – heat transferred $[W]$

U – U-value of a building $\left[\frac{W}{m^2K}\right]$

A – Area of outside exposed surfaces $[m]$

ΔT – Temperature difference between inside and outside $[K]$

If the lowest temperature is used in the equation, then the result is the highest heat transfer through the envelope, which is exactly equal to the capacity parameter that is present in Calliope. For the purpose of the model, the temperature that was used is equal to the lowest hourly temperature in a country (population-weighted), between 2010 and 2018, generated via renewables.ninja (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016).

Appendix B

Ventilation – efficiency calculations

In order to calculate the efficiencies of ventilation technologies that would be used in Calliope, the difference between non-heat recovery systems and heat recovery systems need to be quantified.

From the literature, it is known that 85% of heat can be recovered for state-of-the-art solutions (M. Gustafsson et al., 2016). In reality, the heat recovery efficiency is not constant, and it depends on the outside temperature, however, changes are negligible (Kamendere et al., 2015). Therefore, the relation between heat demand for those two technologies is bound by the following equation.

$$Q_{NHR} = \frac{1}{1 - \eta_{heat\ recovery}} \cdot Q_{HR} = 6.67 * Q_{HR} \tag{9}$$

Where,

Q_{NHR} – Heat demand of a ventilation technology without a heat recovery ventilation $[W]$

Q_{HR} – Heat demand of a ventilation technology with a heat recovery ventilation $[W]$

$\eta_{heat\ recovery}$ – efficiency of the heat recovery process $[-]$

So,

$$\eta_{NHR} = \frac{1}{6.67}\,\eta_{HR} \tag{10}$$

η_{NHR} – efficiency of the ventilation technology without heat recovery $[-]$

η_{HR} – efficiency of the ventilation technology with heat recovery $[-]$

Beforehand it was assumed that 100% of ventilation systems are without heat recovery, therefore the efficiencies that are used in calliope are equal to 1 and 6.67 respectively for non-heat recovery and heat recovery ventilation technologies.

Another parameter that needs to be calculated is the carrier ratio of electrical energy to the ventilation losses. This parameter changes with the outside temperature, so it should be defined for each hour for each country separately. The carrier ratio is calculated as follows.

$$CR = \frac{Q_{el}}{Q_R} = \frac{SFC \cdot \dot{V}}{C_{p_{air}} \cdot \rho_{air} \cdot \dot{V} \cdot \Delta T} = \frac{SFC}{C_{p_{air}} \cdot \rho_{air} \cdot \Delta T} \tag{11}$$

CR – carrier ratio $[-]$

Q_{el} – electrical power consumed by the technology $[W]$

Q_R – heat consumed by the technology $[W]$

SFC – specific fan consumption $\left[\frac{W}{\frac{m^3}{s}}\right]$

$\dot{V}$ – volume flow of air $\left[\frac{m^3}{s}\right]$

$C_{p_{air}}$ – heat capacity of air $\left[\frac{J}{kg\ K}\right]$

ρ_{air} – density of air $\left[\frac{kg}{m^3}\right]$

ΔT – temperature difference between inside and outside of the house $[K]$

This equation needs to be solved for a time series containing ΔT based on the outside temperature in a given location. Specific fan consumption (SFC) was assumed to be equal to 1.5 $\frac{W}{l \cdot s}$ (M. Gustafsson et al., 2016), air's heat capacity under constant pressure 1.005 $\frac{kJ}{kg \cdot K}$ and air density as 1.3 $\frac{kg}{m^3}$.

For the purpose of simplification, the carrier ratio was assumed to be constant and equal to 7.69%, which is the value for the outside temperature of 5°C. As in test runs of the model, almost no heat recovery ventilation was present, therefore the implementation of variable carrier ration was never implemented, as it would not have an impact on the system.

Ventilation - Cost

It may seem that most of buildings are not suitable for an installation of a heat recovery ventilation system. The typical solution requires building a ducting system that supplies and exhausts the air from each room. In this case, the heat recovery happens in the central heat exchanger. There is only one intake and exhaust of air (usually located on the roof of the building). This means that most of the existing multi-family buildings cannot be refurbished because there is no designed space for additional ducting, heat exchanger, etc.

However, there is a solution that mitigates those disadvantages by using decentralized instead of central heat exchangers. In the wall of each room, there is a separate intake and exhaust together with a heat exchanger. This solution is comparably expensive because it requires the installation of more small fans and heat exchangers with the benefit of less ducting (Ghida, 2019). Therefore, it will be assumed that for all buildings the heat recovery can be installed and that it is characterized by the same costs. If the penetration of this technology is too high (higher than feasible), additional constraints can be created to assess this problem.

The biggest part of costs when it comes to heat recovery ventilation is the investment cost. The calculation is based on the data given in (M. Gustafsson et al., 2016) and is following. In this equation, the ventilation losses are according to (Davies, 2006).

$$\frac{CAPEX}{Q_{U,max}} = \frac{CAPEX}{C_{p_{air}} \cdot \rho_{air} \cdot \dot{V} \cdot \Delta T_{max}} = \frac{CAPEX}{C_{p_{air}} \cdot \rho_{air} \cdot ACR \cdot A \cdot h \cdot \Delta T_{max}} \tag{12}$$

Where:

$CAPEX$ – capital expenses $[EUR]$

$Q_{U,max}$ – maximal heat loss of unrenovated ventilation $[W]$

$C_{p_{air}}$ – heat capacity of air $[\frac{\mathrm{J}}{\mathrm{kgK}}]$

ρ_{air} – density of air $[\frac{\mathrm{kg}}{\mathrm{m^3}}]$

$\dot{V}$ – volume flow of air $[\frac{\mathrm{m^3}}{\mathrm{s}}]$

ΔT_{max} – maximal temperature difference $[K]$

ACR – air change rate $[\frac{1}{\mathrm{s}}]$

A – heated area $[\mathrm{m}^2]$

h – wall height $[\mathrm{m}]$

Knowing that the lowest temperature in Sweden between 2010 and 2019 was -31.2°C, the price per kW of the nominal power of the heat exchanger is equal to 2 268 EUR/kW. This number is used in the calliope as a constraint for determining heat-recovery ventilation costs. On the contrary, it was assumed that the non-heat recovery ventilation has a cost of 0 as it is already present in buildings and does not require to be modernized or replacement.

There is also an operational cost related to filter replacement. Which is equal to around 1% of the investment, so it was neglected in calculations (M. Gustafsson et al., 2016), (Cho et al., 2021).

Ventilation – electricity demand

Another factor is the additional power consumption to force air movement. The power consumption is constant throughout the year because of the increased air tightness of the building which makes natural ventilation ineffective. However, electricity consumption-related costs do not need to be added manually, as they are modeled by Calliope.

Appendix C

Storage in construction elements – storage capacity

In this section, the storage capacity of the wall will be discussed. It is more convenient to analyze the one square meter of a wall so that results will be universal for each building and easily scalable according to needs.

The heat capacity of a wall can be calculated in the following way (Tsilingiris, 2006).

$$Cp_{OW,areal} = \rho_{OW} \cdot Cp_{OW} \cdot th_{OW} \tag{13}$$

The same can be done for the layer of insulation.

$$Cp_{OW\ INS,areal} = \rho_{OW\ INS} \cdot Cp_{OW\ INS} \cdot th_{OW\ INS} \tag{14}$$

Where:

$Cp_{OW,areal}$ – areal heat capacity of outside wall (heat capacity divided by the area of wall) $\left[\frac{J}{m^2K}\right]$

$Cp_{OW\ INS,areal}$ – areal heat capacity of insulation (heat capacity divided by the area of wall) $\left[\frac{J}{m^2K}\right]$

ρ_{OW} – density of outside wall material $\left[\frac{kg}{m^3}\right]$

$\rho_{OW\ INS}$ – density of insulation material $\left[\frac{kg}{m^3}\right]$

Cp_{OW} – heat capacity of outside wall material $\left[\frac{J}{kg\ K}\right]$

$Cp_{OW\ INS}$ – heat capacity of insulation material $\left[\frac{J}{kg\ K}\right]$

th_{OW} – thickness of the outside wall $[m]$

$th_{OW\ INS}$ – thickness of the insulation $[m]$

Because the real construction material and the wall thickness are unknown, for this part of the thesis it was assumed that all archetypes are built from concrete and the wall's thickness is equal to 24 cm (Tsilingiris, 2006). Calculations for this input yield the result where the heat capacity is equal to 485 $\frac{kJ}{m^2K}$ or 0.13 $\frac{kWh}{m^2K}$.

Similar calculations were made for insulated walls with varying insulation thicknesses. It was calculated that the heat capacity of insulation is always less than 2% of the heat capacity of a wall, even for thick insulation as shown in Table 16. Therefore, it is reasonable to assume that all insulated and uninsulated buildings have the same heat capacity

Table 16. Influence of insulation thickness on the heat capacity of wall.

Insulation thickness [m]	Heat capacity [J/m²K]	Change
0	485 760	0.0%
0.01	486 014	0.1%
0.05	487 030	0.3%
0.1	488 300	0.5%
0.2	490 840	1.0%
0.3	493 380	1.6%

The next step is to scale the capacity of one building to the location level. In Section 3.3.4, the number of archetypical buildings in each location was calculated. The scaling looks the following.

$$Cp_{OW,location} = Cp_{OW,areal} \cdot A_{OW,archetype} \cdot n \tag{15}$$

Where:

$Cp_{OW,location}$ – Thermal energy storage capacity $[kWh]$

$A_{OW,archetype}$ – Area of outside walls in a building in a location $\left[\frac{J}{m^2K}\right]$

n – number of buildings in a location$[-]$

The last step is to estimate to what extent this storage can be used, which depends on the range of temperature change of the wall. This part will be explained in the charging/discharging section because it is directly related to that.

Storage in construction elements – charging/discharging

Charging and discharging are dynamic processes, therefore the transient model of a wall is needed. It can be made as (Tsilingiris, 2006) in the form of an electric circuit containing capacitors. The physical thermal model is shown on

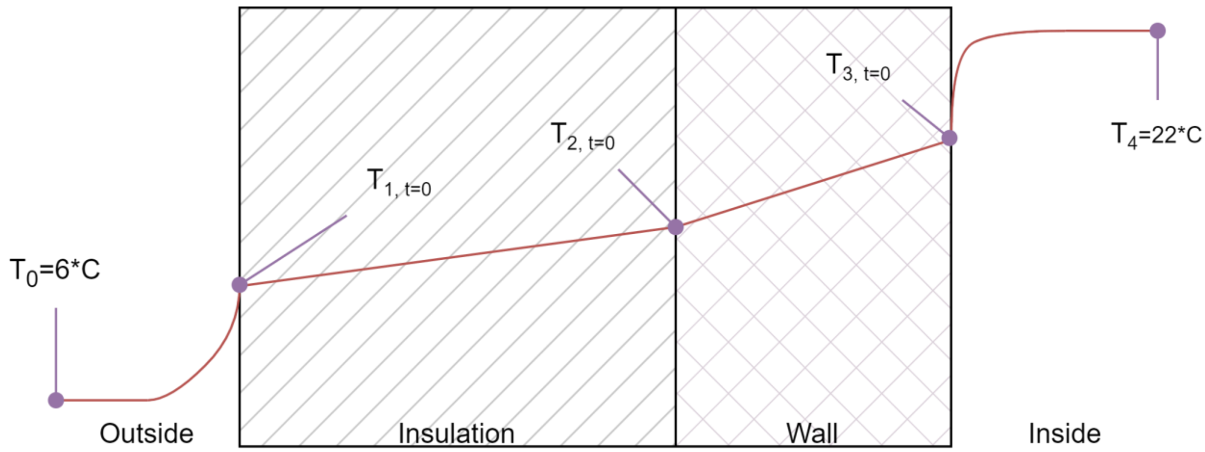

Figure 28. Thermal model of a building's wall

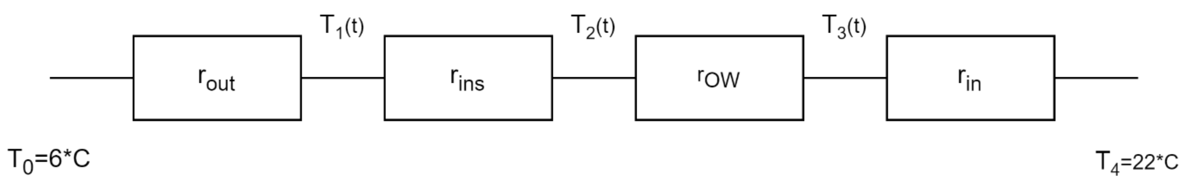

Figure 29. Thermal model of a building's wall. Electrical representation of a steady state.

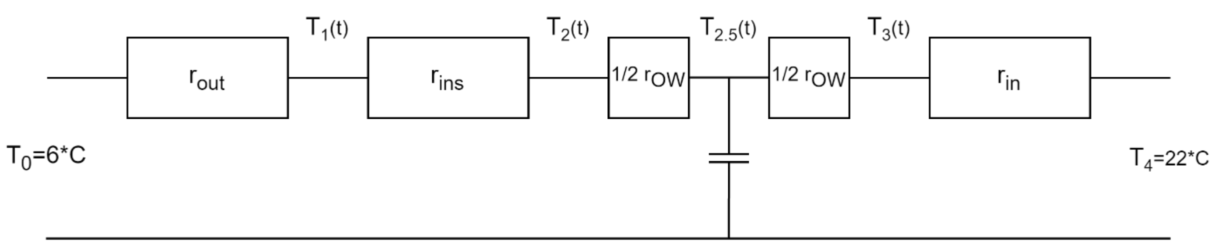

Figure 30. Thermal model of a building's wall. Electrical representation of a dynamic state.

The first step in solving a problem is to solve a model as a static one, which is needed to calculate the constant of integration that will be used in the dynamic version of a model. The electric circuit representation of a static system is shown on

The first step to solve the model as a static one is to calculate all resistances.

$$r_{out} = \frac{1}{\alpha_{out} \cdot A_{OW}} \tag{16}$$

$$r_{ins} = \frac{th_{ins}}{\lambda_{ins} \cdot A_{OW}} \tag{17}$$

$$r_{OW} = \frac{th_{OW}}{\lambda_{OW} \cdot A_{OW}} \tag{18}$$

$$r_{in} = \frac{1}{\alpha_{in} \cdot A_{OW}} \tag{19}$$

Because those resistances are connected in series they can be added.

$$r_{total} = r_{out} + r_{ins} + r_{OW} + r_{in} \tag{20}$$

Then the heat transferred needs to be calculated

$$\dot{Q} = \frac{\Delta T}{r_{total}} \tag{21}$$

As a last step temperature of the wall needs to be calculated. The heat flow is constant for each resistance.

$$T_1 = T_0 + \dot{Q} \cdot r_1 \tag{22}$$

$$T_2 = T_1 + \dot{Q} \cdot r_2 \tag{23}$$

$$T_3 = T_2 + \dot{Q} \cdot r_3 \tag{24}$$

$$T_{2.5} = \frac{T_2 + T_3}{2} \tag{25}$$

Then one can proceed to solve a dynamic model by using solutions from a steady-state model. In the beginning, the two heat flows need to be calculated, one from T_3 to outside and one from T_3 to inside by following Figure 30.

$$Q_{inside \to wall} = \frac{T_4 - T_{2.5}}{R_{in} + \frac{1}{2} R_{OW}} \tag{26}$$

$$Q_{wall \to outside} = \frac{T_{2.5} - T_0}{R_{out} + R_{ins} + \frac{1}{2} R_{OW}} \tag{27}$$

The difference between those flows results in the heat that is accumulated/unaccumulated in the wall (as known the heat capacity of the insulation can be neglected) and results in a change of the temperature of a wall.

$$Q_{absorbed} = Q_{inside \to wall} - Q_{wall \to outside} \tag{28}$$

$$Cp = \frac{dQ}{dT} = \frac{\dot{Q} \cdot dt}{dT} = \frac{\dot{Q} \cdot \Delta t}{\Delta T} \tag{29}$$

$$T_{t=n+1} = T_{t=n} + \frac{\dot{Q} \cdot \Delta t}{Cp} \tag{30}$$

This newly calculated temperature then needs to be used in the next time step. This way, the heat equation is integrated numerically according to time.

For charging it was assumed that the setpoint of an air temperature is equal to 22*C. As the Calliope requires to have the same charge and discharge rates, the discharge air temperature was chosen so that it is slightly below 20°C. After several iterations, the correct temperatures were printed for which the same charge/discharge time was obtained. As the temperature as a function of time is described by an exponential function that approaches the equilibrium temperature, it is not possible to achieve a fully charged status (asymptotic behavior). Therefore, it was assumed that the storage is fully charged when 90% of the theoretical capacity is achieved. It happens after 10 hours. The setpoints and temperatures can be seen in Table 17 and the profile of the wall's temperature is visualized in Figure 31. Calculations were made for 3 different insulation thicknesses: 0, 0.05, and 0.3 m.

Table 17. Summary of heat capacities for different insulation thicknesses.

Insulation thickness	**T air during charge**	**T air during discharge**	**delta T of a wall**	**Heat capacity**	
m	°C	°C	K	J/m2	kWh/m2
0.00	22.00	19.11	0.48	232 462	0.065
0.05	22.00	18.89	0.71	345 381	0.096
0.30	22.00	18.84	0.80	390 188	0.108

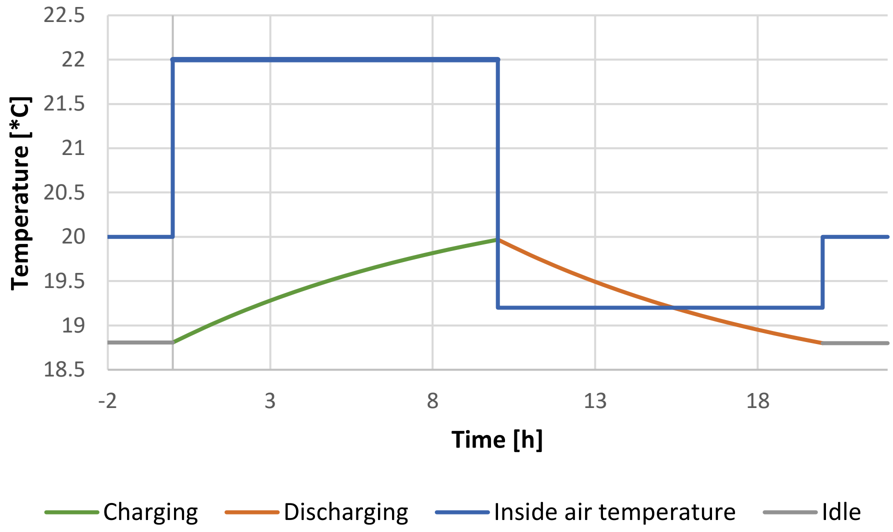

Figure 31. Example of wall's temperature profile during the charging/discharging cycle.

As it is visible that the state of charge of this thermal energy storage behaves nonlinearly as an exponential curve, the linearization is needed. It was assumed that the c-rate is equal to 10%, which is the average c-rate in the 10-hour interval of charging/discharging if the 100% state of charge is expected.

Storage in construction elements – self-discharge

The calculation of ventilation losses is fairly simple. The equation that is used to calculate it can be seen below (Davies, 2006).

$$Q_{vent} = \dot{V} \cdot (T_{IN} - T_{OUT}) = f_{ex} \cdot V_b \cdot (T_{IN} - T_{OUT}) \tag{31}$$

Where:

Q_{vent} – heat loses due to ventilation

$\dot{V}$ – air flow

T_{IN} – temperature inside the building

T_{OUT} – temperature outside the building

f_{ex} – exchange rate, how many times the air in the building needs to be replaced in an hour

V_b –volume of the building

Nevertheless, it is not necessary to use that equation as the model created for charging/discharging already is capable of calculating the self-discharge rate. The excess of heat transferred to the environment can be calculated by subtracting the heat flow from the wall in charged condition from the heat flow in the steady state. By doing that for all 10 hours that the storage is being discharged, the average heat flow in an hour can be calculated. The result of this operation can be used directly in Calliope. Similarly, to the charging/discharging parameters, the self-discharge rate is nonlinear and is higher when the storage has a higher state of charge. Therefore, the linearization of an exponential equation was made by calculating an average value over the cycle.

Storage in construction elements – cost model

There is no cost related to this storage directly. However, there are several things that are needed indirectly. One of them is the optimal control of the heating devices. It is assumed that the thermostat and the temperature sensors are included in the price of a heating device. The second one is the optimal and automatic setpoint modulation, which can decide when to increase and decrease air temperature and to which values so that the charging/discharging is optimal based on the input data. It can be assumed that by 2050 this will be a standard in heating devices, therefore it was also assumed to be included in the price of the heating device.

Appendix D

The modeling of solar thermal collectors was started by calculating the fractions of the north, south, east, and west-faced roof areas. This was done based on the existing data in Euro-calliope, regarding the maximum installable capacity of rooftop PV. Those fractions are constant for every country because the original values used in Calliope are based only on Swiss data.

The second step was about determining the rated power of a collector and its thermal efficiency. It was assumed that flat-plate solar thermal collectors, used in the system, have a rated power equal to 700 $\frac{W}{m^2}$ (Hargassner, 2021). The efficiency of the collector is described by the parabolic function that depends on the temperature difference between the surrounding and the collectors' temperature and the solar irradiation as given below (Suciu et al., 2018).

$$\eta = \eta_0 - a_1 \frac{T_m - T_{amb}}{G} - a_2 \frac{(T_m - T_{amb})^2}{G} \tag{32}$$

Where,

η – efficiency in given conditions

η_0 – maximum efficiency

T_m – temperature of the fluid inside the collector

T_{amb} – ambient temperature

G – solar irradiation

a_1 – empirical parameter 1

a_2 – empirical parameter 2

As this temperature difference can vary significantly on the personal preferences and requirements of the heat user, it was assumed that the efficiency is constant and equal to 70% based on calculations for several different irradiation and temperature conditions by using the efficiency characteristics following the collector's datasheet (Lacaze-Energies, 2017).

The next step is to calculate how much solar irradiation is reaching collectors in each country. If the solar thermal collector would track the position of the sun, excluding efficiency it would be equal to the incident irradiance that is given by (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016) for each hour of the year for each country, population-weighted. Therefore, the relative angle between the plane of the collector and the plane of the sunbeams needs to be calculated. This angle depends on several factors like the Earth's rotation around its axis, the Earth's rotation around the sun, and the varying distance between the Earth and the sun as the orbit is elliptical. Description of the behavior of the sun on the skyline is out of the scope of this thesis but the equations used for that are following (Chwieduk, 2014).

$$B = (day - 1)\frac{360}{365} \tag{33}$$

$$E = 229.2 \cdot (0.000075 \cdot 0.001868 \cdot cosB - 0.032077 \cdot sinB - 0.014615 \cdot cos2B - 0.04089 \cdot sin2B) \quad (34)$$

$$t_{sol} = hour + \frac{4 \cdot lon + E}{60} \quad (35)$$

$$\omega = 15 \cdot (t_{sol} - 12) \quad (36)$$

$$\rho = 23.45\, sin\left(360 \cdot \frac{284 - day}{365}\right) \quad (37)$$

$$\cos\theta = \sin\rho\,(\sin\varphi\cos\beta - \cos\varphi\sin\beta\cos\gamma) + \cos\rho\,(\cos\varphi\cos\beta\cos\omega + \sin\varphi\sin\beta\cos\gamma\cos\omega + \sin\beta\sin\gamma\sin\omega) \quad (38)$$

$$G_{col} = G \cdot \cos\theta \quad (39)$$

Where:

B - B-value, used to solve equation for E $[-]$

day – day of the year $[day]$

E – E-value, value that describes the variability of the Earth's motion around the sun $[min]$

t_{sol} – solar time $[h]$

$hour$ – hour of the day $[h]$

lon – longitude [°]

ω – hour angle of the sun [°]

ρ – sun's declination [°]

θ – incident angle of a beam radiation on the collector's surface [°]

φ – latitude [°]

β – rooftop pitch [°]

γ – solar azimuth angle, orientation of the collector [°]

G_{col} – irradiation on the plane normal to the collector $\left[\frac{W}{m^2}\right]$

G – irradiation on the plane normal to beam $\left[\frac{W}{m^2}\right]$

In that case, the latitude and longitude were different for each country. The G describes the incident solar irradiation for each hour for each country. As a reader might have noticed, the rooftop pitch is required to define the plane of the collector. It was assumed to be 18.4 degrees for all countries (Cope, 2004).

By repeating those calculations for each hour for each country, the heat generation of 1 square meter of a collector can be calculated. Then knowing the rated power of the collector, the capacity factor can be calculated, which is an input to the Calliope.

Appendix E

Heat generation mix

There is no point in showing graphs of the heat generation mix for all 35 countries as most of them are similar. Therefore, there were identified 4 groups that combine locations that share certain features. Table 18 shows what countries were assigned to which groups.

Table 18. Division of countries into groups based on heat generation mix.

Group	Countries
1	ALB CYP BGR BIH CYP HRV MKD MNE PRT
2	AUT FIN LTU LVA SVK POL ROU
3	BEL CHE CZE DEU DNK ESP EST FRA GBR GRC HUN IRL ITA LUX NLD NOR SRB SVN SWE
4	ISL

The first group includes countries that are characterized by a relatively high fraction of solar thermal collectors. The heat generation mix in different scenarios for Cyprus is presented in Figure 32. All those countries have a high availability of solar energy and therefore the thermal collectors penetrated more than in other locations. It is worth noticing that not all countries that have high solar irradiation (Italy, Spain) are in this group as their power generation is very high and, in those conditions, heat pumps are favored more. It is important to mention that the renewable energy availability and renovation did not have a meaningful impact on the energy mix of those countries. Moreover, whenever the share of energy generated by the solar thermal collectors increased, it happened at the cost of the share of heat pumps.

The second group is made up of countries leaning towards heat generation from the biomass. The heat generation mix in different scenarios for Lithuania is presented in Figure 33. It is visible that the availability of the renewable energy had a significant impact on the production from biomass. The abundance of cheap electricity in the 2015 scenario made that the biomass boilers were fully outperformed by heat pumps. As for the first group, the impact of renovation on the penetration of biomass is meaningless.

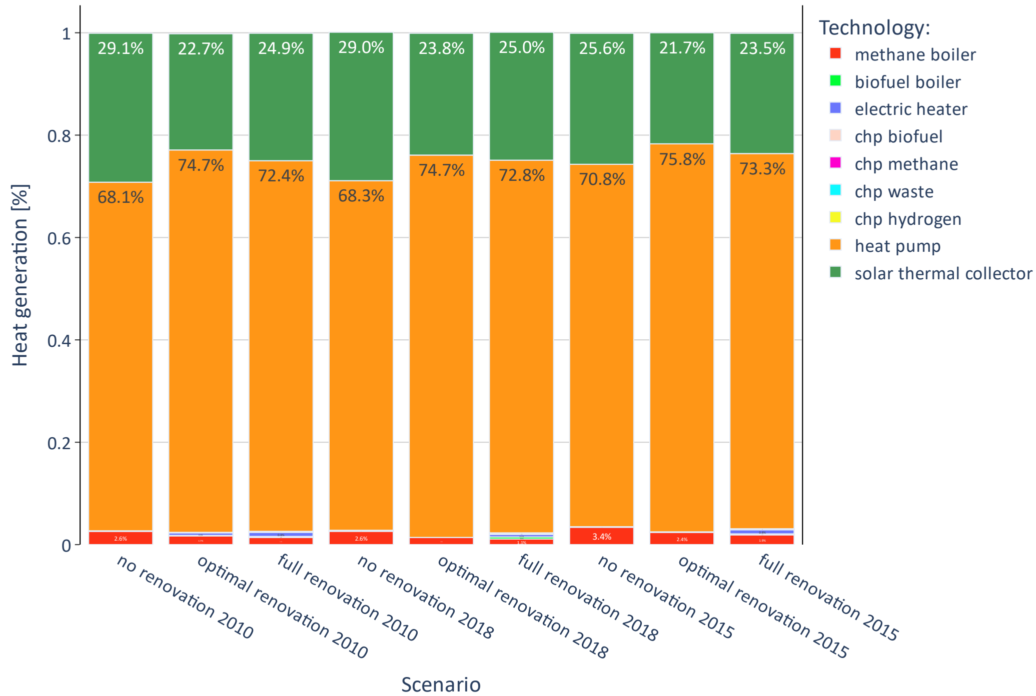

Figure 32. Heat generation mix of Cyprus.

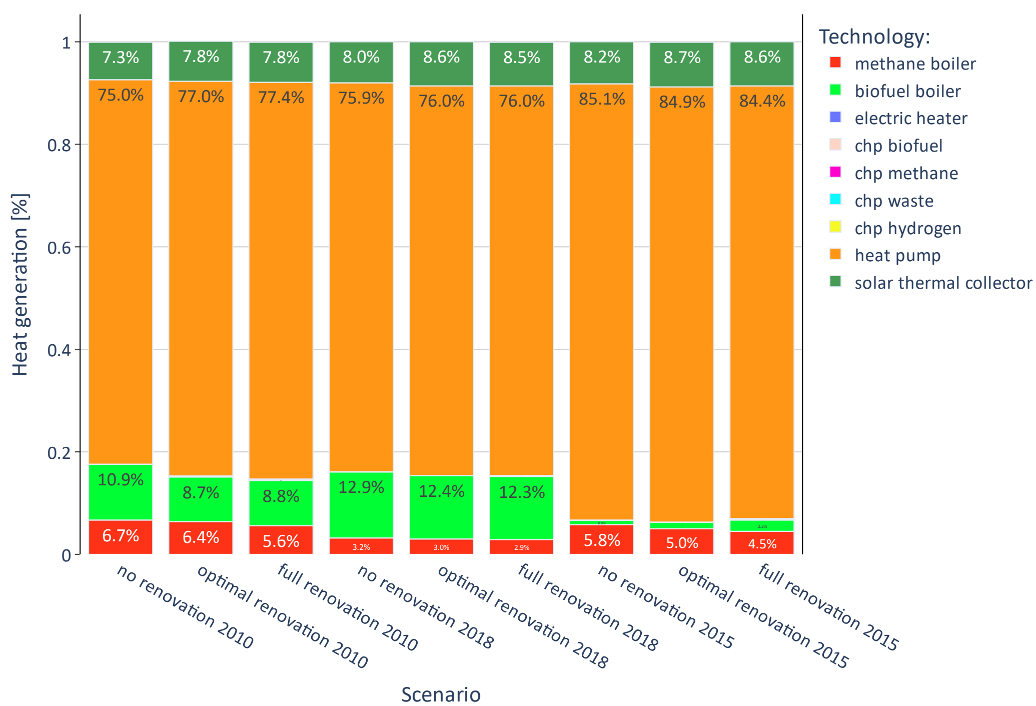

Figure 33. Heat generation mix of Lithuania.

The third identified group consists of countries where almost all heat is generated via heat pumps. This is the biggest group of countries as most of them have an abundance of renewable electricity. For those countries, there is almost no fluctuation of shares in the energy mix between all nine scenarios. An example of an energy mix for Spain is presented in Figure 34.

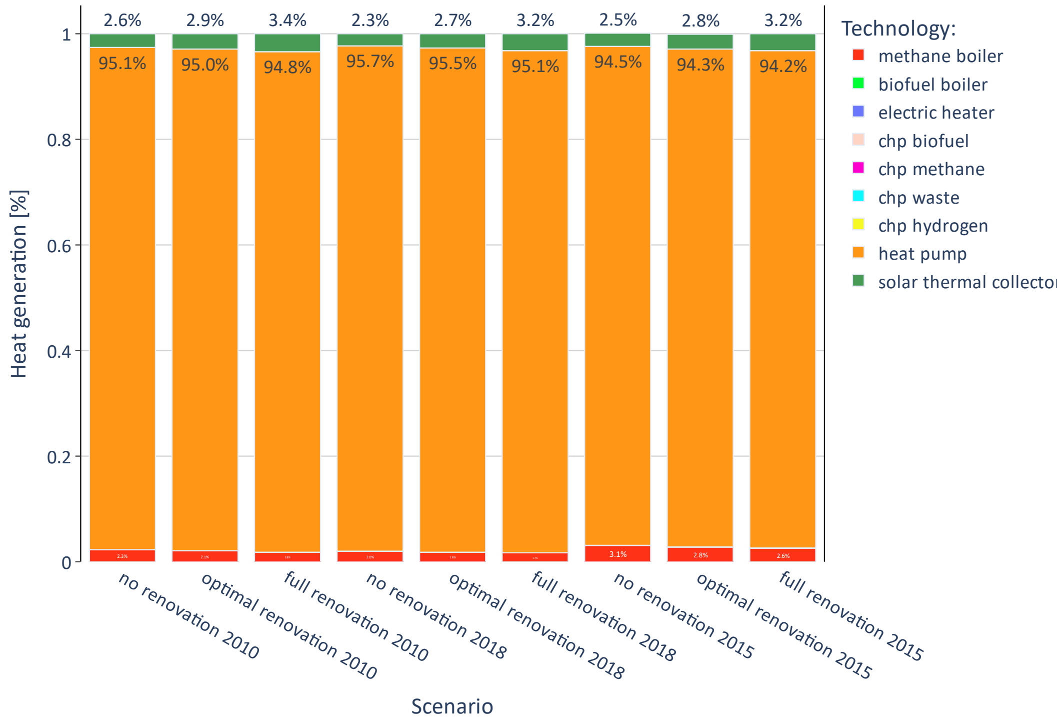

Figure 34. Heat generation mix of Spain.

The fourth group consists only of Iceland as this is the only country, where plenty of heat generation technologies are available with similar shares, as visible in Figure 35. This is a very interesting outcome as for all other countries heat pumps were dominating the heat mix. It is worth reminding that Iceland had a significant electricity supply thanks to wind parks, so having heat pumps seems to be a logical solution. However, two reasons alter this paradoxically logical result. Firstly, in the model there was no residential heat demand defined as it comes mostly from the geothermal plants, therefore there was no storage in construction elements available. Second of all, the heat demand for the commercial sector is so small that the accuracy of calculations is much lower as the model must slightly relax some constraints so that the model can be calculated in a finite amount of time.

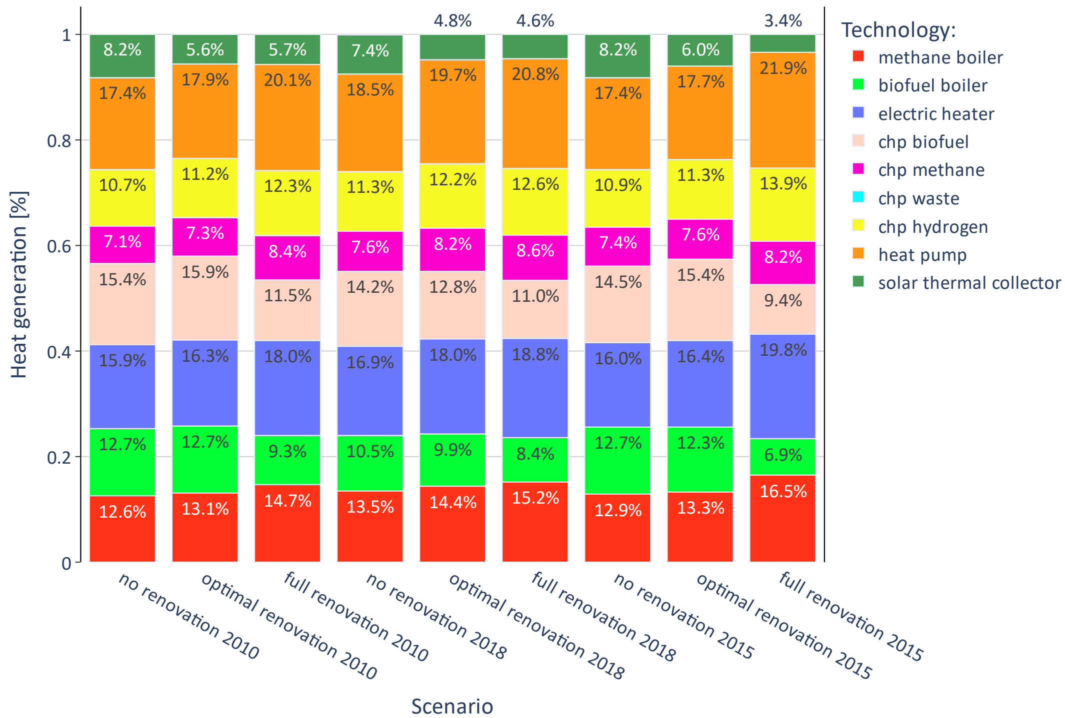

Figure 35. Heat generation mix of Iceland.

Correlation between heat demand, wind, and PV

The results of the investigation regarding the correlation of heat demand, wind, and PV are present in Table 19, where the correlations for all nine scenarios are visible. It can be seen that the Pearson correlation between wind and heat demand is positive (approx. 0.35). On the other hand, the Pearson correlation between solar and heat demand is negative (approx. -0.35).

Table 19. Correlation between heat demand and PV and wind onshore.

	Open field PV	Onshore wind
no renovation 2010	-0.361	0.324
optimal renovation 2010	-0.361	0.325
full renovation 2010	-0.361	0.328
no renovation 2018	-0.344	0.417
optimal renovation 2018	-0.344	0.417
full renovation 2018	-0.344	0.416
no renovation 2015	-0.346	0.336
optimal renovation 2015	-0.346	0.336
full renovation 2015	-0.346	0.333

In addition, profiles of heat demand, wind, and PV (2-week average) are visualized on Figure 36 to see that the heat demand so as the wind supply is higher in winter than in the summer. The opposite behavior is noticeable for PVs. This shows that higher investment in wind technologies is preferred, as it decreases the required storage capacity due to the increase in production when the increase in demand is present. Hence more wind is present for unrenovated scenarios and for years with low renewable potential.

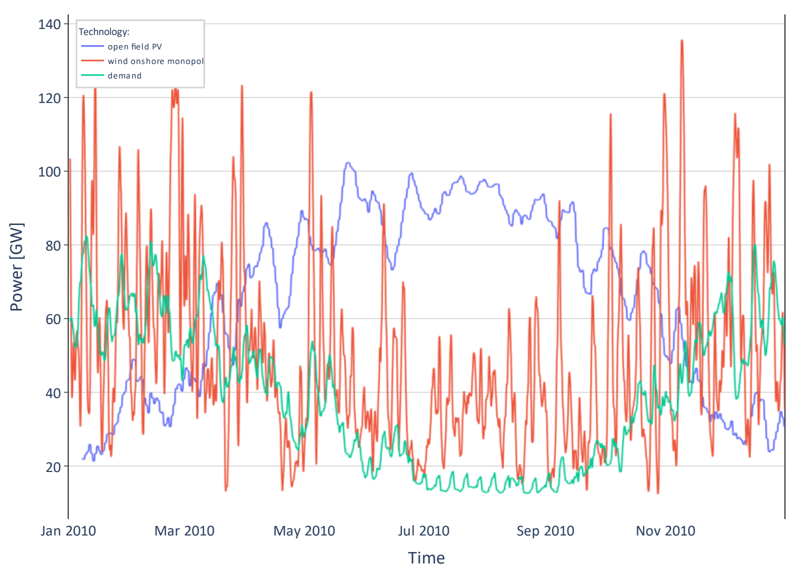

Figure 36. Profile of wind monopoly, open field PV and heat demand, averaged (14 days moving average).

Spatial distribution of generation technologies

This section focuses on showing how the availability of renewables and the renovation affect the spatial distribution of power generation sources. As there were 9 scenarios calculated, they will be grouped accordingly to the weather year, so that the impact of renovation (which is more important) is more noticeable.

In 2010 scenarios (Figure 37) it is visible that the renovation has a small impact on the spatial distribution of power plants. A very interesting fact is that power generation sources are highly concentrated in several countries, which are not necessarily characterized by high final energy consumption. Therefore, the system heavily relies on the transmission of power from locations with concentrated generation like Great Britain, Portugal, Hungary, and Denmark to other countries, with less favorable weather conditions.

By looking at Figure 38, that are showing values for the 2018 scenario, changes caused by the renovation are again very small. On the other hand, the concentration of generation is even more visible. The United Kingdom generates over 3 times more electricity than France, the second country on the list. A very interesting finding is that the generation in some countries increased and in others decreased compared to the 2010 scenario. Moreover, the energy mix in some countries is noticeably different. For example, Portugal decreased the share of photovoltaics-generated electricity in its energy mix. The opposite situation is visible in France, where the PV farms increased their share from 25% to 50% in the energy mix. All those things are caused by the different renewable potentials in different years in specific countries. As the capacity factor of wind farms is the highest in the UK in 2018, the model allocated the generation sources there, because it is the optimal allocation.

Looking at Figure 39 describing the 2015 weather year further proves the presumptions made in the previous paragraph as the capacity factor of wind farms in the UK is even higher there. The concentration is further visible by analyzing countries like Portugal and Spain, which significance in Europe's electricity generation decreased at the cost of Great Britain.

In order to further understand the impact of renovation on the system,

Table 7 and Table 8 were prepared which shows changes in electricity generation of PV and onshore wind (competing and monopoly) as they differ the most significantly between scenarios. As there is limited space, only countries characterized by electrical energy generation above 200 TWh per year were presented.

It can be seen that the penetration of open-field PV, does not change much with the renovation level for most (except Germany) significant countries which is in line with previous findings. On the other hand, the electricity generated in onshore wind parks decreases with the renovation level, which also follows the previously found pattern.

The most important finding is that renewable availability has a very significant impact on the spatial distribution of power generation sources, much more than a renovation.

Figure 37. Electricity generated in 2010 scenarios (top – no renovation, middle – optimal renovaiton, bottom – full renovation) for each of the 35 countries.

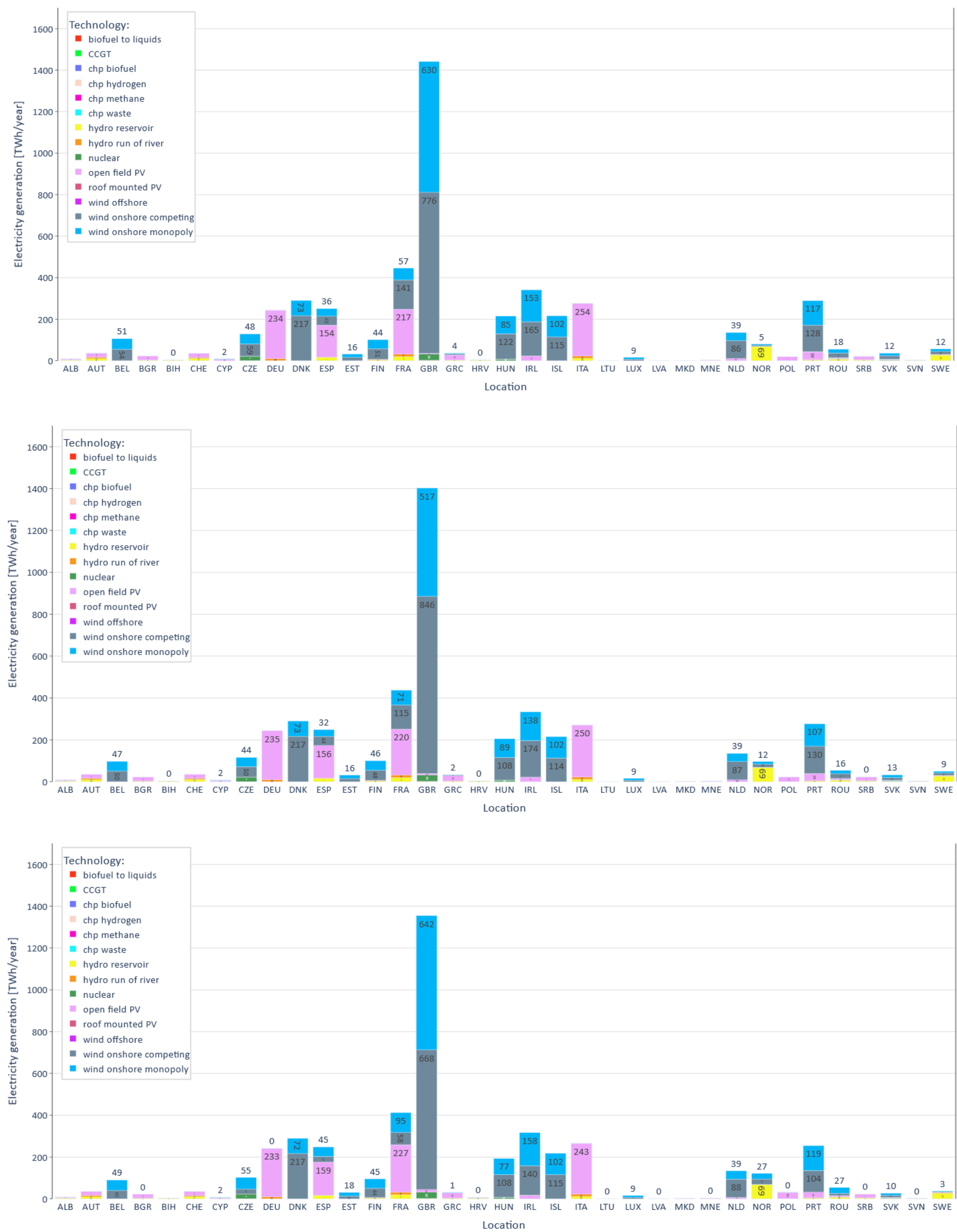

Figure 38. Electricity generated in 2018 scenarios (top – no renovation, middle – optimal renovaiton, bottom – full renovation) for each of the 35 countries

Figure 39. Electricity generated in 2015 scenarios (top – no renovation, middle – optimal renovaiton, bottom – full renovation) for each of the 35 countries

The capacity factor of generation technologies

Capacity factors describe to what extent the installed capacity is being utilized. As costs of generation technologies are, the same for each location (in the model), locations with higher capacity factors should be preferred. To check if this is true and what is the impact of renovation on them, graphs showing capacity factor as a function of yearly energy yield were prepared. Figure 40 presents the dependence of the energy generated on the CF. Similar graphs were prepared for offshore wind competing and monopoly, Figure 41 and Figure 42 respectively. As before, graphs include data for countries for which the electricity generation was above 200 TWh in any scenario.

It can be seen that the capacity factor is not the only factor impacting the energy yield. The costs related to transmitting the power to other countries has also an impact on where the generation sources are installed. For PV, countries that are on the outskirts of Europe like Portugal and Spain, have low installed capacity despite the high-capacity factor. On the other hand, Germany has low-capacity factors but because of being located in the center of Europe, the amount of energy produced via PVs is significant.

When it comes to onshore wind, there is no big difference between monopoly and competing wind farms. Moreover, the correlation between CF and energy generation is much higher for wind farms than for PV parks. It is again visible that countries like Ireland and Iceland which are far from the center of Europe, have high CFs and installed power, by far exceeding domestic needs.

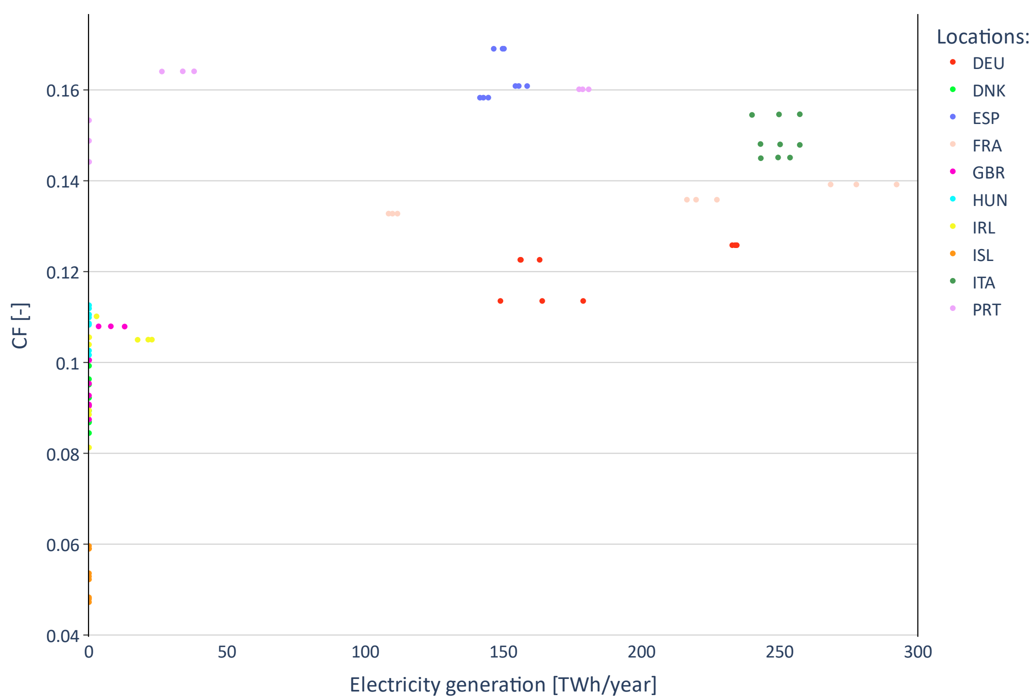

Figure 40. Dependence of the energy generation on CF for open field PV.

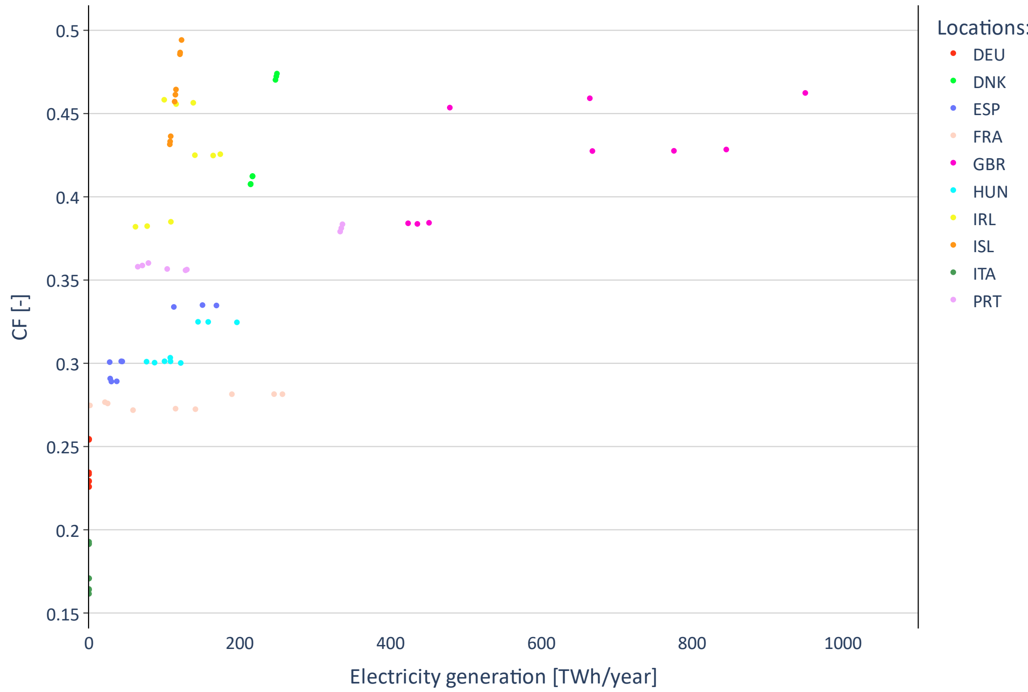

Figure 41. Dependence of the energy generation on CF for onshore wind competing.

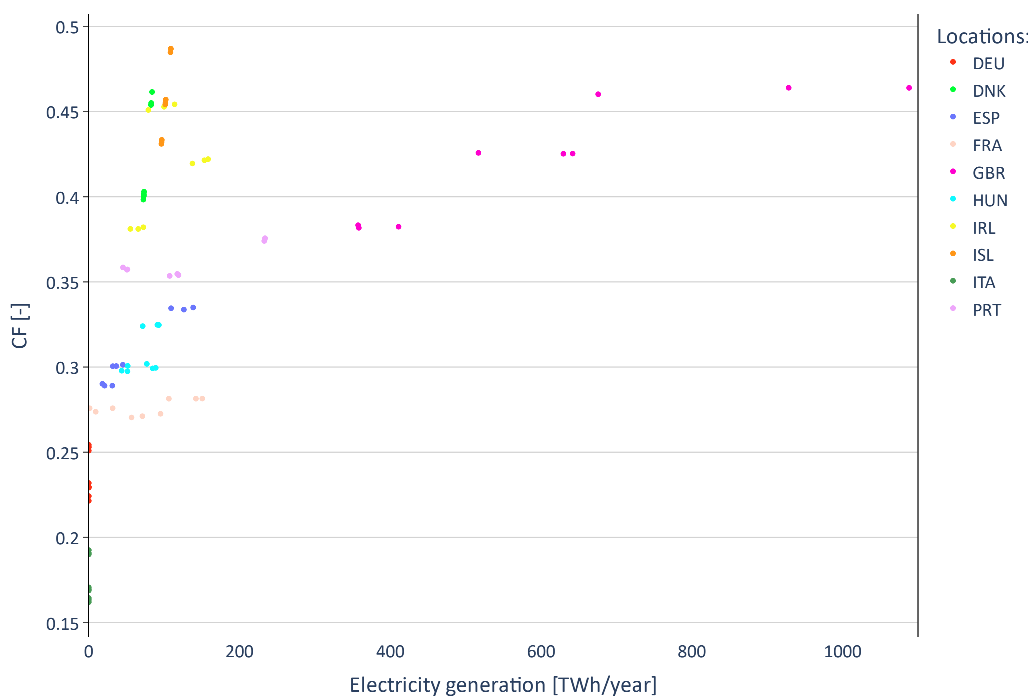

Figure 42. Dependence of the energy generation on CF for onshore wind monopoly.

Energy storage capacity and CF

There are many ways to store different forms of energy used in the model. It was decided that it is good to show the capacity of different storage technologies that store different carriers as it gives a good overview of how the system counteracts the intermittency of renewables. One of the parameters that characterize storage technologies is storage capacity. The store capacity between scenarios is presented in Figure 43 and Table 20. As can be seen most of the storage capacity (over 99%) is within 3 technologies: methane storage, pumped hydro storage, and hydro reservoirs. In the model, the storage capacities of those three technologies are predefined (not optimized) and reflect the currently installed capacities, which are close to the technical maximum.

Figure 43. Comparison of storage capacity of all storage technologies.

Table 20. Comparison of storage capacity between scenarios in GWh.

Scenario	battery	hydro reservoir	pumped hydro	hydrogen storage	methane storage	hot water tank	buildings pre 1945	buildings 1945 1969	buildings_1970_ 1979	buildings_1980_ 1989	buildings_1990_ 1999	buildings_2000_ 2010	buildings_post_ 2010
0	0.20	100 951.24	11 357.76	1.44	1 318 279.42	0.18	256.29	345.17	231.41	197.70	147.05	149.28	59.37
1	1.48	100 951.24	11 357.76	10.52	1 318 279.42	0.93	1.70	8.33	78.62	178.37	897.19	243.24	76.45
2	3.10	100 951.24	11 357.76	18.35	1 318 279.42	1.59	0.00	0.00	0.00	0.00	0.00	0.00	1 530.73
3	0.12	100 951.24	11 357.76	1.11	1 318 279.42	0.13	256.29	345.17	231.41	197.70	147.05	149.28	59.37
4	0.16	100 951.24	11 357.76	1.23	1 318 279.42	0.12	0.26	7.15	95.80	640.25	545.57	107.49	79.01
5	2.77	100 951.24	11 357.76	17.35	1 318 279.42	1.79	0.00	0.00	0.00	0.00	0.00	0.00	1 529.78
6	90.24	100 951.24	11 357.76	1.32	1 318 279.42	0.18	256.29	345.17	231.41	197.70	147.05	149.28	59.37
7	74.59	100 951.24	11 357.76	1.10	1 318 279.42	0.11	0.41	6.95	95.81	481.71	709.72	118.65	63.98
8	55.49	100 951.24	11 357.76	12.93	1 318 279.42	1.24	0.00	0.00	0.00	0.00	0.00	0.00	1 529.23

Therefore, the storage capacity of other techs was analyzed, as visible in Figure 44. Comparison of storage capacity of techs below 2000 GWh of storage capacity. It validates that the model was solved correctly as the storage capacity is in line with the calculations made in Chapter 3.4.1. As can be seen, the storage capacity in the building envelope is much higher than battery, hydrogen, and hot water tank storage. It is visible that the storage capacity in construction elements increases with the renovation, as it result from calculations. It is interesting, that battery energy storage plays the most significant role in the scenario with the highest renewable energy supply, in other scenarios it is almost negligible when it comes to the installed storage capacity.

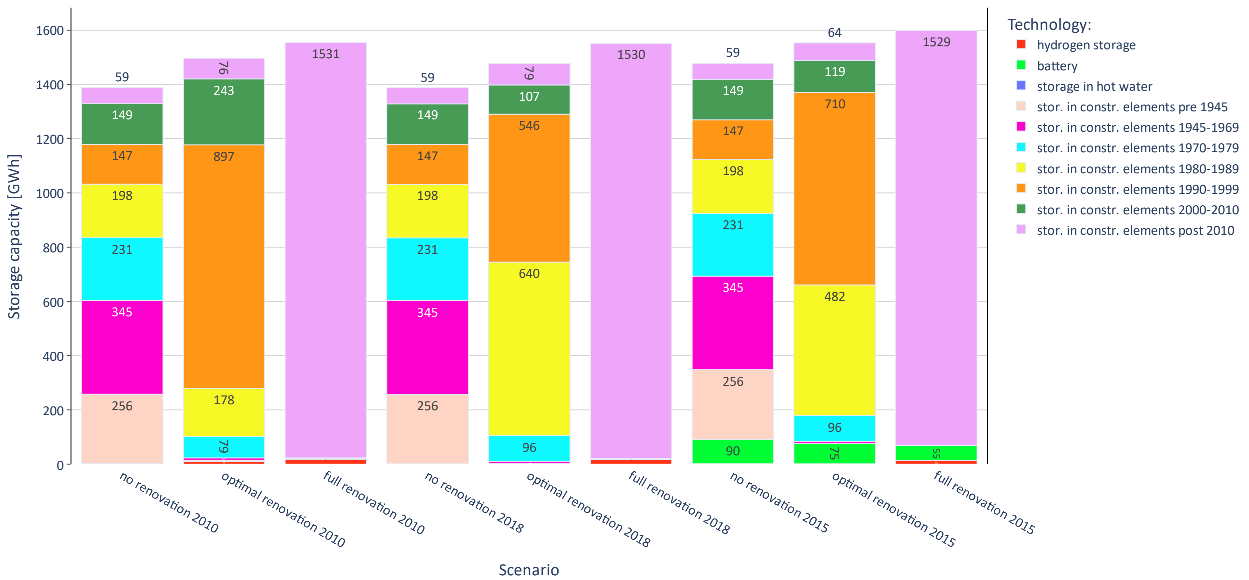

Figure 44. Comparison of storage capacity of techs below 2000 GWh of storage capacity.

To fully understand how energy storage works in the system, a detailed analysis of the three most important technologies (methane storage, PHS, and storage in construction elements) was done. All results presented below describe the full renovation 2018 scenario and presents only one country (Germany) in order to eliminate the impact of different demand profiles and weather patterns between countries. However, a similar analysis was done for two other countries (Spain and Poland) and the results were similar. It is worth mentioning that the battery energy storage was significant only in high renewables availability scenarios.

The first technology analyzed was **methane storage**. In Figure 45, it can be seen that this technology is used for the seasonal storage of energy as the storage is monotonically charged/discharged for weeks. An additional insight is given in Figure 46, where the capacity factor of charging and discharging is shown for the first two weeks of the year. It is noticeable that the storage is almost always charged/discharged with the maximum power. It is worth mentioning that the same pattern is visible for the whole year and not only for the first two weeks. The outcome is that the methane storage is limited by its energy capacity and not the storage capacity, which is additionally supported by the fact that the storage is never discharged below 64 TWh. Therefore, other storage technologies are needed to balance the system during peaks and valley hours.

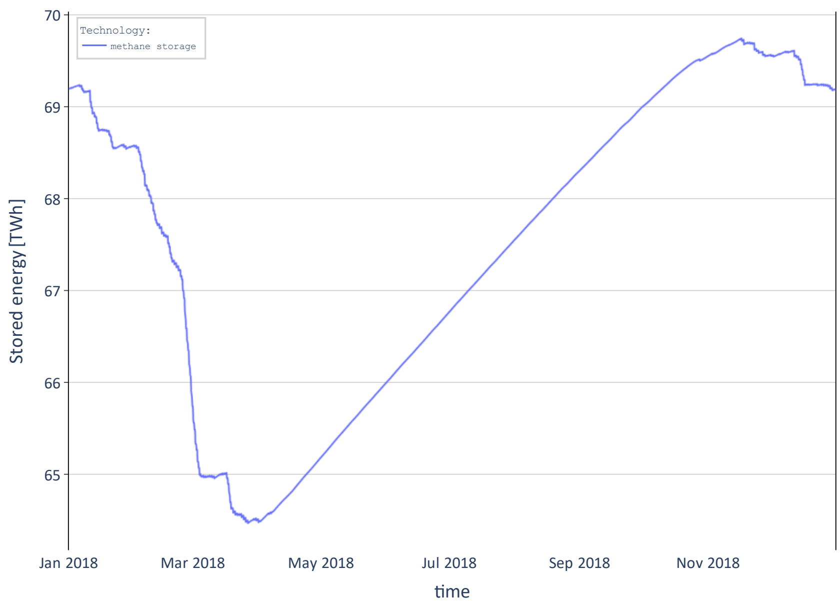

Figure 45. Stored energy in methane storage in TWh.

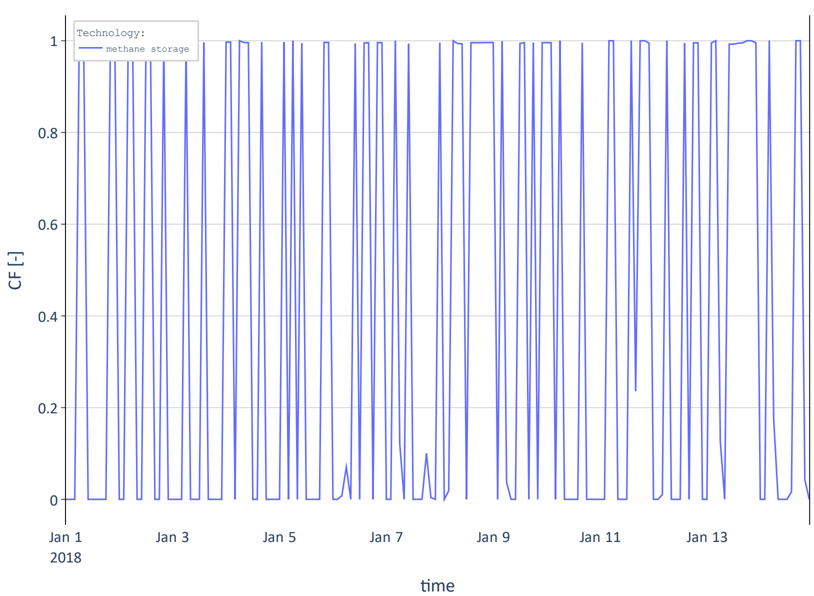

Figure 46. The capacity factor of methane storage in GWh.

The third technology that was analyzed is **pumped hydro storage**. The profile of stored energy is visible in Figure 47 and the profile of CF is given in Figure 48. The behavior of this storage technology is changing over the year. In some parts of the year, it is charged for around 2 weeks and then quickly discharged. At other times it charges and discharges on a daily basis to help with day-night system balancing.

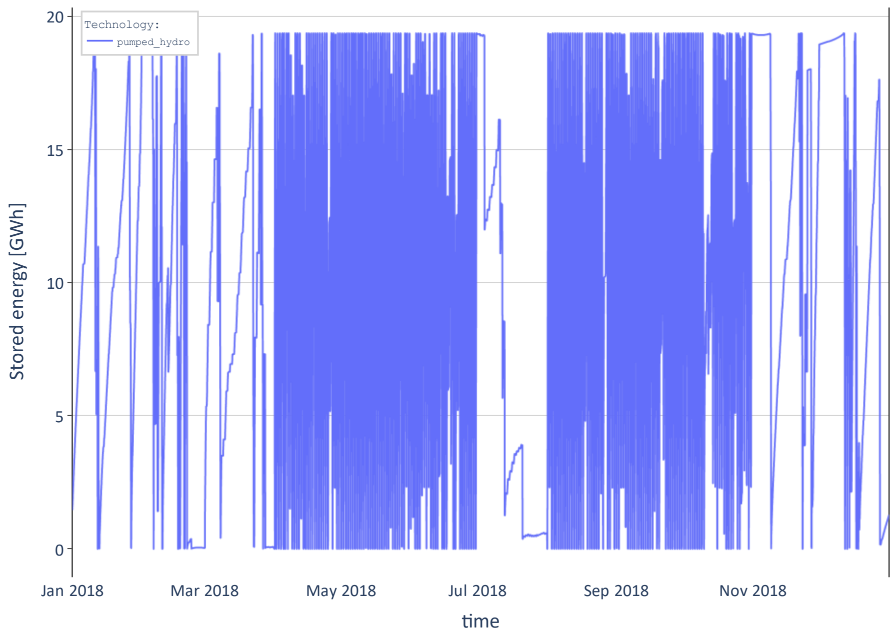

Figure 47. Stored energy in PHS in GWh.

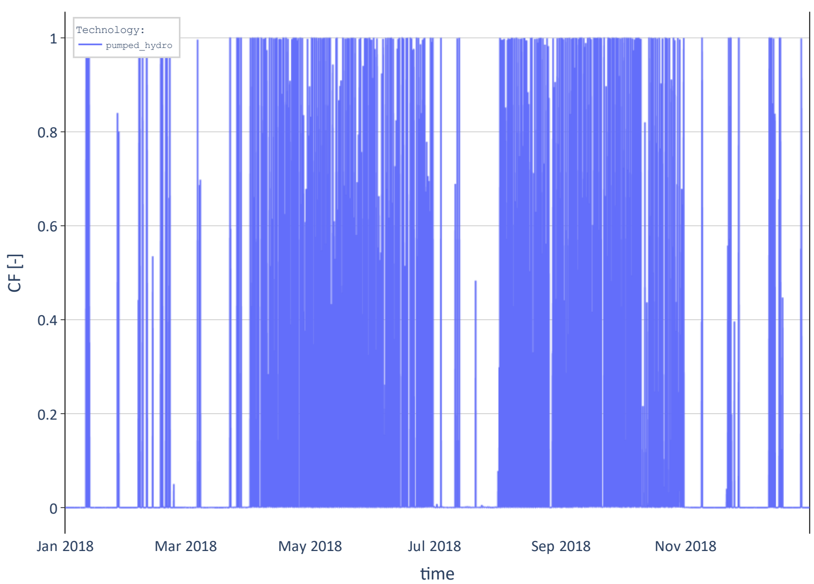

Figure 48. CF of PHS.

The last and the most interesting storage technology is **storage in construction elements of buildings**. As a reminder, the analyzed scenario is a fully renovated scenario, where only mostly renovated buildings are present, so the presented graphs give the most. Figure 49, shows the yearly profile of stored energy of the beforementioned technology. It is visible that the lines are densely spaced, so the storage is balancing an intra-day mismatch between heat supply and demand. There are visible 5 sections to which a year was divided, for two of them the maximal energy stored is equal to approximately 60 GWh, for another two around 100 GWh, and the last around 55 GWh. The moments of transition between, sections are similar to the profile of pumped hydro storage behavior. This is even more interesting knowing that PHS stores electricity and in construction elements, only heat can be stored. Therefore, this suggests that the overproduction of electricity that cannot be stored in PHS (due to the charging power limit) is going to be stored in the form of heat in construction elements.

Figure 50 shows the profile of stored energy for two weeks of September. It can be seen that charging of storage starts at around 06:00 and stops at 14:00, after which it is being discharged. However, in January, the behavior of the storage technology is different. It is charged between 20:00 and 02:00, after which it is discharged. This shows that the storage is used only when the excess of electricity is present in the system (September due to PV production) or when the high heat demand is anticipated (January due to lowest temperatures in the night). The quick discharge can be caused because self-discharge losses are very significant.

Figure 51 shows the profile of CF in January. A similar profile is visible throughout the whole year. The CF equal to one is almost always present in the morning hours when the heat demand increase and then for 4 or 6 hours it is discharged. One of the assumptions when designing the heat model was that the penetration of storage in construction elements would be so low that it would never fully substitute the heat generation and therefore the system can be simplified by not preventing the storage of the potable hot water. This behavior is visible in Figure 52, where the generation profile of the heat pump (which is the main heat source) is shown alongside the PHW demand. The graph shows several days in August, which is the only time when there is no other heat demand than PHW in the residential sector. It can be seen that there are some 2-hour time periods where the PHW demand is higher than the generation of heat pump because the is being stored in the envelope is discharged. This is a mistake in the model, and it proves that the assumption during making a model is not valid. However, as this behavior happens only during summer and for two out of 24 hours, it is probably meaningless from the system's perspective.

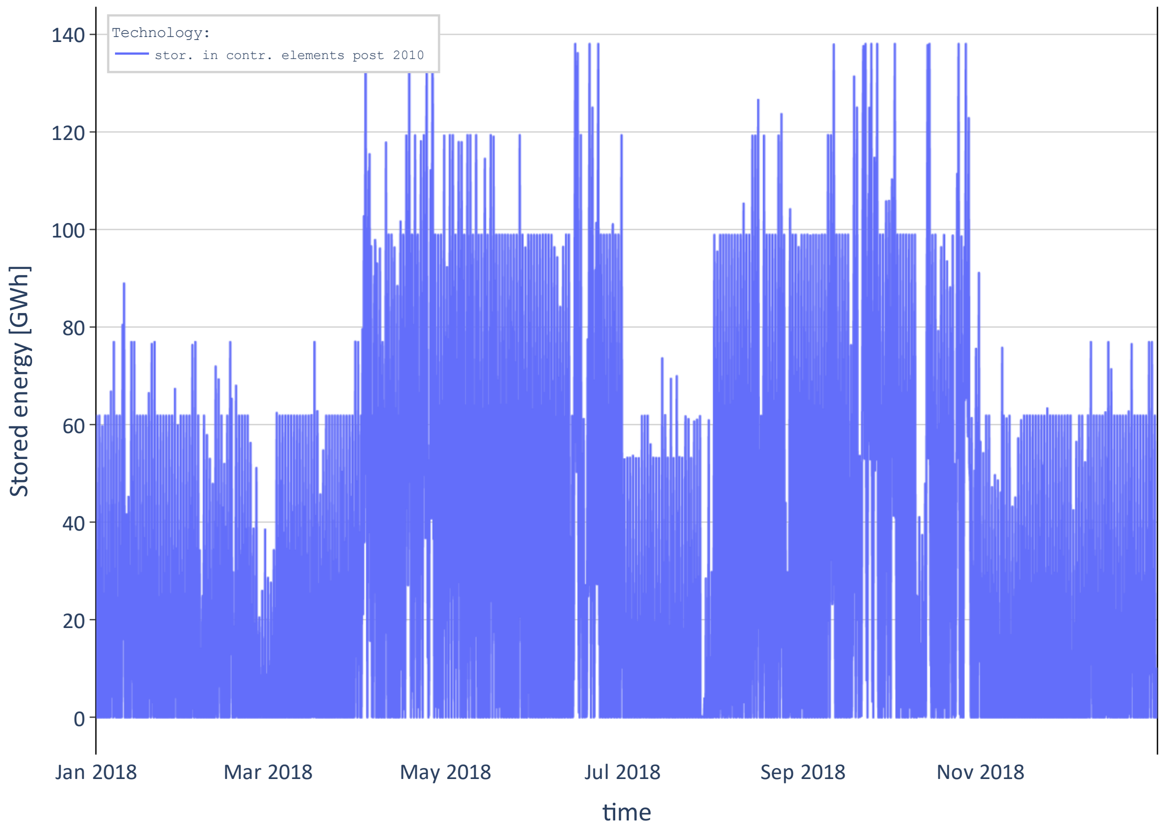

Figure 49. Yearly profile of storage capacity of buildings' envelope.

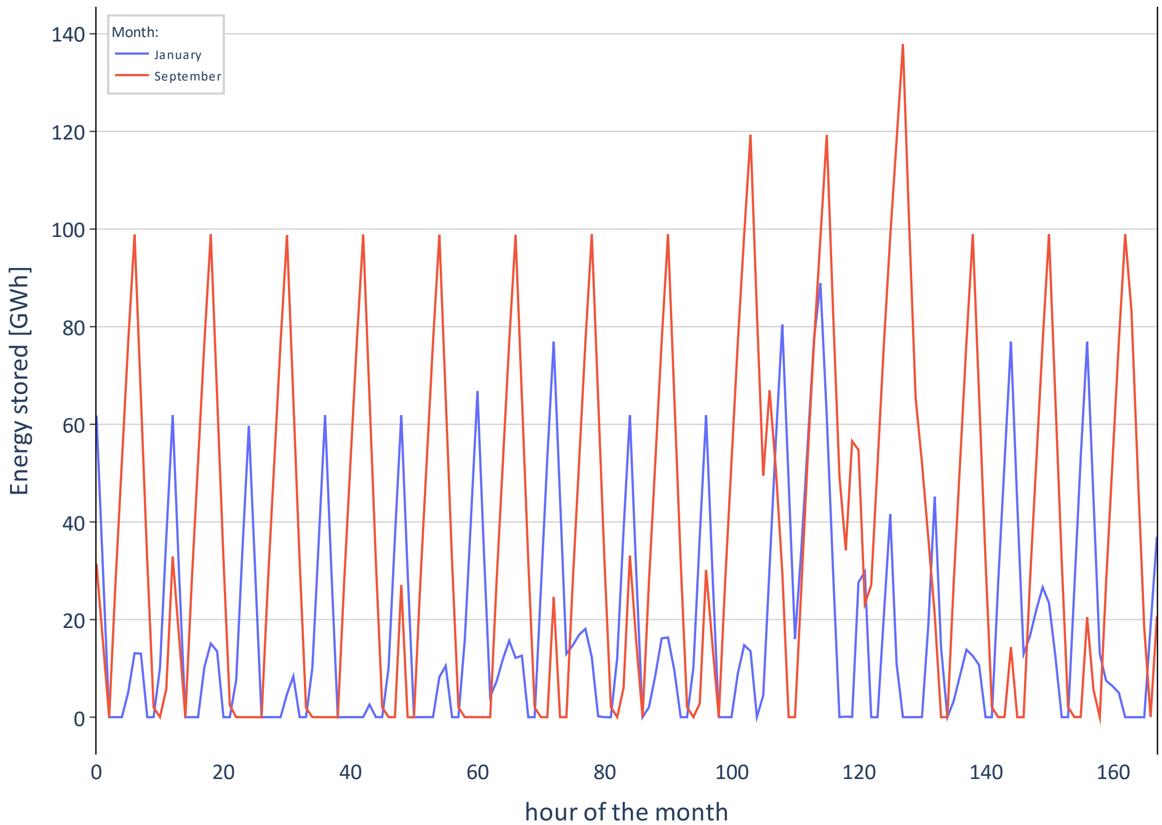

Figure 50. Profile of storage capacity of buildings' envelope in 2 weeks of January and September.

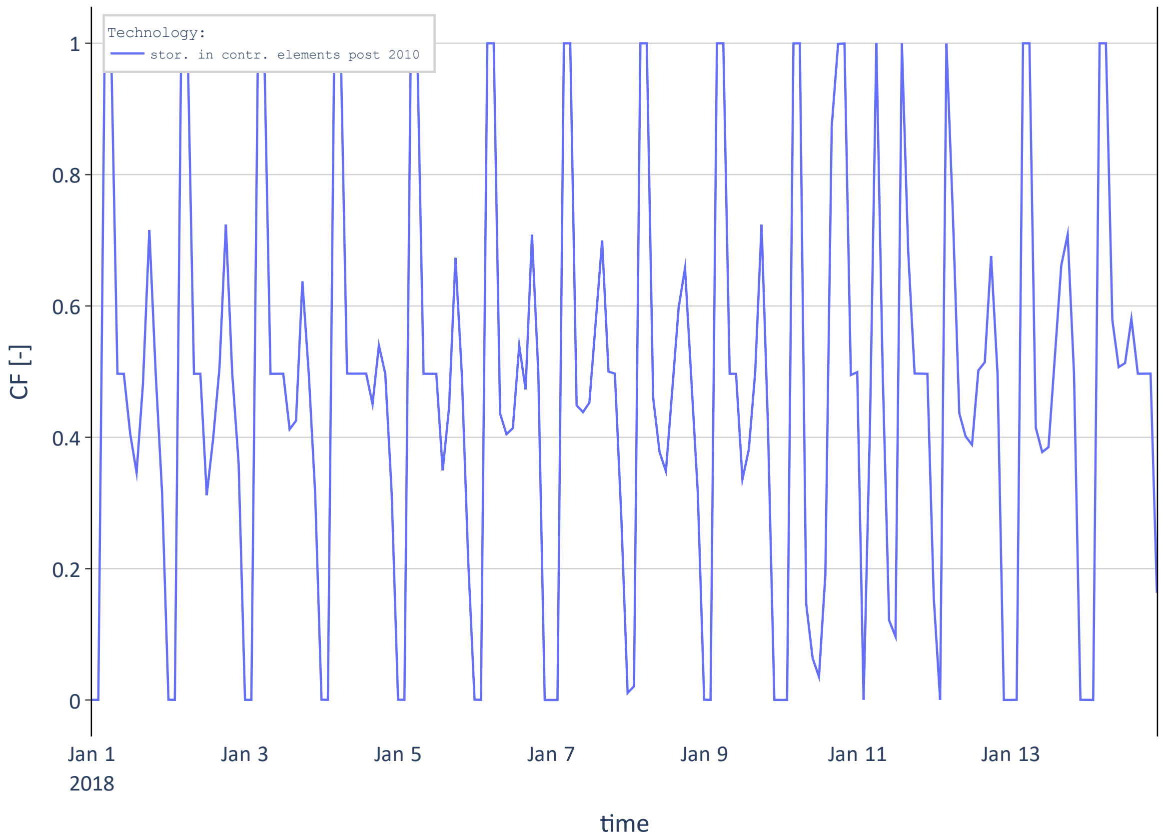

Figure 51. Profile of CF of buildings' envelope in 2 weeks of September.

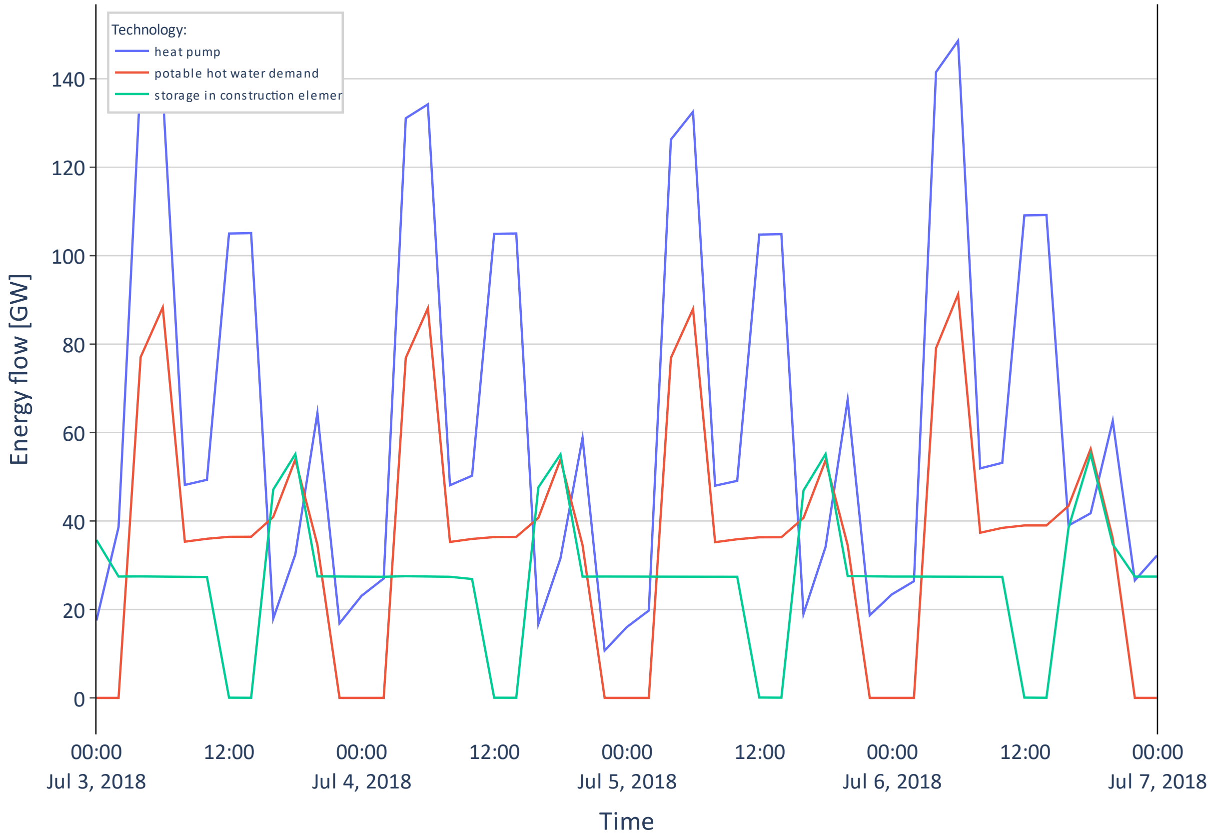

Figure 52. Profile of heat storage in construction, PHW, and HP showing an unphysical behavior of using thermal energy stored in construction elements for heating a PHW.

Appendix F

There was a plethora of changes made to the Calliope in order to model the impact of a building renovation on the energy system. To do this, a series of Python scripts were written that do all the required calculations and the conversion of an input (data in the form of comma-separated files or directly embedded in the script) into the output (CSV and yaml files). The summary of output files and their modifications is presented in Figure 53, where green color means that the file was modified and blue means that it was added.

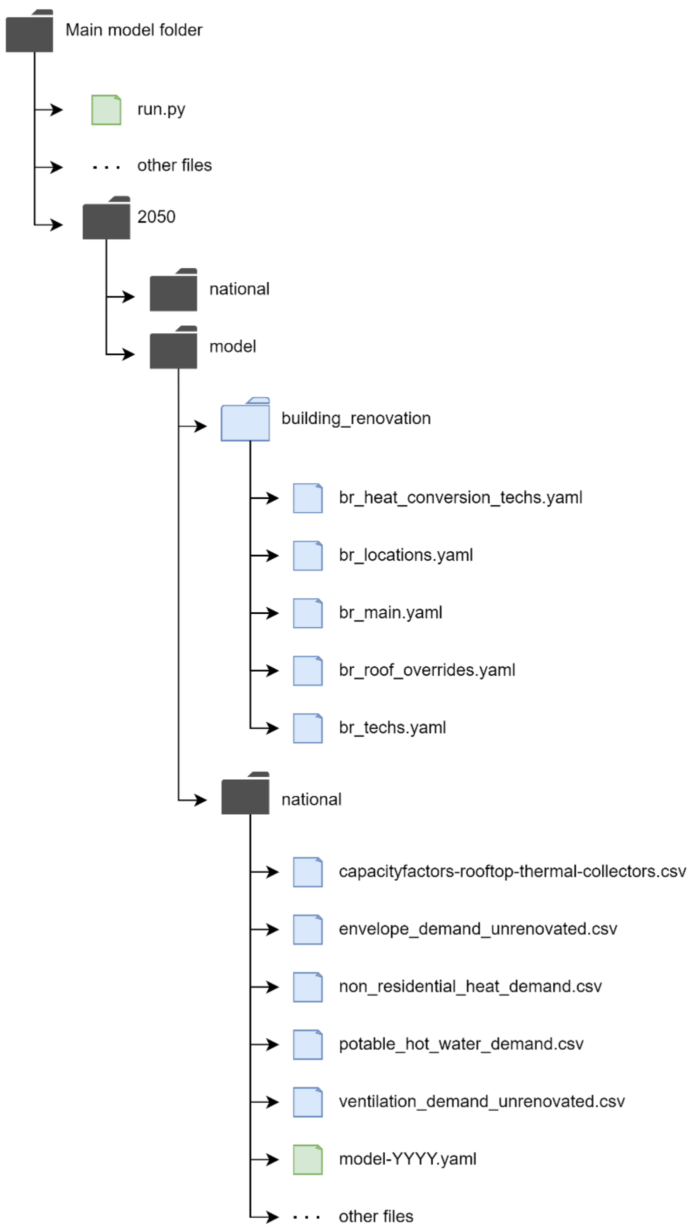

Figure 53. Structure of files.

There were 5 yaml files created:

- br_heat_conversion_techs.yaml contains all inputs regarding technologies that generate heat like heat pumps, solar thermal collectors, or methane boilers.
- br_roof_overrides.yaml defines overrides of the location's available area to reflect changes that were made by adding solar thermal collectors to the model. Furthermore, there are also group constraints that
- br_techs.yaml contains the definition of all envelope, ventilation, storage, and heat demand techs that were added.
- br_locations.yaml defines what heat-related technologies are available in each location including, location-specific costs and parameters like the efficiency of building archetypes and heat capacity of walls. Moreover, group constraints that ensure the correct functionality of envelope and ventilation techs are also there.
- br_mail.yaml which imports other files to the model and defines a scenario.

When it comes to CSV files 5 of them were created. Their titles are self-explanatory:

- capacityfactors-rooftop-thermal-collectors.csv
- envelope_demand_unrenovated.csv
- non_residential_heat_demand.csv
- potable_hot_water_demand.csv
- ventilation_demand_unrenovated.csv

Moreover, modifications to two existing files were made:

- run.py, where custom constraints related to the coupling of the envelope storage capacity with the archetype composition were added
- model-YYYY.yaml, where the location of new files was given so that they can be read by the model