MSc Program
Renewable Energy Systems

ACADEMY FOR CONTINUING EDUCATION

Assessment of data integration and data links between urban building energy models and urban heat planning tools - A case study on a district in the city of Kiel with a focus on the demand side using MITs UBEM and the Hotmaps toolbox

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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11946204

Vienna, 14.03.2022

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Affidavit

I, **JAN FLEMMING VOLLERSEN, B.SC.**, hereby declare

1. that I am the sole author of the present Master's Thesis, "ASSESSMENT OF DATA INTEGRATION AND DATA LINKS BETWEEN URBAN BUILDING ENERGY MODELS AND URBAN HEAT PLANNING TOOLS - A CASE STUDY ON A DISTRICT IN THE CITY OF KIEL WITH A FOCUS ON THE DEMAND SIDE USING MITS UBEM AND THE HOTMAPS TOOLBOX", 242 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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ACKNOWLEDGEMENTS

Energy demand and respective carbon dioxide emissions from the heating sector – including buildings – are amongst the most significant decarbonization challenges for a future energy system. Not least therefore, it deserves more attention and accelerated action than today.

During my studies at the Technical University of Vienna, as well as within the scope of my professional occupation I have been involved with the decarbonization of heating and was fortunate to meet the following special people, who have been central along my journey:

Marcus Hummel, M.Sc., who has been supervising this thesis. He provided me with excellent stimuli and advice on how to structure the content, conduct the analysis, and present the results of this thesis. By investing his valuable time into the supervision of this thesis, I enjoyed the privilege of having very focused discussions on the topic of heat planning and simulation, the status quo of the thesis, and received lots of encouragement. This was more than I could have expected as a student. I recognize the excellent supervision and would like to express my deepest gratefulness.

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Renewable energy systems (RES) class of 2020-2022. The submission of this thesis furthermore marks the in-official completion of my studies for an M.Sc. in Renewable Energy Systems at the Technical University of Vienna. It is a pleasure to be part of the group. I hope we will stay closely connected beyond the completion of the studies.

Michael Pomrehn and Jens Müller-Belau, my professional supervisors during the years of studies. Thank you for your unconditional encouragement and support. You thereby enabled me to follow my desire to continue my academic journey alongside my professional occupation.

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ABSTRACT

Heat provision for buildings notably contributes to global carbon dioxide emissions, especially in cities. Heat planning and simulations tools can help decision-makers to develop decarbonization roadmaps for the heating sector of their city. This motivates to conduct research in the field. Within the scope of the thesis two heat planning and simulation tools will be applied in a new integrated toolchain approach for the first time: The Hotmaps toolbox (development led by Technical University of Vienna (TUW)), and an Urban Building Energy Model (UBEM) (development led by Massachusetts Institute of Technology (MIT)). The integrated toolchain will consist of an UBEM on the demand side, as well as the Hotmaps toolbox on the supply side.

The research question of the thesis aims to identify impacts of model calibrations on heat demands, reductions of carbon emissions, heating costs, and carbon abatement costs. Alongside the integrated toolchain, four sensitivity blocks (1. Initial refurbishment status; 2. Refurbishment options; 3. Allocation of heat demand to hectares; 4. Supply-side calibrations) impacts will be assessed. The case study shall help future users to create an understanding of the consequences and limitations of different approaches to calibrate their models. Applied methodologies, input data, and model calibrations will be described in detail throughout the thesis.

The new approach of an integrated toolchain will be identified as feasible. Different approaches to initial model calibration will lead to 13.61% deviation in heat demands from UBEMs. This will cause knock-on-effects for applicable refurbishment options: Reductions of heat demand between refurbished versions of the initial models will vary from 1.48 to 32.68% depending on the refurbishment measures being employed. Accordingly, different supply options will be considered optimal, leading to deviations in total costs over lifetime (up to 12.67%), carbon emissions (up to 24.64%), and carbon abatement costs (up to 119.87%). Hence, by the knock-on-effects along the toolchain, initial calibrations of UBEM (Sensitivity block 1) will have the greatest impact on results. In general, the earlier along the integrated toolchain a variation, the more significant its impact on results will be. Therefore, future users should pay utmost attention to the initial calibration of their UBEM and try to verify it with metered or available data before proceeding. In conclusion, considering its high spatial granularity of results and substantial efforts required in the process, the integrated toolchain will be identified as a preferential approach for heat planning, when high levels of detail are required and sufficient data, time, and expertise are available.

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1 INTRODUCTION

This chapter will provide an overview of the relevance of heating of buildings for global decarbonization strategies, the role of heat planning and simulation tools, and the consequent motivation to research the topic. A research question will be presented, which is going to be followed up with an overview of the structure of the thesis.

1.1 Relevance

Energy demand and corresponding carbon emissions from the heating of buildings are the contexts of this thesis. Provision of heat for various sectors, such as industries, domestic hot water, and heating of buildings contribute to approximately 50% of the global final energy demand (International Energy Agency (IEA), 2021a: p. 1) and cause around 40% of the global carbon emissions (IEA, 2021b: p. 2). This holds for the European Union (European Commission (EUC), 2021a: p. 1). The heating of buildings accounts for approximately 46% of total heat demand globally (IEA, 2019: p. 129). Accordingly, almost 20% of global emissions are caused by the heating of buildings, making the sector one of the most emission-intensive (IEA, 2021c: p. 1). Furthermore, figure 1 and figure 2 show, that if emissions from electricity and heat generation are reallocated to consumption sectors, buildings account for approximately 28% of global carbon emissions annually, while sectors demanding heat for buildings increased their total final energy consumption by 39, respectively 80% since 1990.

GLOBAL CARBON EMISSIONS AND TOTAL FINAL ENERGY CONSUMPTION FROM BUILDINGS

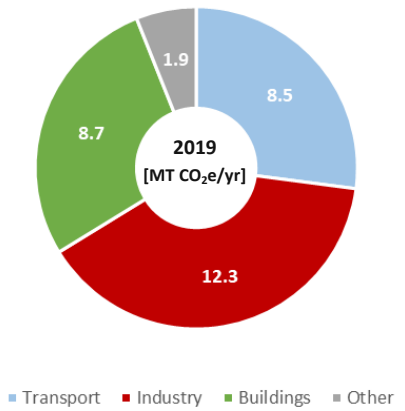

Figure 1: Global carbon emissions per sector.
Own approach based on IEA, 2021d: p. 1.

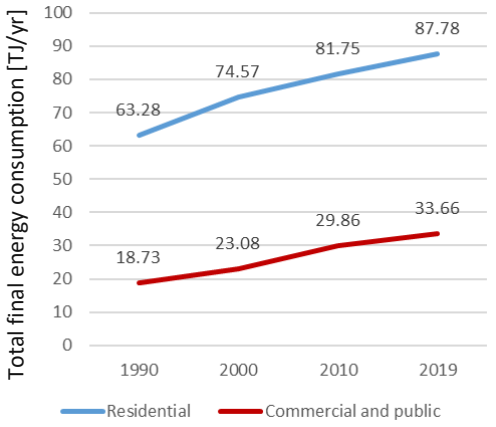

Figure 2: Global total final energy consumption per sector.
Own approach based on IEA, 2020: p. 2.

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In the future, heat demand for buildings is expected to grow in line with the global population (Lucon et al., 2014: p. 7), while global warming and energetic refurbishments of buildings are expected to reduce the demand simultaneously (Arent et al., 2014: pp. 5-8). Due to its widely decentral nature on a global level, the decarbonization of heat for buildings is considered as one of the most challenging items for global decarbonization strategies (Henry, Prasher, and Majumdar, 2020: p. 1). The sector needs decisive action on both, the demand and supply sides to comply with global ambitions for climate protection (The Royal Society, 2021: p. 2), which are described in greater detail in section 2.1. However, energy efficiency measures, such as energetic refurbishments are adopted at slow rates (Esser et al., 2019: p. 6). In Germany for example, the average rate of buildings being energetically refurbished remains at approximately 1% per annum (Deutsche Energie Agentur (DENA), 2019: p. 7).

Cities concentrate population and heat demand (UN, 2021: p. 1). Hence, they provide with low incremental system costs to accelerate the decarbonization of heating for the built environment on both, the demand- and the supply-side by economies of scale (Gurria, 2014: p. 3). On the demand side, today's building stocks hold the potential to integrate energy-efficient refurbishment measures (Friege and Chappin, 2014: p. 3), while on the supply side, there are opportunities to switch to less carbon-intensive energy carriers (Nijs, Tarvyday, and Toleikyte, 2021: p. 5), as well as either use and expand, or to develop efficient district heating networks (Navarro and Pablo, 2020: p. 3). When thinking about integrating efficiency measures and developing supply infrastructure, strategic decision-makers, be it city representatives, planning agencies, or investors benefit from urban heat planning and simulation tools (Büchele, Kranzl, and Hummel, 2019: p. 2). As a basis for evaluation, these tools can help them to gain a better understanding of decarbonization options being available (Ancelle, 2021: p. 1). Recognizing these opportunities, more effective and efficient systems can be designed (Joubert, 2019: p. 1).

1.2 Motivation

Within this thesis, consequences of data integration and data links for the option of an integrated application of two heat planning and simulation tools will be assessed. Given the above relevance of decarbonizing the building stock, there is intrinsic motivation to conduct research on the topic and thereby help develop effective and efficient decarbonization strategies for building stocks in cities.

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It is not the aim of this work to advocate for the integrated use of tools, as to be assessed in this case study, but to help users of heat planning and simulation tools to develop a better understanding of their options to apply tools either in an integrated fashion or in isolation. Their decisions should depend on the specific requirements of their use case always.

1.3 Research Question

As mentioned above, the thesis will focus on the assessment of an integrated toolchain option for heat planning and simulation, combining two existing tools. Therefore, the integrated toolchain will be applied to a case study district in the city of Kiel, Germany. The assessment will focus on the demand side using the Massachusetts Institute of Technology (MIT)´s Urban Building Energy Model (UBEM). For the supply side, the Hotmaps toolbox developed by a project team consisting of the Technical University of Vienna (TUW), e-think, Fraunhofer Institut für System- und Innovationsforschung (ISI), Haute Ecole Spécialisée de Suisse Occidentale (HES SO), University of Aalborg, EURAC Research, Centre for energy and municipal research (CREM), and Planergie will be applied.

It is of interest to future users to better understand the impacts of applying an integrated toolchain and respective model calibrations. As the calibration of the demand side in UBEM is assumed to create a significant impact on the results of the integrated model. Hence, as described above, it will be the focus of the assessment. However, there are further calibration options along with the integrated toolchain also creating an impact on results. Accordingly, also those will be assessed to allow future users to understand the consequences of model calibrations holistically. The findings shall help them to decide, how to calibrate their model, and whether for their specific use case they want to apply an integrated toolchain approach or not. Accordingly, the thesis aims to answer the following research question:

"*What impacts do sensitivities on the demand-side in UBEM and further alongside an integrated toolchain with the Hotmaps toolbox on the supply-side have on indicators of heat demand, reduction of carbon emissions, total costs of heating over the lifetime of energetic refurbishments, and carbon abatement costs?*"

1.4 Structure of the thesis

Following this introductory chapter, the thesis will be structured in 5 subsequent chapters, each including a set of subsections, as visualized by figure 3:

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Chapter 2	**Context**: Decarbonization ambitions and policies on various levels; Introduction to case study district
Chapter 3	**Methodology**: Description of UBEM and Hotmaps toolbox; Integrated toolchain; Process descriptions
Chapter 4	**Case study application**: Presentation of input data and calibration; Explanation of customized processes
Chapter 5	**Results**: Impact of sensitivities on demand side, supply side, and on feasibility of refurbishment options
Chapter 6	**Conclusions**: Recommendation for future users; Critical review of methodology and results; Outlook

Figure 3: Chapter-wise overview of the structure of the thesis. *Own approach.*

In chapter 2, the context of the case study will be outlined: This will include information on climate protection policies and strategies being adopted on various levels of decision-making in politics and public administration. Furthermore, the case study district in the city of Kiel, Germany, will be characterized in terms of its location, history, and building stock.

The scientific methodologies adopted within the scope of the thesis will be explained in chapter 3. This is going to include general descriptions of functionalities and capabilities for both heat planning and simulation tools being applied. Also, the block-wise structure of assessing sensitivities in model calibrations alongside the integrated toolchain will be introduced. Additionally, practical process descriptions of relevant tool applications will be provided.

Subsequently, in chapter 4, the integrated toolchain of UBEM and the Hotmaps toolbox will be applied to the case study district to identify the impact of sensitivities alongside the toolchain on the model. Relevant input data, customized processes, as well as calibrations for each sensitivity block, will be described accordingly.

Following the application of the case study, its results will be presented in chapter 5. Differences in demand and supply-side indicators are going to be identified, but not interpreted yet. Akin, the environmental and economic feasibility of various combinations of decarbonization measures will be indicated for all calibrations of sensitivity blocks.

In the final chapter 6, the results of the case study application from chapter 5 will be summarized and interpreted to answer the research question. In connection with a critical review of the methodology and the application of the assessment a recommendation for future users of heat planning and simulation tools, on when and how to adopt which approach to heat planning and simulation is going to be derived. Furthermore, in an outlook section, opportunities for ongoing research on the topic of integrated toolchains will be addressed.

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2 CONTEXT OF THE CASE STUDY

This chapter will provide context to the topic of global decarbonization ambitions including a special focus on the heating sector, as well as an introduction to the case study district, to which the integrated toolchain of UBEM and the Hotmaps toolbox will be applied in chapter 4.

2.1 Global climate protection policies and climate strategy of the city of Kiel

Climate change is one of the most pressing challenges in the 21st century (Wrigth, 2008: p. 1). In the Paris agreement, governments have committed action to – compared to pre-industrial levels – limit global warming to "well below 2 degrees, preferably to 1.5 degrees Celsius" (UN, 2015: p. 3). The agreement has been adopted by 196 countries at the 21st Conference of the Parties (COP21) in Paris in December 2015 (United Nations Framework Convention on Climate Change (UNFCCC), 2021: p. 1).

Among the parties to the agreement is the European Union (Official Journal of the European Union (EUJ), 2016: p. 3). Following the ratification of the agreement, it has developed its European "Green Deal" strategy (EUC), 2020a: p. 2) as its enhanced joint National Determined Contribution (NDC) to the agreement, aiming at making Europe the first carbon-neutral continent by 2050 (EUC, 2020b: p. 1). For 2030, a reduction of annual carbon emissions by -55% compared to 1990 levels is targeted (EUC, 2020c: p. 2). Member states are required to adjust their national energy and climate protection policies according to the enhanced versions of European mechanisms and directives, including the "European Union Emission Trading System" (EU ETS), requiring the industry, energy and aviation sectors to trade emission allowances (EUC, 2018: p. 1), the "Effort Sharing Mechanism", covering remaining energy consumption sectors (EUC, 2021b: pp. 2-4), the "Renewable Energy Directive", requiring at least 40% of energy consumption from renewable energies by 2030 (EUC, 2021c: pp. 1-2), the "Energy Efficiency Directive", providing with minimum efficiency thresholds of energy conversion technologies (EUC, 2021d: p. 1), the "Energy Taxation Directive", defining principles for energy taxation schemes (EUC, 2021e: pp. 1-3), as well as a "Carbon Border Adjustment Mechanism", which will adjust prices of imported products to align with local market conditions including the carbon pricing mechanisms mentioned above (EUC, 2021f: pp. 2-4).

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The city of Kiel, in which the case study district of this thesis is located, is a German city (Association of German cities (AGC), 2021: p. 105). Germany, following the adoption of the Paris Agreement by the EU, has amended its climate protection policies several times: Initially, Germany was aiming at a range of carbon reduction between 80% and 95% for 2050 and 55% for 2030, both compared to 1990 levels (German Federal Ministry for the Environment (GFME), 2016: pp. 2-4). The need to accelerate the implementation of Germany´s energy transition strategy to still achieve its ambition for 2030 was recognized by Germany´s federal government in 2019. The consequent "Climate Package for 2030" (GFME, 2019) included various measures, such as fixed carbon budgets per sector for all years until 2030 (German Federal Ministry for Justice and Consumer Protection (GFMJ), 2019a: p. 10), a carbon pricing scheme for sectors, which are not in the scope of the European carbon trading scheme already (GFMJ, 2019b: p. 7), as well as concrete plans for an exit from coal-powered electricity generation by 2038 (GFMJ, 2020: p 7). All are enabled by increased growth ambitions for renewable electricity generation capacities (German Federal Ministry for Economic Affairs and Climate Action (GFMEC), 2019: p. 2).

In 2020, in response to the requirement for EU member states to adjust their national climate protection policies according to the EU´s "Green Deal" strategy, the German federal government increased its ambition to achieve carbon neutrality by 2050 (GFME, 2020: p. 1). Afterward, however, the EU announced more detailed information on its ambition to become carbon neutral by 2050 (EUC, 2020d: p. 3), putting pressure on Germany to overachieve the EU´s ambition allowing for economically weaker member states to underachieve and thereby avoid economic hardships caused by high costs of transition (Government of the Federal Republic of Germany (GFRG), 2021: p. 1). Additionally, Germany´s constitutional court sentenced the federal government to define more proactive decarbonization plans for the period until 2030 and more concrete plans for the period until 2040 (German Constitutional Court (GCC), 2021: p. 8). Hence, the government has announced an even more ambitious climate protection policy, aiming to achieve carbon neutrality by 2045 (German Federal Law Gazette (GFLG), 2021: p. 1). For 2030, instead of the initial target reduction of annual carbon emissions by 55%, now 65% are required. By 2040 88% reduction compared to 1990 levels shall be achieved (GFME, 2021: p. 5).

The case study city Kiel is the capital of the federal state of Schleswig-Holstein, Germany´s most northern federal state (German Federal Court (GFC), 2021: p. 1). Schleswig-Holstein is fortunate to be located between the North- and Baltic Sea,

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implicating excellent conditions for wind power generation (Schleswig-Holstein Federal State Government (SHG), 2019: p. 2). On a statistical basis, renewables supplied approximately 160% of local electricity demand in 2020 (Statistik Nord, 2021a: p. 1) and 19.2% of local heat demand in 2019 (Schleswig-Holstein Federal State Parliament (SHP), 2021: p. 10). According to its progress on the energy transition and further potential (Schleswig-Holstein Ministry for the Energy Transition, Agriculture, Environmental Affairs, Nature, and Digitalization (SHME), 2021: pp. 7-8), Schleswig-Holstein has adapted its climate protection policy to align with national ambitions of carbon neutrality by 2045 recently (Schleswig-Holstein Ministry for the Interior (SHMI), 2021: p. 31).

The city itself is even more ambitious regarding its climate protection policies. It was one of the first cities in Germany to declare a “State of climate emergency” in 2019 (Kiel, 2019a: p. 1). It aims at achieving climate neutrality “well before 2050” (Kiel, 2020a: p. 1). Technically, this implies a reduction of carbon emissions by at least 95% (Kiel, 2019b: p. 1). A local climate strategy has been developed, including measures for various energy demand sectors within the city (Beer et al., 2017). The building sector accounts for 37% of final energy consumption and 36% of carbon emissions in the city – above global averages – and therefore offers significant potential for reduction (Kiel, 2019c: p. 1).

The city´s government introduced subsidy schemes for energetic consultancies, energetic refurbishments, and awareness campaigns (Kiel, 2019b: p. 2) in addition to measures on European (EUC, 2021g; EUC, 2021h; European Investment Bank (EUIB), 2021a; EUIB, 2021b), federal (GFMEC, 2021a; GFMEC, 2021b; GFMEC 2021c), and federal state (Investitionsbank Schleswig-Holstein (IBSH), 2021a; IBSH, 2021b) level. The local environmental protection agency has defined seven pilot districts to demonstrate climate protection measures for buildings on selected objects (Kiel, 2021a: p. 1). For these pilot districts, reports on the building stock, and potential decarbonization measures are available (Zentrum für Energie, Bauen, Architektur und Umwelt GmbH (ZEBAU), Averdung, and Harten, 2021; complan Kommunalberatung GmbH (Complan), 2013; Kiel, 2017; ZEBAU, 2017; etc.). Furthermore, the city has been helping building owners to finance demonstration projects for energetic refurbishments and other energy efficiency measures in the building sector (Kiel, 2020b: p. 4).

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In line with the local climate protection strategy, 95% reduction of carbon emissions from heat provision will be considered as benchmarks for the case study in chapter 4.

2.2 Case study district within the city of Kiel

Kiel Gaarden Ost is a district of the city of Kiel (Kiel, 2020c: p. 18), of which a part is considered as a case study district for this thesis. The case study part of Gaarden Ost is one of the pilot districts being described in the previous section (Complan, 2018). Kiel is located at the Baltic Sea. It provides a home to approximately 248,000 inhabitants (Kiel, 2020c: p. 25). Population growth is in stagnation currently (Statistik Nord, 2021b: p. 4).

Its economy is highly focussed on public and commercial services, as well as manufacturing industries (Kiel, 2020c: p. 165). The total number of students being enrolled in one of Kiel´s universities is higher than 27,000, making Kiel a local centre for innovation and research (Christian-Albrechts-Universität (CAU), 2020: p. 1). Figure 4 shows the Kiel Gaarden Ost from a south-eastern flight perspective and frames the case study area to be considered in yellow. Characteristic locations are indicated by white text layers.

Figure 4: Flight perspective on the case study district Kiel Gaarden Ost. *Own approach based on Google, 2021.*

The city, as well as the case study district, have a multifaceted history: Kiel was founded by the Earl of Holstein in the 13th century (Junge, 2021a: p. 1). It joined the northern European trade union “Hanse” (Schleswig-Holstein State Chancellery (SHSC), 2021: p. 2), but due to the direct influence of the earl, it did not emerge as a major centre of free trade within the bound of mostly free cities and was expelled in the 16th century (Junghölter, 2016: p. 14). The King of Denmark, who also was Earl of Holstein in the 16th century, changed the division of earl-ships in Schleswig and Holstein (Lohmeier, 2021, p. 3). Thereafter, Kiel belonged to the earlship of

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Schleswig-Holstein-Gottorf and became its capital in the 18th century (Junge, 2021a: p. 2). In the 17th century, the University of Kiel was founded (Jahnke, 2021: p. 2) and has contributed approximately 10% of Kiel´s population ever since. The son of the Earl, Peter, later became a Russian czar (Britannica, 2021: p. 1). His widow Catherine the Great, returned the earl-ship to Denmark (Junge, Lange, and Lorenzen-Schmidt, 2021b: p. 3), where it remained until a coalition of Prussian and Austrian troops invaded Denmark in 1864 (Junge, 2021b: p. 1).

Subsequently, the Prussian king ordered his Baltic fleet to be moved from Danzig to Kiel, marking the beginning of Kiel´s position as the centre of the German navy in the 19th and 20th centuries (Kiel, 2021b: p. 1). Especially the German Emperor Wilhelm II., who was building the German navy to compete with the British in world war I was supportive of Kiel´s development into a major German city (Basting, 2017: p. 3). Its population rose quickly from around 20,000 in 1865 to 220,000 in 1910 (Kiel, 2020c: p. 26). Especially, Gaarden Ost, which is located on the eastern bank of the Kiel Bay, developed from a fisher´s village into a densely populated district for workers being employed at one of the many new shipyards on the eastern bayside (Projektgesellschaft Kiel-Gaarden GmbH (PKGG), 2020: p. 2).

Gaarden´s population rose from well below 3,000 inhabitants in 1870 to more than 30,000 in 1910. Accordingly, 90% share of the built environment was constructed before 1918 at the time, the second world war began in 1939. During the war, Kiel´s population rose to a maximum of above 300,000 people (Kiel, 2020c: p. 25), as many were ordered to work in the shipyards and for the navy.

At the end of the war, approximately 80% of Kiel´s building stock was destroyed by air raids (Geckeler, 2005: p. 2). Because of its proximity to the shipyards, which were strategic targets of the air raids, and the allies' tactic to demoralize the German workforce by air-raiding residential areas (Brühns, 2021: p. 3), Gaarden Ost was destroyed during the last years of the war. The population shrunk immensely (Kiel, 2020c: p. 26).

However, following the western allies had restructured the economy of Western Germany after the war, the shipyards were competitive again and Kiel, as well as Gaarden, began to re-develop (Junge, 2021a: p. 4). During the 1950es and 1960es a sharp recovery of the maritime sector in Kiel and governmental support schemes to rebuild destroyed districts (Heidenfelder, 2020: p. 1), led to a dominance of gross floor area from this age classes in today´s building stock of Kiel Gaarden Ost (Complan,

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2013: p. 41). Also, during this period, the technical faculty of Kiel´s university, a residential tower in the north, as well as the establishment of a major logistics centre of the German Postal Service were built within the case study district.

In conjunction with growing global competition for the shipyards in an increasingly globalized world market (Deutsches Schifffahrtsmuseum (DSM), 2021: p.3), local employment sharply shrunk from approximately 12,000 jobs in 1980 to only 5,595 in 2020 (Kiel, 2020c: p. 154). However, the population of the district remained constant at around 30,000, of which approximately 18,650 are living in the sub-district of Gaarden-Ost (Kiel, 2020c: p. 33). This is because, despite the loss of the working population, the low-priced housing market in the district next to the city centre (Kiel, 2020d: p. 23) has attracted social welfare recipients and immigrants. In 2020, approximately 2,340 residents were receiving their income from governmental social welfare programs, which causes the highest unemployment rate for a district in Kiel (Kiel, 2020c: p. 147), and more than 40% of the population had a migration background. In consequence, the city has been subsidizing the urban development in the district since the early 2000es (PKGG, 2021: p.1).

Unfortunately, the district still has the status of a deprived area with cultural conflicts and criminalization rates significantly above the local average, (Kiel, 2020c: p. 222). However, in recent years, new cruise ship terminals and office building developments on the ground of former shipyards, as well as a re-design of the central Vineta square led to new perspectives for the district´s development (Kiel, 2020e).

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3 METHODICAL APPROACH

This chapter will provide general descriptions of the heat planning and simulation tools being applied for this case study. This is going to include their key functionalities and capabilities. Consequently, the block-wise sensitivity assessment alongside the integrated toolchain of both tools will be explained and followed up with practical process descriptions.

3.1 Selected urban heat planning and simulation tools

Digital urban heat planning and simulation tools can contribute to accelerating the decarbonization of urban heating systems by identifying optimal and synergetic combinations of measures (Giovannini, 2020: p. 1). While in academia engineering models aiming to estimate building energy consumption based on building information, such as size, shapes, and constructions exist since the 1970es (Mills, 2004: pp. 866-867), applications of tools for multiple buildings only have emerged during recent years (Reinhart and Davila, 2016: p. 198).

Various approaches to heat simulation and planning for individual and groups of buildings exist, which can be distinguished by their scope of application: Their focus is either on the demand- or the supply-side or both. The following table 1 provides an overview of a selection of existing tools.

Table 1: Overview of existing heat planning and simulation tools. *Own approach based on Ang et al., 2021; Malhotra et al., 2021; Wang et al., 2018; Chen, Hong, and Piette, 2017; Remmen et al., 2018; Nouven et al., 2015; Pezzutto et al., 2019; Sonvilla, Lopez, and Torres, 2021; SOPHENA, 2020. With abbreviation: INSEL = Integrated Simulation Environment Language (Schumacher, 2021).*

Focus: Demand side		
Tool name	**Description**	**Availibility**
UBEM	Web based; Large-scale application; Simulation based on energy plus	Open source
CESAR	Software; Multiple buildings; Simulation based on energy plus	Restricted
CityBES	Web-based; Large-scale for US; Simulation based on energy plus	Open source
TEASER	Web-based; Multiple buildings; Simulation based on modelica	Open source
SimStadt	Software; Multiple buildings; Simulation based on INSEL	Restricted
Focus: Supply side		
Tool name	**Description**	**Availability**
Hotmaps toolbox	Web based; Default demand indications available	Open source
THERMOS	Web based; Demand data required	Open source
SOPHENA	Software; Demand data required	Registration required

UBEM allows for large-scale heat demand simulations based on the commonly used simulation algorithm of energy plus. The Hotmaps toolbox allows for supply-side simulations based on existing demand data. Accordingly, both tools feature the most attractive functionalities, are web-based and are freely available. Users are likely to

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choose these tools for the heat planning and simulation exercises in their case study area.

In line with the research question presented in chapter 1, it is of interest to assess the consequences of integration between heat planning and simulation tools. Hence, both tools, integrated into a joint toolchain, will be applied to the case study district within the scope of this thesis to assess data links and options for data integration between different heat planning and simulations tools.

3.1.1 Demand-side: Urban building energy model (UBEM)

Urban Building Energy Models are bottom-up simulation tools allowing for the evaluation of strategic decarbonization options for built environments in cities (Ang et al., 2021: p. 1). Extending the scope of individual building simulation models to an urban scale was first realized by Reinhart, Dogan, Jakubiec, Rahka, and Sang in 2013 via the development of the urban modeling interface (UMI) (Reinhart et al., 2013: pp. 478-481). UBEMs are a feature of the UMI environment. UMI utilizes the computer-aided design and drafting (CAD) software Rhinoceros (McNeel, 2021: p. 1) to visualize three-dimensional (3D) models, including simulation results.

In line with a growing societal interest in decarbonization and the inherent importance of the urban building sector as described in section 1.1, led to a growing interest in UBEMs by both, academia, and applicants. Accordingly, the number of available UBEM variants was expanded during recent years (Ang, Berzolla, and Reinhart, 2020: pp. 4-6). For these variants, many add-ons and features for additional simulation aspects have been developed. These include the “shoeboxer algorithm”, which is essential in reducing computational capacities required to allow for larger building sets to be processed by the simulation algorithms. It is creating smaller size representations of building configurations as inputs for the algorithms while scaling results back to fit the initial model size (Dogan and Reinhart, 2017: pp. 141-147). Large-scale demonstrations, including several thousand buildings, were realized during recent years (Davila, Reinhart, and Bemis, 2016; Buckley et al., 2021). The latest feature is the ubem.io website, intended to scale access to, and application of UBEM globally, helping users to design decarbonization strategies for their use case areas (Ang et al., 2021: p. 4).

While the application of ubem.io´s frontend to create UMI files will be described in more detail in section 3.3, a basic understanding of scripts and algorithms being employed in the backend of UBEM is necessary for users to follow the application of

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UBEM to the case study district in chapter 4. Hence, a brief overview shall be presented below, while for a more detailed understanding the paper “UBEM.io: A web-based framework to rapidly generate urban building energy models for carbon reduction technology pathways” by Ang et al. is advisable (Ang et al., 2021). Figure 5 provides a schematic overview of the functionalities of an UBEM.

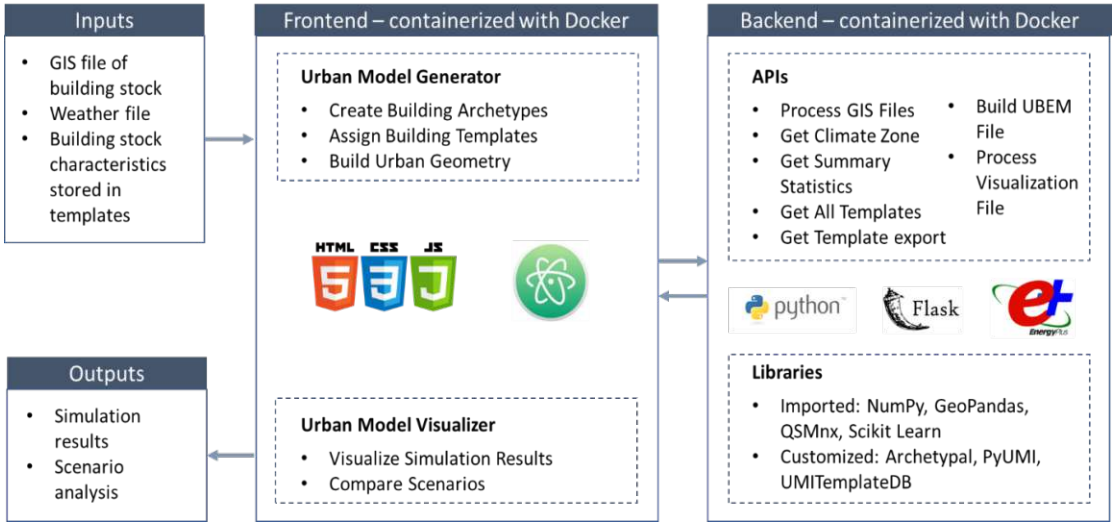

Figure 5: Schematic overview of front- end back end functionalities of UBEM. *Own visual based on Ang et al., 2021: p. 5.*

There are three necessary inputs to an UBEM: Geo-data as shapefile for the building stock, a weather file for the location of the use case, and information on the building stock´s energetic characteristics (Ang, Berzolla, and Reinhart, 2020: p. 4).

The operational framework of ubem.io is split into a user-interfacing frontend and a calculating backend. Both of which are containerized using Docker container solutions (Docker, 2021). The backend utilizes flask (Pallets, 2010), a flexible and scalable python web-server interface (Ang et al., 2021: p. 4) to employ the energy plus algorithm, a commonly used (see table 1) energy buildings energy simulation algorithm developed for the United States Department of Energy ((USDOE), 2021a: pp. 11-14).

To assess the energy demand of buildings being in scope of the respective analysis the energy plus algorithm by USDOE considers various input parameters. These include the temperature conditions present in the environment provided by a weather file, the aspired temperature levels inside the buildings, and information on the building envelope. The central calculations performed by the algorithm to assess the respective energy demand will be represented by the following equations.

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Via equation 1 below energy stored within the air mass inside a building is defined, considering factors such as internal loads, convective heat transfers from building surfaces, infiltration of outside air, mixing of internal air, and the loads of the heating system employed.

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i \left(T_{si} - T_z\right) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p \left(T_{zi} - T_z\right) + \dot{m}_{\inf} C_p \left(T_\infty - T_z\right) + \dot{Q}_{sys} \quad \textbf{[1]}$$

With:

$C_z \frac{dT_z}{dt}$ = *Energy stored within the air mass of a building [kW]*

$\sum_{i=1}^{N_{sl}} \dot{Q}_i$ = *Sum of the convective internal loads [kW]*

$\sum_{i=1}^{N_{surfaces}} h_i A_i \left(T_{si} - T_z\right)$ = *Convective heat transfers from building´s surfaces [kW]*

$\dot{m}_{\inf} C_p \left(T_\infty - T_z\right)$ = *Heat transfer by infiltration of air from outside of the building [kW]*

$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p \left(T_{zi} - T_z\right)$ = *Heat transfer by internal mixing of air masses [kW]*

Q_{sus} = *Heating system loads [kW]*

Source: USDOE, 2021b: pp. 26-27.

Equation 1 describes an equilibrium state, a heat balance, which will always be maintained (USDOE, 2021b: p. 26). Depending on the strength of the influencing factors, energy stored in the air mass - hence temperatures - inside a building, are either increased or decreased. Provided the condition of a certain air temperature within the buildings to be constantly maintained, as defined by the building templates (database containing the respective parametrization of the UBEM. See section 3.3.2 for more detail), alternating influence of variations in temperatures outside of the building via convection, infiltration, and mixing of air need to be balanced by the heating system. For example, if the difference between the pre-defined inside temperature and the actual outside temperature increases, the heating system must provide more energy in form of heat to be stored in the internal air mass - or less, if the difference decreases. Hence, loads of the heating system can be determined by reorganizing equation 1 above to solve for heating system loads in equation 2:

$$-\dot{Q}_{sys} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i \left(T_{si} - T_z\right) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p \left(T_{zi} - T_z\right) + \dot{m}_{\inf} C_p \left(T_\infty - T_z\right) \quad \textbf{[2]}$$

With the same symbols as in equation 1; Source: USDOE, 2021b: p. 27.

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Put differently, the load of the heating system can be expressed as the difference between the enthalpy of heat supply to the building and the enthalpy of the air mass leaving the building (USDOE, 2021b: p. 27):

$$\dot{Q}_{sys} = \dot{m}_{sys} C_p \left(T_{\sup} - T_z\right) \quad \textbf{[3]}$$

With the same symbols as in equation 1; Source: USDOE, 2021b: p. 27.

Based on these relationships the energy demand for heating the built environment of the use case area at any given time with respective temperature conditions outside can be determined. To derive the annual heat demand per building, its heating system´s loads for all hours in the year needs to be summed, as per equation 4. To compute the total annual heat demand for the entire use case area of the UBEM application, the individual total annual heat demands per building need to be summed, as in equation 5 below:

$$THD_b = \sum_{n=1}^{8760} Q_{sys} \quad \textbf{[4]}$$

With: THD_b = Total annual heating demand of the building [kWh/yr];

Q_{sys} = Heating system loads per hour [kW]; n = unit of time [h/yr];

Source: Own approach based on: SDL, 2021: p. 2.

$$THD_{uca} = \sum THD_b \quad \textbf{[5]}$$

With: THD_{uca} = Total annual heating demand of the use case area [kWh/yr];

THD_b = Total annual heat demand per building [kWh/yr];

Source: Own approach based on: SDL, 2021: p. 2.

As mentioned above, the results of the simulation of heat demands via the energy plus algorithm and their subsequent aggregation to total annual heat demands per building and use case area in UBEM are highly sensitive to input parameters provided via so-called building templates, which will be described in greater detail in section 3.3.2). This allows for quick and precise evaluation of different building parameters.

Within the backend container of UBEM´s operational framework, core processes of UBEM are facilitated using imported, as well as custom phyton packages. Imported libraries are publicly available, including “NumPy” (numerical arrays (NumPy, 2021)), “GeoPandas” (geospatial analysis (GeoPandas, 2021)), “OSMnx” (analysis of street-networks from OpenStreetMap (Boeing, 2017; Boeing, 2021)), “Scikit learn”

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(predictive analysis (Scikit learn, 2021)), and options for further extensions. Custom libraries include “Archetypal” (Python library for building archetypes (Duchesne and Leroy, 2020)), “PyUMI” (customized library), “UMITemplateDB” (Database of existing templates (Duchesne, 2021)), and options to include further functionalities.

Core backend processes include “Process GIS Files” (Aligns coordinate reference systems of geo-data input for use in a Geographic information system (GIS) – in this case the World Geodetic System 84 standard (GIS, 2021)), “Get Climate Zone” (returns climate zones based on coordinates of geodata coordinates), “Get Summary Statistics” (Summarizes the building information form the geo-data input in JSON-file format for later frontend representations), “Get All Templates” (Integrates information from building templates (see section 3.2) for energy simulations), “Get Template Export” (Enables users to export template libraries to employ these for other models), and “Build UBEM File” (Builds geometries from geo-data input and integrates information from template assignments for simulations) (Ang et al., 2021: pp. 4-5). Results of backend processes are communicated to the frontend via an Application Programming Interface (API), offering optionality for direct queries.

The frontend is split into two user interfaces: There is the “Urban Model Generator” (ubem.io, 2021a) by which UMI files for further simulation in Rhinoceros can be created. It will be practically described in section 3.3.1. In addition, there is the “Urban Model” visualizer (ubem.io, 2021b), which offers to visualize simulation results in connection to surrounding geographical information as available on default maps, such as OpenStreetMap (OSM) (OpenStreetMap Foundation (OSMF), 2021).

Users can simulate various scenarios of building refurbishment options and compare results of heat demand per building and on an absolute district scale. All results from UBEM simulations are available as downloads in a comma-separated-value (CSV) file-format and can be considered as inputs for supply-side heat assessment tools.

Furthermore, the developers of the UMI environment are working on extending its capabilities to the energy supply-side: A plugin simulates supply plant options (Duchesne et al., 2018).

3.1.2 Supply-side: Hotmaps toolbox

The Hotmaps toolbox is an open-source heat planning and simulation tool (Djørup, Bertelsen, Mathiesen, 2019: p. 3) providing a broad variety of calculation modules to simulate heating supply options for default or customized heat demands (Energy Cities (EC), 2020: p. 5). However, it is important to note, that Hotmaps – in contrast

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to the title of this section and its application within the scope of the thesis – is not focussed on the supply side only, but provides default perspectives on heat demand for the former EU28+3 states (Müller et al., 2019: p. 1).

In section 3.1.3, an integrated toolchain option of Hotmaps and UBEM will be introduced. To allow for a better understanding of the differences between bottom-up approaches to the demand side, as considered by UBEM, and top-down approaches, as considered by the toolbox, Hotmaps´ top-down approach to the demand side will be explained in the following paragraphs based on Müller et al., 2019 and Pezzutto et al., 2019.

For the top-down approach, information has been derived from building datasets being publicly available on various levels of public administration (Fallahnejad, 2019a). To allow for application on various levels of spatial resolution, data have been kept available on different degrees of aggregation. These range from a national level, Nomenclature of units for territorial statistics (NUTS) level 0, down to individual hectare scale (Pezzutto et al., 2019: p. 17). The allocation of data to lower levels of geography is described by Müller, Hummel, Kranzl, Fallahnejad and Büchele (Müller et al., 2019: pp. 4-14) and visualized in figure 6.

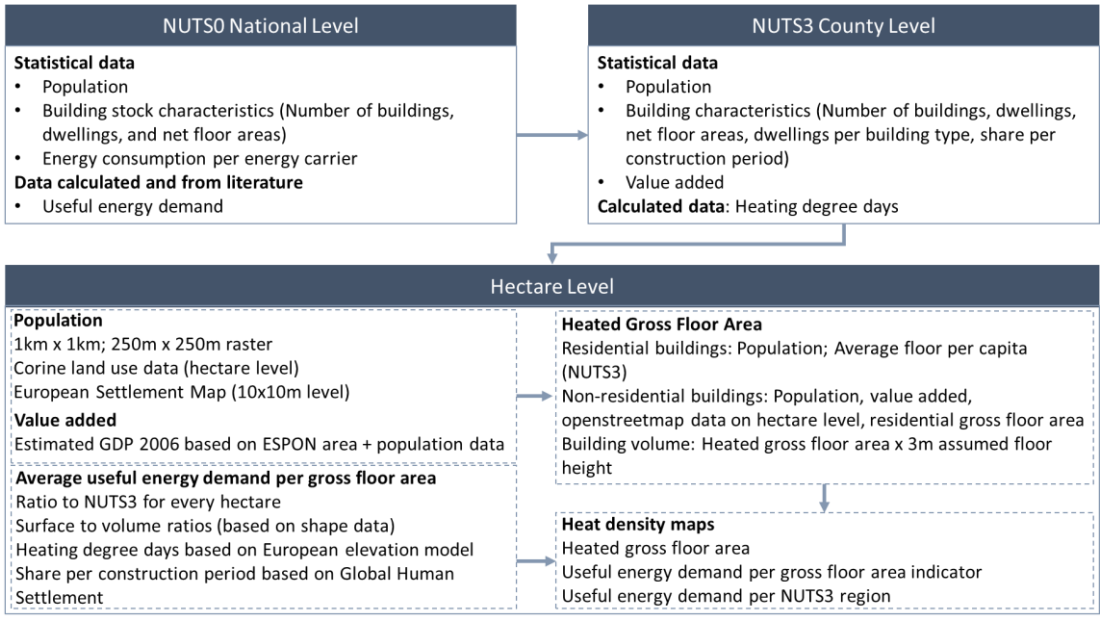

Figure 6: Overview of heat demand estimation by the Hotmaps toolbox. *Own visual based on Müller et al., 2019: p. 4.*

Initially, on the national level, statistical data on population, building stock characteristics, such as numbers of buildings, dwellings, and net floor areas (Statistical Office of the European Communities (Eurostat), 2021), as well as energy

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consumption per energy carrier in the heating sector (Fleiter et al., 2016) are considered to estimate useful energy demand per NUTS0 area.

These results are refined and allocated to lower levels of areal aggregation. Again, the allocation is oriented at respective levels of public administration in the EU28. NUTS3 equals the level of provincial districts or counties. Refinement of data is conducted by integrating additional statistics from the ESPON Locate report (Schremmer et al., 2017). The report offers overviews of shares of buildings built in certain construction periods of the total building stock and, in combination with further data (Eurostat, 2013; Haylock et al., 2011), allows for the calculation of heating degree days per area. Furthermore, an indication of economic value added is integrated into the dataset based on Eurostat, 2016.

For finer granulation of data down to the hectare level, further sets of data are involved, including statistics of settlement and useful energy demand in finer areal resolution. Population data is the basis to estimate useful energy demand from heating for local building stock per hectare. The more people live in an area the more heat demand is allocated to the area (Pezzutto et al., 2019: p.34). Hence, additional population statistics on a 1kmx1km scale (Gallego, 2012), a 250x250m scale (Joint Research Centre (JRC), 2015), from the “European Settlement Map” on a 10x10m scale (JRC, 2017), as well as the “Corine land use data” (European Environmental Agency (EEA), 2012) on hectare scale are integrated into the model. However, to avoid overestimations in rural areas, a weight factor is applied (Müller et al., 2019: p. 6). Data on economic value added is refined by the EPSON Locate report again.

Subsequently, average floor areas per person for residential and value-added for non-residential buildings on a NUTS3 level, as well as OpenStreetMap data (OSMF, 2018) are considered to estimate heated gross floor areas per hectare (Müller et al., 2019: pp. 8-11). To further estimate useful energy demand for these gross floor areas per hectare, the indicator of average useful heat demand per gross floor area needs to be defined. This is a numerical ratio between the average value for useful energy demand on the NUTS3 level and the individual hectare (Pezzutto et al., 2019: p. 40). Three inputs are needed to define the ratio: Surface to volume ratios for buildings per hectare based on the OSM data, individual heating degree days based on information from the “European Digital Elevation Model” (EEA, 2017) on a 30x30m scale, as well as the individual hectare´s share of buildings within the different building periods (Pesaresi et al., 2015). Both, the estimated heated gross floor areas per hectare and

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the indication of useful energy demand per hectare are combined to produce heat density maps for each hectare. These maps not only include useful energy demand, but gross floor areas and heat density information (Müller et al., 2019: p. 14).

Consequently, the heat density and gross floor area maps on various levels of spatial resolution (Hasani, 2019a) can be used to simulate supply-side indicators by application of calculation modules (Hasani, 2019b). As an option, the Hotmaps toolbox provides users with the opportunity to apply the supply side calculation modules (CM) for customized heatmaps (Fallahnejad, 2020a), which they can upload to the toolbox via a customized module. This will be described in greater detail in section 3.3.4. The calculation modules are part of a scenario toolchain, displayed in figure 7 on the next page, but can be applied independently too.

Three calculation modules produce additional demand side information: "CM – Demand projection" can adapt initial heat demand data to scenarios for the future, considering the potential refurbishment of buildings in the area (Müller and Hummel, 2019). The "CM - Scale heat and cool density maps" offers optionality to scale heat demand densities by a variable factor, allowing for frontend calibration of the underlying demand-side information in the backend (Bernhard, 2019). This can be used to correct the default dataset, if additional – but different – information on the heat demand in the area is available, which shall be considered for supply-side simulations. "CM – Heat load profiles" provides the user with information on the timely distribution of heat demand per hour (Aydemir and Schilling, 2020a). This can be used to improve sight on base- and peak-load levels, which cannot be derived from yearly total demand for heat only but are necessary to design optimal heat supply solutions.

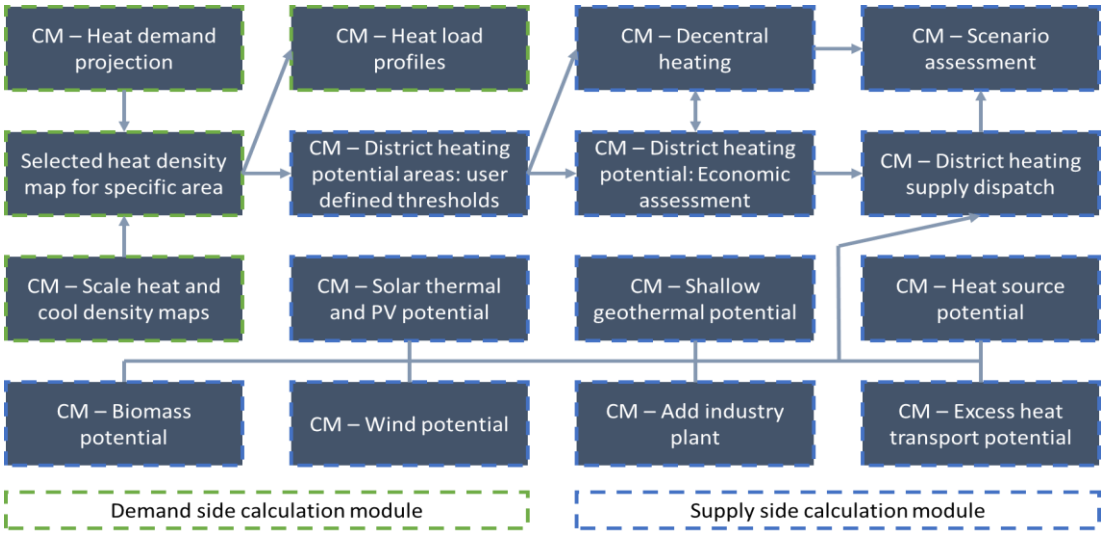

Figure 7: Overview of calculation modules available in the Hotmaps toolbox. *Own approach based on Hotmaps, 2020*

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All further modules focus on supply-side indications. For any given heat demand, the calculation module "CM – District heating potential areas: user-defined thresholds" can estimate the amount of heat demand being considered feasible for district heating supply (Fallahnejad, 2019b). This always depends on user-defined framing conditions, such as the selected area and heat density thresholds required to be met by the module.

"CM – District heating potential: Economic assessment" proceeds beyond and calculates the cost of heat distribution for respective district heating supply infrastructure (Fallahnejad, 2020b). The module defines grid infrastructure costs as the sum of capital cost for the transmission grid and the capital cost for the distribution grid of the district heating network. This is shown by equation 6 below:

$$C_{grid} = C_{trans} + C_{dist} \quad [6]$$

With: C_{grid} = Average specific costs of grid infrastructure [€/MWh]; C_{trans} = Average specific costs of transmission grid infrastructure [€/MWh]; C_{dist} = Average specific costs of distribution grid infrastructure [€/MWh]; Source: Fallahnejad et al., 2018: p. 144.

In addition to providing cost indications for required infrastructure for both transmission and distribution grids of district heating networks in the respective use case areas, the logic of the module includes a cost ceiling. By including and defining the cost ceiling, infrastructure costs calculated by the module must keep within a pre-defined range to keep the district heating network economically feasible. This condition is reflected by equation 7 below:

$$c_{grid} \leq c_grid_max \quad [7]$$

With: C_{grid} = Average specific costs of grid infrastructure [€/MWh]; c_grid_max = Maximal specific costs of grid infrastructure allowed [€/MWh]; Source: Fallahnejad et al., 2018: p. 144.

Average capital costs for transmission grid infrastructure of the district heating network are calculated by applying a stepwise approach: First, based on the underlying heat density maps, hectares below a certain minimum threshold of heat density are excluded from further calculations, as they are not considered economic for operating a district heating network. Also, the hectare with the highest heat density is identified as the centre of the district heating network infrastructure to be modelled.

The following modelling objective is to maximize the positive difference between income connected to supplying heat to the buildings in hectares considered for the

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district heating network and associated costs of building the infrastructure. This is expressed by equation 8 below:

$$\max \quad c_grid_max * \sum_i Q_{\max,i} * q_i - \sum_i \sum_j TLC_{ij} * l_{ij} * y_{ij} \qquad \forall (i,j) \in A \qquad [8]$$

With: c_grid_max = Maximal specific costs of grid infrastructure allowed [€/MWh]; A = All hectares considered for district heating operations; $Q_{max\,i}$ = Heat demand supplied in area i during the investment period [MWh]; q_i = Boolean variable determining if area i is considered for a connection to the district heating network; TLC = Annualized specific costs of a transmission connection between areas i and j [€/m]; l_{ij} = distance between areas i and j [m]; y_{ij} = Boolean variable determining if area j is connected to the district heating network centred in area i;

Source: Fallahnejad et al., 2018: p. 145.

The maximization problem reflected by equation 8 is subject to three groups of constraints, which will be presented by the following paragraphs:

The first set of constraints aims to minimize the required length of transmission grid infrastructures to supply the optimized district heating area (Minimum spanning tree (Fallahnejad et al., 2018: pp. 145-146)). This involves the following boundary conditions in equations 9 to 16:

$$\sum_i \sum_j y_{ij} = \sum_i q_i - 1 \qquad \forall (i,j) \in A \qquad [9]$$

$$\sum_i \sum_j y_{ij} \le |S| - 1 \qquad \forall S \subseteq A \;;\; \forall (i,j) \in A : i \in S, j \in S \qquad [10]$$

$$y_{ij} + y_{ji} \le 1 \qquad \forall (i,j) \in A \qquad [11]$$

$$q_i \le \sum_j \sum_i y_{ji} \qquad \forall i \in A - \{G\} \;;\; \forall j \in A \qquad [12]$$

$$y_{ij} \le \sum_h \sum_i y_{hi} \qquad \forall i \in A - \{G\} \;;\; \forall (j,h) \in A \qquad [13]$$

$$2 * (y_{ij} + y_{ji}) \le q_i + q_j \qquad \forall (i,j) \in A \qquad [14]$$

$$y_{ii} = 0 \qquad \forall i \in A \qquad [15]$$

$$q_G = 1 \qquad [16]$$

With: q_i = Boolean variable determining if area i is considered for a connection to the district heating network; y_{ij} = Boolean variable determining if area j is connected to the district heating network centred in area i; S = Ratio of accumulated energy savings; G = Area with the highest heat demand; A = All hectares considered for district heating operations; h = Secondary area h

Source: Fallahnejad et al., 2018: p. 146.

Accordingly, there shall be less transmission lines than areas considered (9), no (self-) loops in the system (10; 15), and one-directional flows only (11). Considered areas need to be connected to the transmission grid (12). Transmission lines can be built from considered areas only (13), end in considered area only (14), while must be included in the system design (16).

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Another block of constraints is related to the physical restrictions posed by the pipeline infrastructure. These constraints are sensitive to the capacities required, full load hours of the district heating system, and total annual energy demand supplied by the system. The influencing factors are represented by equations 17 to 22 below:

$$Cap_{ij} \geq y_{ij} * Q_{\max,j} / FLH \qquad \forall (i,j) \in A \qquad [17]$$

$$Cap_{ij} \leq \left(\sum_h Q_{\max,h} - \sum_r \left(y_{ri} * Q_{\max,r}\right)\right) / FLH \qquad \forall (i,j) \in A \; ; \; \forall h \in A - \{G,i\} \; ; \; \forall r \in A - \{G\} \qquad [18]$$

$$Cap_{ij} - y_{ij} * Q_{\max,G} \leq 0 \qquad \forall (i,j) \in A \qquad [19]$$

$$\sum_j Cap_{ij} - \sum_j Cap_{ji} = q_i * Q_{\max,i} / FLH \qquad \forall i \in A \; ; \; \forall j \in A - \{G\} \qquad [20]$$

$$\sum_j Cap_{Gj} = \left(\sum_j q_j * Q_{\max,j}\right) / FLH \qquad \forall j \in A - \{G\} \qquad [21]$$

$$Cap_{ii} = 0 \qquad \forall i \in A \qquad [22]$$

With: Cap = Required capacity of the pipeline [MW}; FLH = Full load hours [h/yr]; Qmax = Heating demand per area [MWh]; y_{ij} = Boolean variable determining if area j is connected to the district heating network centred in area i; G = Area with the highest heat demand; A = All hectares considered for district heating operations; Source: Fallahnejad et al., 2018: p. 146.

Beyond the logic of minimization of pipeline infrastructure required and its physical constraints there are economic constraints to be considered: In equation 23 pre-defined characteristics of district heating pipeline infrastructure, such as dimension and specific costs are mapped with the simulation via “PowSteps”. These “PowSteps” are 12 categories depending on the required pipeline capacities: The larger the capacity required, the higher the “PowStep”, the dimension and the specific costs:

$$C = \{1,2,3,\ldots,12\} \qquad \forall (i,j) \in A \qquad [23]$$

$$TLC_{ij} = AF * \sum_k TLB_{ijk} * \left(SPCTL_k - SPCTL_{k-1}\right) \qquad \forall (i,j) \in A \qquad [24]$$

$$TLB_{ijk} \leq y_{ij} \qquad \forall (i,j) \in A \qquad [25]$$

$$TLB_{ij(k+1)} \leq TLB_{ijk} \qquad \forall (i,j) \in A \qquad [26]$$

$$0 \leq Cap_{ij} - \sum_k \left(\left(PowStep_k - PowStep_{k-1}\right) * TLB_{ij(k+1)}\right) \qquad \forall (i,j) \in A \qquad [27]$$

$$0 \leq \sum_k \left(PowStep_k - PowStep_{k-1}\right) * TLB_{ijk} - Cap_{ij} \qquad \forall (i,j) \in A \qquad [28]$$

$$0 \leq \sum_i \left(q_i * Q_{\max,i} * \left(c_grid_max - c_{dist_i}\right)\right) - \sum_i \sum_j \left(TLC_{ij} * l_{ij}\right) \qquad \forall (i,j) \in A \qquad [29]$$

With: C = Set of pipeline dimension steps; TLC = Annualized specific costs of transmission line [€/yr]; AF = Annuity factor; TLB = Boolean variable indicating whether a transmission line should be build; SPCTL = Specific costs of transmission lines [€]; y_{ij} = Boolean variable determining if area j is connected to the district heating network centred in area I; PowStep = Pipeline capacity for a given dimension; Source: Fallahnejad et al., 2018: pp. 146 – 147.

Based on TLC, the Boolean variable TLB in equation 29 determines, whether an area can be supplied with district heat on economically and is considered or not.

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Distribution costs for the areas considered for a connection to the transmission grid before are calculated as per equation 32, considering linear heat densities as per equation 30 for estimation of average pipe diameters in the distribution grid as per equation 31.

$$L = \frac{1}{w} = \frac{1}{(61.8 * e^{-0.15})} \quad \textbf{[30]}$$

With: L = Linear heat density; w = Effective width;
Source: Fallahnejad et al., 2018: p. 144.

$$d_a = 0.0486 * \ln\left(\frac{Q_t}{L}\right) + 0.0007 \quad \textbf{[31]}$$

With: d_a = Average pipe diameters in distribution grid [m]; Q_t = Annual heat demand supplied by the distribution grid [MWh/yr]; L = Linear heat density according to equation 8;
Source: Fallahnejad et al., 2018: p. 144.

$$Inv_T = \frac{C_{1,T} + C_{2,T} \cdot d_a}{\left(\sum_{t=0}^{m} \frac{Q_{T+t}}{(1+r)^t} + \sum_{t=m+1}^{n} \frac{Q_{T+m}}{(1+r)^t}\right) / L} \quad \textbf{[32]}$$

With: Inv = Investment cost [€/MWh]; C_1 = Construction cost constant [€/m]; C_2 = Construction cost coefficient [€/m^2]; d_a = Average pipe diameters in distribution grid [m]; L = Total trench length [m]; Q_t = Annual heat demand supplied by the distribution grid [MWh/yr]; T = First investment year; t = Specific year within investment period; r = Interest rate [%]; m = Investment period [yr];
n = Depreciation time [yr];
Source: Fallahnejad et al., 2018: p. 144.

Following the determination of both, the average specific costs of transmission and distribution, equation 6 is applied to conclude the total costs of district heating network infrastructure levelized per unit of heat supplied. This is a necessary component to evaluate and compare the economic feasibility of district heating network operations within a use case area.

Building on this infrastructure cost assessment, the „CM – District heating supply dispatch" calculates final energy demands, carbon emissions, and supply costs for various energy carriers (Hasani, 2020). The module can be applied in two different modes: “Dispatch”, assessing the cost-optimal dispatch from a given portfolio of heat sources for a defined district heating network, and “Invest”, assessing the cost-benefit-optimal allocation of heat-source capacities for a given district heating demand

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area. In this thesis the focus will be on the “Invest” mode, as changes to an urban heat energy system on the demand and the supply side shall be evaluated. This implicates investments for different constitutions of district heating systems are required.

To solve for a cost-benefit-optimal allocation of generation capacities for the district heating network, a linear programming problem is defined as per equation 33 below:

$$min\ (c_{total} - rev_{total}) \qquad [33]$$

With: c_{total} = Total heat generation costs [€]; rev_{total} = Total revenue from electricity production [€];
Source: Hasani, 2020.

Accordingly, the supply set up for the network shall minimize the total costs of supply over respective total revenues if applicable. Put differently, optimize the cost-benefit performance. The optimization is subject to the condition of equations 34 and 36:

$$\sum_{j,t} x_{th_{j,t}} + \sum_{hs,t} (x_{unload\ hs,t} - x_{load\ hs,t}) \geq demand_{th_t} \qquad [34]$$

$$\forall j = \{CHP, heat\ pump, Power\ To\ Heat, Solar\ Thermal, waste\ treatment, boiler, Waste\ Heat, Geo\ Thermal\}$$
$$\forall hs = \{heat\ storage\}$$
$$\forall t = [1,8760]$$

With: $X_{th\ jt}$ = Heat generation from generator j at time t [MWh]; $X_{unload\ hs\ t}$ = Discharge of heat from heat-storage hs to grid at time t [MWh]; $X_{load\ hs\ t}$ = Charge of heat to heat-storage hs from grid at time t [MWh]; $demand_{th\ t}$ = Thermal energy demand of the network at time t [MWh];
Source: Hasani, 2020.

Hence, the sum of all heat generated by generation capacities connected to the district heating network, combined with the net energy being charged and discharged from storage capacities must be greater than the demand from consumers in the district heating network at any given point in time.

As mentioned above, some options considerable for the set-up of district heating supply capacities generates additional revenues. This applies to waste incineration and combined-heat-and-power generation plants (CHP). These generate electricity which can be sold to the wholesale market. The calculation module considers these revenues via equation 35:

$$x_{el_{j,t}} = x_{th_{j,t}} \cdot \frac{\eta_{el_j}}{\eta_{th_{j,t}}} \qquad [35]$$

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$$\forall j = \{CHP, heat\ pump, Power\ To\ Heat, Solar\ Thermal, waste\ treatment, boiler, Waste\ Heat, Geo\ Thermal\}$$

With: $X_{el\,jt}$ = Electrical generation of generator j at time t [MWh]; $X_{th\,jt}$ = Heat generation from generator j at time t [MWh]; $\eta_{el\,j}$ = Electrical efficiency of generator j [%]; $\eta_{th}jt$ = Thermal efficiency of generator j at time t [%]; Source: Hasani, 2020.

Furthermore, energy flows being charged, discharged, generated as thermal, or electrical energy can only be larger than 0, considering the physical constraint of generation technologies. For example: While a thermal generation plant can convert energy carriers into thermal useful energy, useful thermal energy cannot be re-converted to energy carriers by the same generation plants. This is expressed by the condition in equation 36:

$$x_{load\,hs,t}, x_{unload\,hs,t}, x_{el_{j,t}}, x_{th_{j,t}}, \ldots \geq 0 \qquad [36]$$

$$\forall j = \{CHP, heat\ pump, Power\ To\ Heat, Solar\ Thermal, waste\ treatment, boiler, Waste\ Heat, Geo\ Thermal\}$$
$$\forall hs = \{heat\ storage\}$$
$$\forall t = [1,8760]$$

With: : $X_{th\,jt}$ = Heat generation from generator j at time t [MWh]; $X_{el\,jt}$ = Electricity generation from generator j at time t [MWh]; $X_{unload\,hs\,t}$ = Discharge of heat from heat-storage hs to grid at time t [MWh]; $X_{load\,hs\,t}$ = Charge of heat to heat-storage hs from grid at time t [MWh] ; Source: Hasani, 2020.

Total costs of heat generation consist of investment costs (equation 37 and 38), capital costs (equation 39), and operational costs (equation 40):

$$IC = \sum_{j} Cap_j \cdot i_j \cdot \alpha_j + \sum_{hs} sCap_{hs} \cdot i_{hs} \cdot \alpha_{hs} \qquad [37]$$

$$\alpha_{j,hs} = \frac{(1+z)^{LT_{j,hs}} \cdot z}{(1+z)^{LT_{j,hs}} - z}, \qquad [38]$$

$$CC = \sum_{j} Cap_j \cdot opex_{FIX_j} + \sum_{hs} sCap_{hs} \cdot opex_{FIX_{hs}} \qquad [39]$$

$$OPEX = \sum_{j,t} x_{th_{j,t}} \cdot (opex_{var_j} + \frac{p_{ec_{j,t}}}{\eta_{th_{j,t}}} + \frac{f_{em_{ec_j}} \cdot p_{CO_2}}{\eta_{th_{j,t}}}) \qquad [40]$$

With: IC = Investment costs []; Cap_j = Capacity of generator j [MW]; $i_{j,hs}$ = Specific investment cost of generator j or heat-storage hs [€/MW; €/MWh]; $a_{j,hs}$ = Annuity of the generator j or heat-storage hs; $sCap_{hs}$ = Capacity of heat-storage hs [MWh]; z = interest rate [%]; $LT_{j,hs}$ = Lifetime of generator j or heat-storage hs [yr]; $opex_{fix\,j,hs}$ = Capital cost of generator j or heat-storage hs [€/MW; €/MWh]; $opex_{var\,j}$ = Operational cost of generator j [€/MWh]; $p_{ec\,j,t}$ = Price of energy carrier consumed by generator j at

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time t [€/MWh]; $f_{em\ ec\ j}$ = Carbon dioxide emission factor of energy carrier consumed by generator j [t CO_2e/MWh]; p_{CO2} = Price of carbon dioxide emission certificate [€/t CO_2e]; Source: Hasani, 2020.

CHPs and waste incineration plants cause ramping costs for operations. These are considered by equation 41 below. Also, they incur costs for electrical loads of peak production in winter seasons (equation 42).

$$\sum_{j,t}(x_{th_{jt}} - x_{th_{j,t-1}}) \cdot 100\frac{€}{MWh}\Big|(x_{th_{jt}} - x_{th_{j,t-1}}) > 0 \qquad [41]$$

$$\forall j = \{CHP, waste\ treatment\}$$
$$\forall t = [1,8760]$$

$$\sum_{j,t} x_{th_{jt}} \cdot 10k\frac{€}{MWh} \qquad [42]$$

$$\forall j = \{CHP, waste\ treatment\}$$
$$\forall t = [1,1440] \cup [8040,8760]$$

With: $X_{th\ jt}$ = Heat generation from generator j at time t [MWh]; Source: Hasani, 2020.

Revenues from electricity generated by waste incineration plants and CHP are considered by equation 43:

$$\sum_{j,t} x_{el_{jt}} \cdot p_{s.el_{j,t}} \qquad [43]$$

With: $X_{el\ jt}$ = Electricity generation from generator j at time t [MWh]; $p_{s.el\ jt}$ = Wholesale electricity price applicable for the grid zone if generator j at time t [€/MWh]; Source: Hasani, 2020.

In consequence, considering the above conditions and logics, the calculation module returns the cost-benefit solution for generation capacities serving the respective demand from the underlying district heating network. Results are derived on a levelized basis in €/MWh.

For the remaining parts of assessed areas, which cannot be connected to a district heating infrastructure on economic terms, the "CM – Decentral heating" provides users with information on final energy demand, carbon emissions, and supply costs for decentral heating equipment (Hasani, 2019c).

The calculation module is again based on the underlying information about heating demands for the use case area. Building on the total heat demand for the area, peak loads are calculated employing the logic of equation 44 on the next page:

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$$Q_{max} = 1.2 * ued_i \quad [44]$$

With: Q_{max} = Peak load of heating system [kW]; ued_i = annual total heat demand of area i [MWh]; Source: Hasani, 2019c.

In addition to the total heat demand of the assessed area, its total peak load, and pre-determined information on characteristics of considerable decentral systems, both, the investment- and operational costs of decentral systems can be estimated via the exponential equation 45:

$$k_1 * Q_{max}{}^{k2} \quad [45]$$

With: Q_{max} = Peak load of heating system [kW]; k_1 = Constant factor for investment- and operational costs of decentral heating systems; k_2 = Exponential factor for investment- and operational costs of decentral heating systems; Source: Hasani, 2019c.

Cost constants and exponents, as well as further parameters are defined by the user or drawn from the toolbox´s pre-defined database depending on the location, time-horizon, and underlying building types, as well as chosen technologies for the simulation. These parameters include variable operational costs, thermal efficiencies, and lifetimes of chosen heating systems, as reflected by equation 46 below:

$$f_{get_data}(loc, type, tec, timeh) = k_{1op\ fix}; k_{2op\ fix}; op_{var}; k_{1\ io}; k_{2io}; \eta; n \quad [46]$$

With: $k_{1op\ fix}$ = Constant factor for operational fix costs [€/kW]; $k_{2op\ fix}$ = Exponential factor for operational fix costs; op_{var} = Constant factor of variable costs of operations [€/kWh]; k_{1io} = Constant factor for investment costs [€/kW]; k_{2io} = Exponential factor for investment costs; η = Thermal efficiency of the heating system [%]; n = Lifetime of the heating system [yr]; Source: Hasani, 2019c.

Following the parametrization of variables, the toolbox proceeds to calculate respective cost relationships (investment costs in equation 47; operational fix costs in equation 48; variable costs of operation in equation 49) as indicated by equation 45:

$$I_o = k_{1io} * Q_{max}{}^{1 + k_{2io}} \quad [47]$$

$$OP_{fix} = k_{1op_{fix}} * Q_{max}{}^{1 + k_{2op\ fix}} \quad [48]$$

$$OP_{var} = op_{var} * \frac{ued_i}{\eta} \quad [49]$$

With: I_o = Investment costs [€]; k_{1io} = Q_{max} = Peak load of heating system [kW]; Constant factor for investment costs [€/kW]; k_{2io} = Exponential factor for investment costs; OP_{fix} = Operational fix costs [€], $k_{1op\ fix}$ = Constant factor for operational fix costs [€/kW]; $k_{2op\ fix}$ = Exponential factor for operational fix costs; OP_{var} = Variable costs of operations [€]; op_{var} = Constant factor of variable costs

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of operations [€/kWh]; ued_i = annual total heat demand of area i [MWh]; η = Thermal efficiency of the heating system [%]; Source: Hasani, 2019c.

Respective fuel cost applicable for the assessed set-up are again defined by the user, or drawn from the toolbox´s database by applying the logic of equations 50 and 51:

$$f_{get_data}(loc, tec, timeh) = p_{ec} \quad \textbf{[50]}$$

$$F = \frac{ued_i}{\eta} * p_{ec} \quad \textbf{[51]}$$

With: pec = Price of energy carrier required for operating the heating system [€/MWh]; ued_i = annual total heat demand of area i [MWh]; η = Thermal efficiency of the heating system [%]; F = Fuel costs [€]; Source: Hasani, 2019c.

Based on these parameters levelized costs of heating (LCOH) can be calculated for decentral heating systems using equation 52:

$$LCOH = \frac{I_o + \sum_{t=1}^{n}(OP_{fix\ t} + OP_{var\ t} + F_t) * \frac{1}{(1+r)^t}}{\sum_{t=1}^{n} hp_t * \frac{1}{(1+r)^t}} \quad \textbf{[52]}$$

With: LCOH = Levelized cost of heating [€/MWh]; $OP_{fix\ t}$ = Operational fix costs in period t [€]; $OP_{var\ t}$ = Variable costs of operations in period t [€]; F_t = Fuel costs in period t [€]; r = interest rate [%]; hp_t = Heat production in period t [MWh], Source: Hasani, 2019c.

Beyond the calculation module provides an annualized version of the levelized cost of heating by applying an annuity factor. For the scope of the thesis, potential changes in LCOH caused by reductions of heat demand from energetic refurbishments are of interest. Hence, the approach of annualized values will not be explained further, but can be reviewed in Hasani, 2019c.

In sections 3.3.5 and 3.3.6, the functionalities of the calculation modules “CM – District heating potential: Economic assessment”, “CM – District heating supply dispatch” and “CM – Decentral heating” will be described in more detail from a user´s perspective. Furthermore, in section 4.5 their parametrization for the case study of this thesis will be outlined.

Operating heating systems requires sufficient potential for all renewable heat supply options considered for the system being available on site. Hence, the calculation modules “CM – Solar thermal and PV potential” (Garegnani, 2019), “CM – Shallow geothermal potential” (Garegnani and Zambelli, 2020a), “CM – Heat source potential”

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(Zambelli, 2020a), “CM – Biomass potential” (Zambelli, 2020b), “CM – Wind potential” (Garegnani and Zambelli, 2020b), “CM – Add industry plant” (Aydemir and Neusel, 2020), and “CM – Excess heat transport potential” (Aydemir and Schilling, 2020b) provide indications on whether sufficient local renewable energy potentials are available.

For an integrated perspective on several scenarios being calculated with the previous calculation modules, the "CM – Scenario assessment" provides a stand-alone Excel sheet solution (Conforto and Schmidinger, 2020). Users can enter the results of their simulations, enabling them to compare results more intuitively and receive visualizations.

3.1.3 Data integration: Combining urban heat planning and simulation tools

As described by the previous sections, UBEM and the Hotmaps toolbox are two different approaches to heat planning and simulation. While Hotmaps is providing optionality for supply-side assessment, both provide a perspective of the demand side of heating systems. Differences are found in the approach: While the toolbox follows a top-down approach to heat demand estimation, UBEM adopts a bottom-up approach. The approaches show different characteristics, which may or may not suit a user´s needs under different circumstances. As use cases for heat planning and simulation tools are diverse, for some users a convenient overview on dimensions of solutions will be preferred, while for others, a more detailed, but also more demanding view on heat planning options will be required:

The UBEM bottom-up approach is expected to provide more granularity and precision in heat demand assessment and local distribution as it assesses and geolocates heat demand on a building by building-, instead of hectare-basis. Even if results of UBEM results are not found to be 100% precise on an individual building level (Nagpal et al., 2019), spatial precision is still higher than on a hectare level. In addition, the physics-based approach of UBEM provides with optionality to trace back the causality of refurbishments towards decreasing heat demand (Ang et al., 2021: pp. 2-3). While the toolbox anticipates reduced heat demand for the future too, this is always bound to an average reduction factor (“CM – Scale heat and cool density maps” (Bernhard, 2019)) and cannot directly be connected to individual refurbishment measures being applied to specific buildings.

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In turn, applying an UBEM on the demand side is expected to require higher computational efforts, involvement of experts on the local building stock (Ang et al., 2021: p. 3), longer preparation- and calibration times (Ibid: p. 9), as well as higher costs of the application, compared to the Hotmaps toolbox. This will suit some, but not all user´s preferences.

Eventually, integration of tools might create synergies in combining advantages. The integrated toolchain of UBEM and Hotmaps, which will be assessed via sensitivities within the scope of this thesis is depicted in figure 8 below. Sensitivity blocks will be described in more detail in the next sections.

Demand side simulation	Supply side simulation
Input: • Weather files • Geo-dataset of building stock of use case area • Information on energetic performance of buildings **Simulation**: UMI energy via energy plus algorithm **Results**: • Useful energy demand for heating and domestic hot water per building within the use case area • Timely resolution	**Input**: UBEM simulation results **Calculation modules**: • CM – District heating economic assessment • CM – District heating supply dispatch • CM – Decentral heating • Expendable to other CMs and custom calculations **Results**: • Total reduction of carbon emissions • Total heating costs over 50 years • Carbon abatement cost per refurbishment option

Figure 8: Overview of an integrated toolchain of UBEM and the Hotmaps toolbox. *Own approach based on previous sections.*

When comparing and integrating both tools, it is important to note, that neither the developers of UBEM (Ang et al., 2021: p. 3) nor of the Hotmaps toolbox (Müller et al., 2019: p. 3) aim to replace, but to complement different approaches to heat planning and simulation. Equally, the explicit aim of this thesis´ application of an UBEM integrated with the toolbox is to complement the capabilities and functionality of both tools. There will be no indication or advice on whether top-down-, bottom-up-, or integrated approaches to heat planning and simulation are best – it should depend on the individual use case always.

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3.2 Assessed sensitivities of data links between UBEM and the Hotmaps toolbox

The assessment will be conducted in five blocks, which are visualized in figure 9 below.

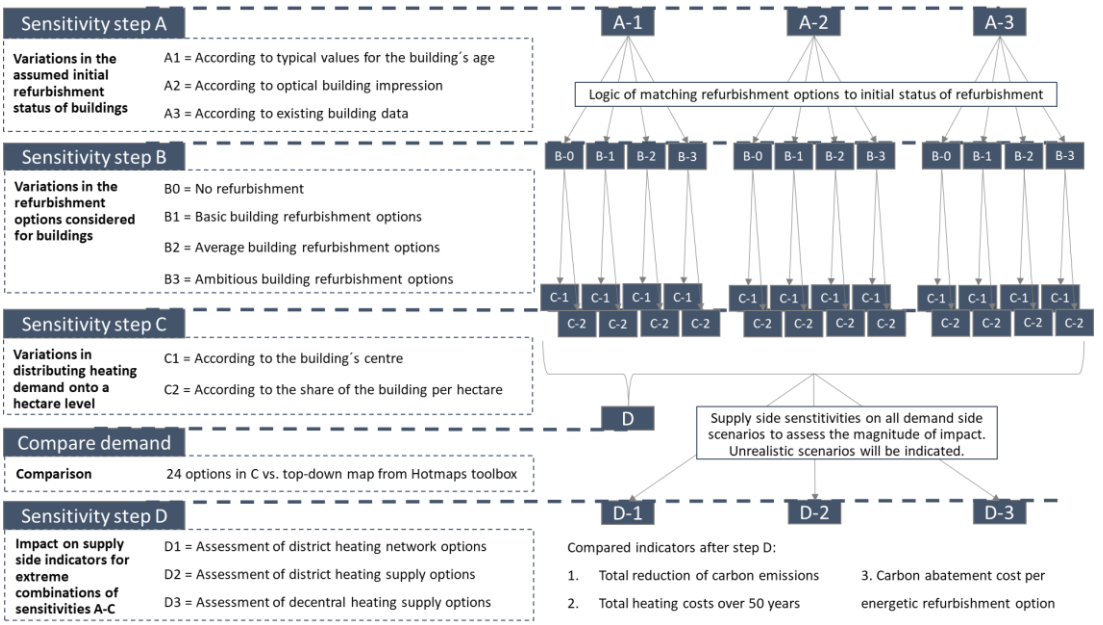

Figure 9: Assessed sensitivities of data links between UBEM and the Hotmaps toolbox. *Own approach.*

The case study application of sensitivities to integrating an UBEM with the Hotmaps toolbox will be structured in four sensitivity blocks (A, B, C, and D) as well as one comparison block for demand-side scenarios. They will be described in more detail in the following sections.

3.2.1 Sensitivity Block A: Variations in initial refurbishment status of buildings

Users of an integrated approach of UBEM and the Hotmaps toolbox might find different levels of detail and precision in the data of their use case being available to them. However, based on whatever information, they will need to calibrate the baseline model of the respective set of buildings, district, or city. Depending on their access to official databases by the city or community, or expert opinions on the local building stock´s energetic performance characteristics, their assumptions about the initial refurbishment status of buildings might vary.

The UBEM methodology offers the opportunity to calibrate various inputs to the model, during the process of initial model creation, and by subsequent amendment via the frontend. As described in section 3.1.1, the three major inputs to UBEM are weather data, building shape data, and information on the energetic performance of buildings, stored in data templates per building type. While the model is sensitive to

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all inputs, information on the energetic performance of buildings is the most controversial, but influential (Ang et al., 2021: pp. 3-4).

Weather data (e.g., National Oceanic and Atmospheric Administration (NOAA), 2021; Deutscher Wetterdienst (DWD), 2021; etc.) and building geometries (e.g., OSMF, 2021) are publicly available for most locations. Furthermore, the few existing alternative sources vary in marginal details only. In contrast, information on the energetic performance of a diverse building stock on a building-by-building level – if existing – is not publicly available. Hence, users might be required to estimate the energetic performance of buildings to be considered by their model (Djørup et al., 2019b: p. 12).

Potential approaches include referencing information from existing building typologies, being publicly available on national (e.g., Institut für Wohnen und Umwelt e.V. (IWU), 2012; Reyna et al, 2021; etc.) and local level, as well as from potentially existing publications on the local building stock or assessing initial refurbishment status according to the visual impression of the buildings. Furthermore, users might be – or involve – experts on the local building stock to develop building templates including expert perspectives and judgement of the energetic performance of buildings within the examined area (Ang et al., 2021: p. 4).

However, the chance of diverse approaches to baseline model calibration due to the fact of different interpretations of the building´s initial refurbishment status by users is high. Accordingly, within sensitivity block A, three different versions of the baseline model, including three different approaches to defining the initial refurbishment status of buildings in the case study district shall be created. These shall represent the most likely user approaches to model calibration and include the approaches mentioned above.

Based on the simulation of energetic performances of these three sensitivities to the calibration of the baseline model, it will be of interest to evaluate potential differences in total energy heating demand, spatial distribution, and density of heat demand. Additionally, the three versions of the baseline model shall be compared to the default top-down approach offered by the Hotmaps-toolbox. In a subsequent step, effects on the choice of optimal heat supply options for the district will be quantified via the Hotmaps toolbox. It is expected that variations in the initial refurbishment status of buildings assessed lead to differences in indicators of heat demand and supply as mentioned above. Furthermore, it is expected, that variations in sensitivity block A will

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have an impact on subsequent sensitivity blocks B-D, as the difference in baseline heat demand might lead to knock-on effects: Different refurbishment strategies might be chosen, leading to different approaches to optimal heat supply strategies.

To consider differences in initial refurbishment status, the above sensitivities will be implemented by assigning individual initial status for all buildings within the model. For a more detailed description of the model creation and amendment process see sections 4.1.2 - 4.1.4.

3.2.2 Sensitivity Block B: Variations in refurbishment options for buildings

Once users have created their baseline model, UBEM allows for model calibrations to simulate the effect of energetic refurbishments on heat demand. However, as for the variations in the initial refurbishment status of buildings described in 3.2.1, the flexibility of the tool allows users to apply an infinite amount of different building templates to represent the energetic properties of any refurbishment option (Ang et al., 2021: p. 6). Most likely, there will be differences in the calibration of building templates regarding the characterization of refurbishment options.

While exact discrepancies between energetic performances implied in various customized building templates by users cannot be foreseen, there is a likelihood that user´s model calibrations can be approximated by a set of three representative refurbishment options:

A low effort / low-cost refurbishment option, named “basic refurbishment option”, a medium effort / medium-cost refurbishment option, named “average refurbishment option”, and a high effort / high-cost refurbishment option, named “ambitious refurbishment option”.

To integrate refurbishment options into UBEM, the baseline models from sensitivity block A will be amended. While weather files and building shape data remain unchanged, building templates shall be amended to reflect alternative sets of information on energetic building performance. This will include changing construction properties, window properties, as well as respective building materials and costs associated with the refurbishment options. Again, users are assumed to either be – or consult – experts on the local building stock, or reference building stock typologies being publicly available. Accordingly, for sensitivity block B, properties of refurbishment options, provided by a public building typology (see 4.), shall be referenced.

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As for the baseline model variations in sensitivity block A, for every variation within sensitivity block B, potential differences in total energy demand for heating, spatial allocation, and density of heat demand will be examined. Again, results shall later be uploaded into the Hotmaps toolbox to compare with its default top-down approach to heat demand estimation. Also, results from the sensitivity block B will be considered as input to the Hotmaps toolbox to simulate effects on determining optimal heat supply options.

Provided that energetic building performance indicators in building templates will be the only parameters being changed for creating model sensitivities during block B, results are expected to vary for the same indicators of heat demand and supply as for sensitivity block A. These again include heat demand, spatial allocation of heat demand, and heat demand density. Furthermore, the same type of knock-on effects on sensitivity blocks C and D are expected.

To integrate changes to building template information into the model, building templates will be amended to include respective properties of the refurbishment options defined. The amendment process and is described in section 3.3.2, utilized data for the case study in 4.2.

3.2.3 Sensitivity Block C: Variations in distribution of heat demand to hectares

Following a successful UBEM creation, a subsequent amendment to consider effects of refurbishment options, and simulation, users are assumed to have obtained results for the demand side of the model, such as total heat demand and gross floor area for the complete model as well as per building.

They can transfer the information to the Hotmaps toolbox to utilize its extensive analytic capability. To consider customized datasets on heat demand as a basis for analysis, the toolbox requires a certain format of data (Fallahnejad, 2020a). Therefore, heat demand and gross floor area per hectare are the most important parameters to be defined.

However, while UBEM generates the required information on a building level, it does not aggregate the information to hectare values automatically (Ang et al., 2021: p. 2). Hence, users are required to allocate both, heat demands and gross floor areas from buildings to hectares to meet requirements to customized input data format by the Hotmaps toolbox.

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Users are assumed to adopt two different approaches to allocating heat demand and gross floor area onto hectares:

One option to allocate the information to hectares might be geo-referencing the information at the exact location of the individual building´s centre and summing the values for all building centres identified within the scope of each hectare.

Alternatively, users might not interpret buildings as indivisible entities. Accordingly, they might virtually split buildings and allocate resulting fractions of the individual building´s information. Thereby they might artificially create two or more partial buildings out of one initial building and geo-reference the respective information at the centres of these newly created partial buildings. Afterward, again, information – heat demand and gross floor areas – at geo-referenced locations within the scope of each hectare would be summed.

Technically, both approaches are assumed to be feasible. This will be verified in chapter 4. However, it is uncertain which approach users might adopt and whether their choice causes differences in result, which will serve as input files for subsequent use within the Hotmaps toolbox. Hence, both allocation approaches shall be applied to all sensitivities and baseline models generated within sensitivity blocks A and B to check for differences in heat demand indicators.

The variations – C1 and C2 – are to be generated as input files for the Hotmaps toolbox. Beyond, they shall be considered for calculations of optimal heat supply options in sensitivity block D. Knock-on effects are expected in case of discrepancies in heat demand caused by different approaches to allocation of building information to hectare-level.

Section 4.3 will examine the different allocation processes and transfer of information on heat demand and gross floor area from UBEM into the Hotmaps toolbox in detail, while the standard approach of converting UBEM results into input files for the toolbox will be described in 3.3.4.

3.2.4 Comparison of heat demand for blocks A-C and the Hotmaps toolbox

As mentioned in sections 3.2.1, 3.2.2, 3.2.3, the variations of model calibration to be assessed on the demand side are expected to generate a diverse set of input files for the Hotmaps toolbox. It is of interest to compare them to each other, as well as to the default dataset of heat demand and gross floor areas provided by the Hotmaps toolbox (Müller et al., 2019; Hunacek and Zuber, 2020a). Special focus shall again be

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on the following demand-side indicators: Total heat demand, Total gross floor area, heat density, and spatial distribution of heat demand.

Therefore, UBEM information on heat demand and gross floor areas being transferred into the Hotmaps toolbox will be compared to all other variations of the model generated in sensitivity blocks A-C, as well as to the default version provided by the Hotmaps toolbox on both, a visual, and a quantitative basis. Variations in the calibration of initial refurbishment status (Block A), refurbishment options (Block B), and spatial allocation of heat demand (Block C) are expected to influence the resulting heat demand indicators across the different versions of the model.

Independent from the impact of these variations on supply-side indicators to be assessed in the subsequent sensitivity block D, the comparison shall focus on the demand side results only. However, there might be an interesting point of comparison of results after sensitivity block D. Potentially, knock-on-effects from sensitivity blocks A-C on supply-side indicators can be explained by the comparison of differences of results between block C and D alongside the integrated toolchain of UBEM and the Hotmaps toolbox.

Further information on the comparison process and indicators compared will be discussed in section 4.4.

3.2.5 Sensitivity Block D: Impact on supply-side indicators

Users having transferred their heat demand information from UBEM into the Hotmaps toolbox are assumed to be interested in running the toolbox calculation modules to evaluate and optimize heat supply options for their respective use case areas. Specifically, the supply-side indicators of the total cost of heating, carbon emissions, and carbon abatement costs are assumed to be their focus of interest.

Given the ambitious climate protection goals defined in global, regional, national, and local policies, as discussed in 2.1, users are expected to aim for effective decarbonization strategies for the building stock of their selected areas. For the case study in chapter 4, these decarbonization strategies are required to meet a reduction level of at least 95% of carbon dioxide emissions, in line with the cities decarbonization ambitions, as presented in 2.1.

As described in section 3.1.2, the Hotmaps toolbox offers specialized calculation modules for the assessment of district heating and decentral heating systems. These calculation modules provide users with a range of calibratable input parameters,

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including costs of emissions, costs of energy carriers, emission factors for energy carriers, investment cost for energy generation infrastructure, general information on investment horizons, interest rates, et cetera (etc.) (Hasani, 2019b). While the toolbox offers a set of default values for the input parameters to begin with, users might not keep these default values for their calculations, as the default values are reflecting typical European market conditions roughly from 2015 to future scenarios (Kranzl et al., 2018; Geipel, 2018; Müller and Fallahnejad, 2020; etc.). Depending on the location and timing of their use case, users might instead alter various input parameters to reflect the expected local market conditions and forecasts for a future low- or no-carbon energy system accordingly.

To calibrate the input parameters of their model, users will most likely again be dependent on available publications, such as scenarios on the development of market conditions into the future (e.g., Kranzl et al., 2018; Haas and Auer, 2019; Auer et al., 2020; etc.). Alternatively, they need to create their own scenarios to calibrate the model. However, likely, the future will always remain uncertain. In consequence, users are expected to apply sensitivities to their base input parameters to consider market conditions for a variety of different scenarios than their base case.

However, for the case study, it is of interest to understand the consequences of sensitivities to input parameters of calculation modules to the overall performance of the integrated toolchain. Accordingly, approximate ranges of input parameter sensitivities, which users might adopt, need to be considered as sensitivities for the case study too. Hence, in sensitivity block D, the calculation modules of the Hotmaps toolbox will be applied - always considering a set of variations to the input parameters, such as prices of carbon dioxide, electricity, and infrastructure. Each of these variations is assumed to be a realistic reflection of scenarios sensitivities for a future low-carbon energy system, which users might adopt. Further details on these values are presented in section 4.5.

Beyond creating an understanding of the impact of the user´s calibration of the demand-side to the supply-side of the integrated toolchain, within sensitivity block D, potential knock-on effects on the supply side will be assessed. These knock-out effects are expected to be stemming from variations to the demand side during sensitivity blocks A-C and were mentioned in sections 3.2.1, 3.2.2, and 3.2.3 already. There, variations in initial refurbishment status (Block A), applied refurbishment options (Block B), and allocation of identified heat demand and gross floor area (Block

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C) were suspected to impact supply-side indicators via knock-on-effects alongside the integrated toolchain.

Results from the calculation modules are highly dependent on the user´s selection of maps containing information on heat demand and gross floor areas (Hasani, 2019a). In turn, the expected knock-on effects from the demand side to supply-side indicators can be evaluated by varying the selection of input maps considered for the calculation modules, while all other input parameters to the modules are kept constant. Hence, all model sensitivities from the demand side, being created during sensitivity blocks A-C, will be run through all relevant calculation models of the toolbox on the supply side of the integrated toolchain to identify potential knock-on-effects.

Again, a more detailed description of the respective calibrations of input parameters to calculation modules will be provided in section 4.5, while the processes of calibrating and simulating the modules are going to be explained in next section 3.3.

3.3 Process descriptions for model creation, calibration, and simulation

This section will describe relevant processes for model calibration and subsequent simulation. According to the integrated toolchain, this includes the creation, calibration, and simulation process for the UBEM demand-side models, their integration into the Hotmaps toolbox, as well as the calibration and simulation of supply-side models in the Hotmaps toolbox.

3.3.1 UBEM creation process

As described in section 3.1.1, the creation of an UBEM requires the following input data to be available: A weather file for the location to be assessed, a shape-file including geometries for the building stock to be assessed, as well as information on the respective building´s energetic performance stored in building templates. Also, it was described, that UBEM is a feature of the wider scope urban modeling interface (UMI) by MIT. To create UMI files, which is the file format required to simulate all respective features of UMI, MIT hosts an online application (ubem.io, 2021a). It can be used to generate UMI files based on geo-datasets being available to users. The application, which was described from a technical perspective before, is available at: www.ubem.io.

Before generating UMI files via ubem.io, users are required to harmonize the sets of geodata, in exemplum shapefiles, of the building stock being available to them (Ang et al., 2021: p. 4). UMI files require certain categories of information to be part of the

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input dataset. Beyond the sheer geometries, these include a categorization of building types, building´s age, and a unique identification number per building (Sustainable Design Lab (SDL), 2017a). If some of these information categories are not defined or included within the default geo-dataset available to users, they need to integrate respective information categories into their geo-dataset.

Ubem.io is compatible to most geo-data file-formats (Ang et al., 2021: p. 4), including ".shp" (shapefile holding the geometries (Environmental Systems Research Institute (ESRI), 1998: p. 1)), ".shx" (index allowing for navigation in the shapefile (Ibid: p. 23)), ".cpg" (indicates how to encode/interpret the data), ".sbn", ".sbx" (spatial indexes of features), et cetera. To amend geo-datasets being stored in the file-formats listed above any GIS editor software can be used. Some of these programs are available as open-source software online (e.g., QGIS, 2021). To integrate potentially missing information categories on the building stock required by ubem.io, users need to add columns within their datasets.

Once all information categories are integrated into the user´s geo-dataset, it can be uploaded to ubem.io to begin the creation process of an UMI file, serving as the basis for any UBEM application. On the front page of ubem.io´s frontend, users need to click the blue button "Urban Model Generator" to begin the creation process (ubem, 2021a).

In process step 1, "Defining Base Geometry", which is represented by figure 10 below, users are required to drag and drop their completed geo-dataset into the upload box (ubem.io, 2021c). The online application verifies the file´s format for compatibility with the algorithm and functions being employed in the backend of ubem.io.

Once the file has been successfully verified, the application returns a green box featuring the name of the geo-dataset within the upload box (ubem.io, 2021d). Next, in process step 2, users are required to confirm whether the name of the dataset returned by the frontend corresponds to the dataset intended to be used for creating the UBEM by clicking the "next" button in the lower right-hand corner of the screen, as visualized by figure 11 below.

The backend of ubem.io scans the information being provided by the geo-dataset and returns a "Shapefile Summary", featuring the dataset´s geometries at their identified locations on a map, as in the example of figure 12 below. Furthermore, users are receiving information on the number of geometries, the number of different building

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types, as well as the number of missing fields in the dataset, as recognized by the backend (ubem.io, 2021e). Users are advised to check back with the geo-dataset being uploaded, whether the numbers of geometries and building types are correct. If yes, users again need to confirm the "Shapefile Summary" by pressing the button "next" in the lower right-hand corner of the screen.

In process step 4, "Select and Match Key Field", users are required to select key information categories included in their geo-datasets and match them to data categories given by ubem.io, 2021f. The respective frontend mask is displayed in figure 13 below. For example, a user has declared the "Unique identifier (ID)" of the building´s geometry as "Building ID" in his or her geo-dataset, he or she needs to match the "Building ID" with the key information category of the ID. Another example: A user has defined the height of the building´s geometries as "Height" in his or her geo-dataset. Hence, he or she needs to match "Height" and “Building height (m)”. Once all required data categories have been matched with their respective counterparts from the geo-data input, users are required to confirm their selection via a blue “Confirm” button below the selection pane.

Process step 5, “Organize Buildings”, provides the user with the opportunity to verify the correct calibration of the model and interpretation of required data categories in steps 1 to 3 (ubem.io, 2021g). Per building type, the name of the building type as defined within the geo-dataset, as well as the number of geometries recognized for the respective building type are displayed. An example is provided in figure 14 below.

Users are advised to double-check with their geo-datasets for any unexpected changes in building type names or their numbers of occurrence in the dataset.

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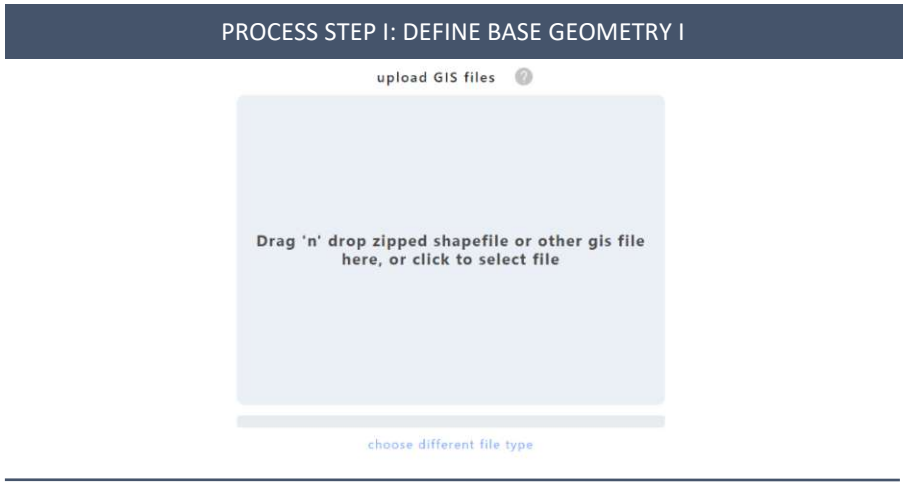

Figure 10: UBEM creation process I: Define base geometry I.
Own application of UBEM: ubem.io, 2021c.

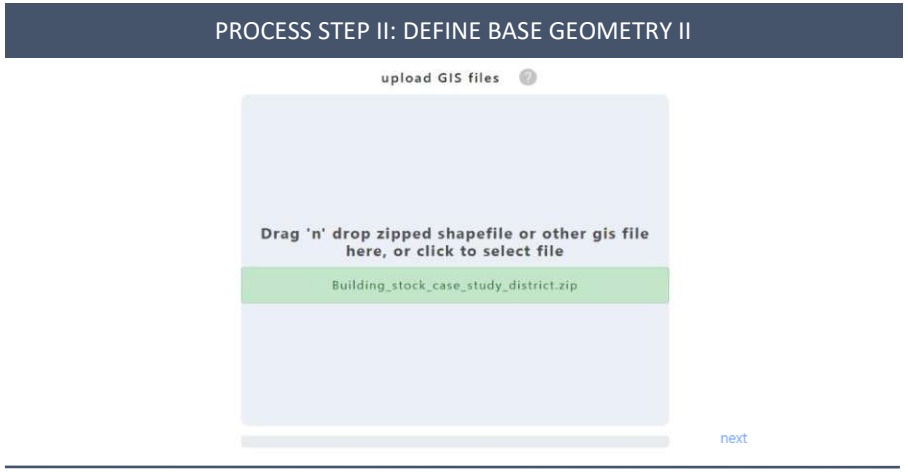

Figure 11: UBEM creation process II: Define base geometry II.
Own application of UBEM: ubem.io, 2021d; Geo-data based on Kiel, 2020f.

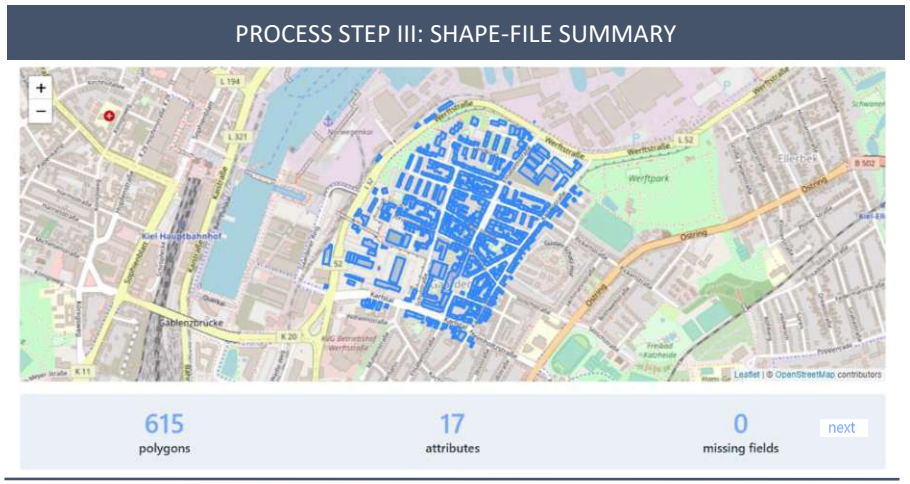

Figure 12: UBEM creation process III: Shape-file summary.
Own application of UBEM: ubem.io, 2021e; Underlying geo-data: Kiel, 2020f.

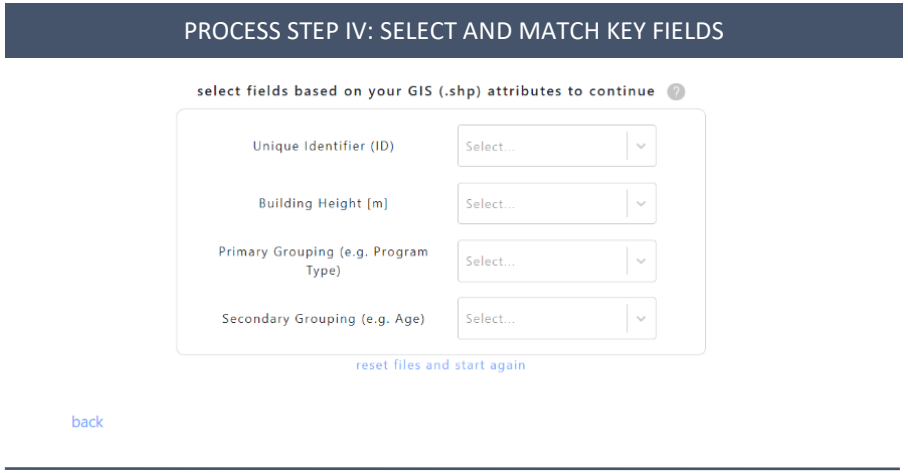

Figure 13: UBEM creation process IV: Select and match key fields.
Own application of UBEM: ubem.io, 2021f.

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PROCESS STEP V: ORGANIZE BUILDINGS

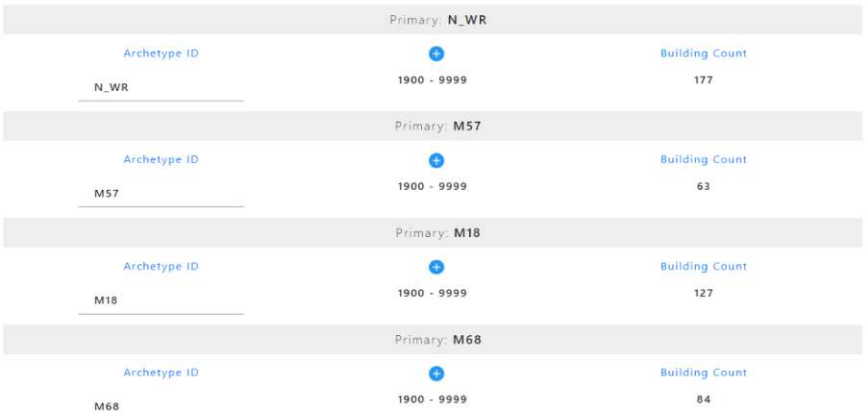

Figure 14: UBEM creation process V: Organize buildings.
Own application of UBEM: ubem.io, 2021g.

PROCESS STEP VI: ASSIGN VALUES AND TEMPLATES

Archetype ID	Primary Field	Secondary Field	W:W Ratio	Template
N_WR	N_WR	1900-9999	40 %	choose template
M57	M57	1900-9999	40 %	choose template
M18	M18	1900-9999	40 %	choose template
M68	M68	1900-9999	40 %	choose template
M78	M78	1900-9999	40 %	choose template
GL_SS	GL_SS	1900-9999	40 %	choose template
M87_SVP	M87_SVP	1900-9999	40 %	choose template
NT_NWG	NT_NWG	1900-9999	40 %	choose template
NT_WG	NT_WG	1900-9999	40 %	choose template

Figure 15: UBEM creation process VI: Assign values and templates.
Own application of UBEM: ubem.io, 2021h.

PROCESS STEP VII: VERIFY AND EXPORT I

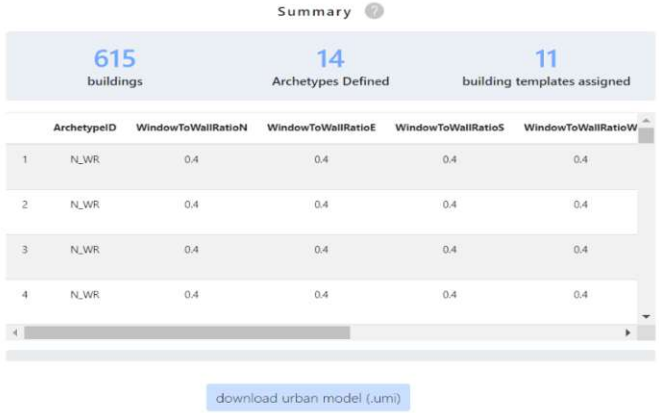

Figure 16: UBEM creation process VII: Verify & export I.
Own application of UBEM: ubem.io, 2021i.

PROCESS STEP VIII: VERIFY AND EXPORT II

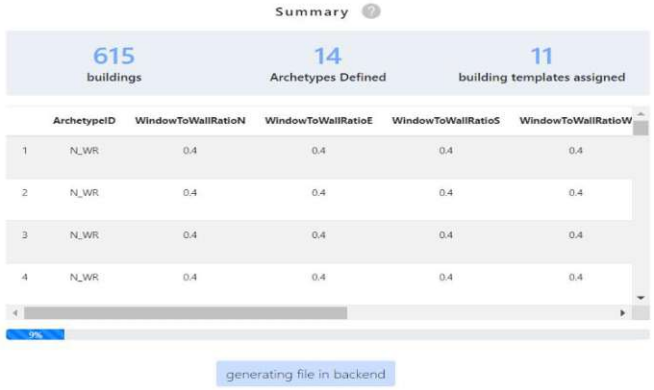

Figure 17: UBEM creation process VIII: Verify & export II.
Own application of UBEM: ubem.io, 2021i.

If users would like to manually change the name of a building type, ubem.io provides them with a final chance at this stage of the process (ubem.io, 2021g).Again, to proceed, users are required to confirm their review by pressing the "next" button in the lower right-hand corner of the screen.

"Assign Values and Templates" is the sixth process step, where users can assign building templates containing information on the building's construction, windows, and energetic performance of building materials et cetera to each building type (ubem.io, 2021h). Templates need to be prepared by the user in advance. This will be discussed in the next section, 3.3.2 in greater detail. However, an example of process step 6 was provided by figure 15 above. To select templates, users need to click on the hyperlink in the right-most column of the table of recognized building types and select the name of the intended building template for the respective building type from a drop-down menu. Additionally, users can adjust the window-to-wall ratios of the buildings for the backend of ubem.io to consider when creating the UMI file. By default, ubem.io considers a 40% window to wall ratio, which is assumed to be compatible with average building stocks in Europe and the United States of America.

Next, in process step 7, “Verify / Export”, which was represented by figure 16 above, ubem.io provides the user with a list of recognized geometries, each reflecting an individual building and its properties (ubem.io, 2021i). The summary includes building IDs, building types, window to wall ratios, and assigned building templates for all geometries within the assessed geo-dataset. Users are advised to scroll through the list and check for any unexpected list items. Once confirmed, users can click the blue button "download urban model (UMI)" below the summary list.

Following the activation of the UMI-file generation, a blue bar chart indicates the progress being made by the backend (ubem.io, 2021j). Once the bar hits 100%, a download of the newly generated UMI file is automatically started.

UMI files can be visualized by Rhinoceros, a CAD rendering software, which was described in section 3.1.2 and is shown on the next page. Rhinoceros 3D is available online and offers a 90-day free evaluation option, as well as reduced license fees for academic users (McNeel, 2021b). For UMI, Rhinoceros versions 6 and 7 are preferred.

To simulate energy data, hence create an UBEM based on UMI files, an UMI add-in for Rhinoceros needs to be downloaded from ubem.io and installed on the user´s

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machine (ubem.io, 2021k). Users can open their UMI file in Rhinoceros, using the UMI-toolbar being installed in conjunction with the UMI add-in for Rhinoceros (SDL, 2017b). Users need to select "Open project" and navigate to the location of the UMI file on their machine, as shown in figure 18 on the next page.

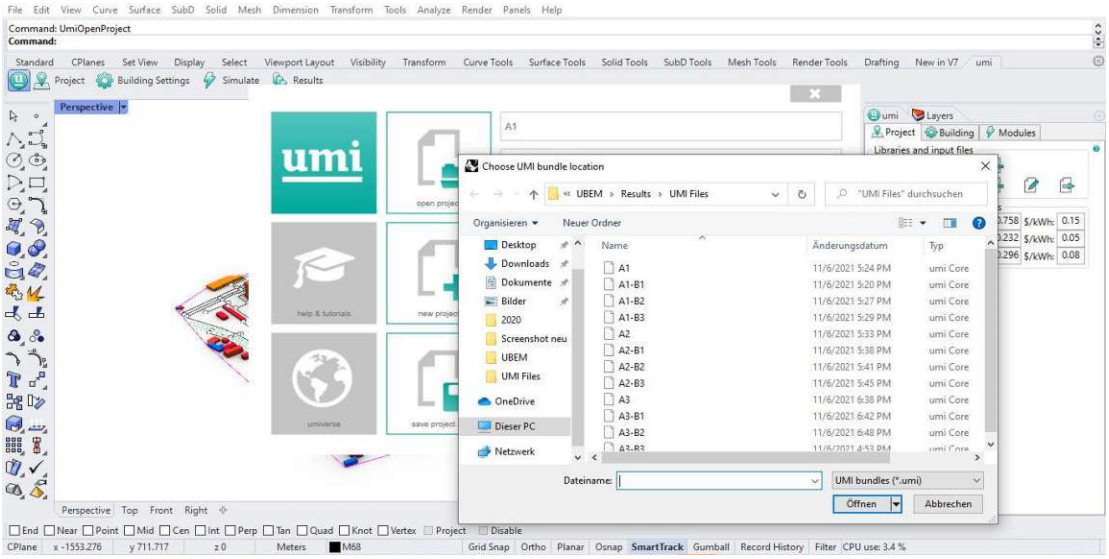

Figure 18: UBEM creation process IX: Load UMI-file to Rhinoceros 3D. *Own application of UBEM visualized in Rhinoceros 3D.*

Once users have selected their UMI-file, Rhinoceros automatically loads a 3D-rendered model of the geometries defined in the UMI-file, as shown in figure 19 below.

Figure 19: UBEM creation process step X: Complete model in Rhinoceros 3D.
Own application of UBEM visualized by Mc Neel, 2021a.

This model includes all shapes of buildings included in the geo-dataset previously being uploaded to ubem.io. Different colours indicate different building types at this

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initial stage of modelling. Now, users have created their base model for UBEM in UMI and can continue to calibrate its parameters, as well as to simulate its energy demand.

3.3.2 UBEM calibration process

This section describes how building templates can be created, edited, and assigned to buildings in UBEM.

As described in section 3.1.1, building templates are one of the three central inputs to UBEMs, as they include information on the building´s energetic performance. Templates are structured as dependent blocks of information, meaning information is grouped in blocks according to topics and referenced by other blocks (SDL, 2017c). This modular structure allows reusing information in several other information blocks across a wider span of topics within the template structure. Hence, there is no need to duplicate information from existing blocks to consider it for other blocks. Figure 19 below illustrates the structure and mutual dependencies of information blocks within templates. As described in section 3.1.1, the UBEM backend applies phyton as an interpreter. Accordingly, figure 20 can also be viewed from a programming perspective: Its header elements represent phyton classes, while the items below represent python functions (Ang et al., 2021: p. 5).

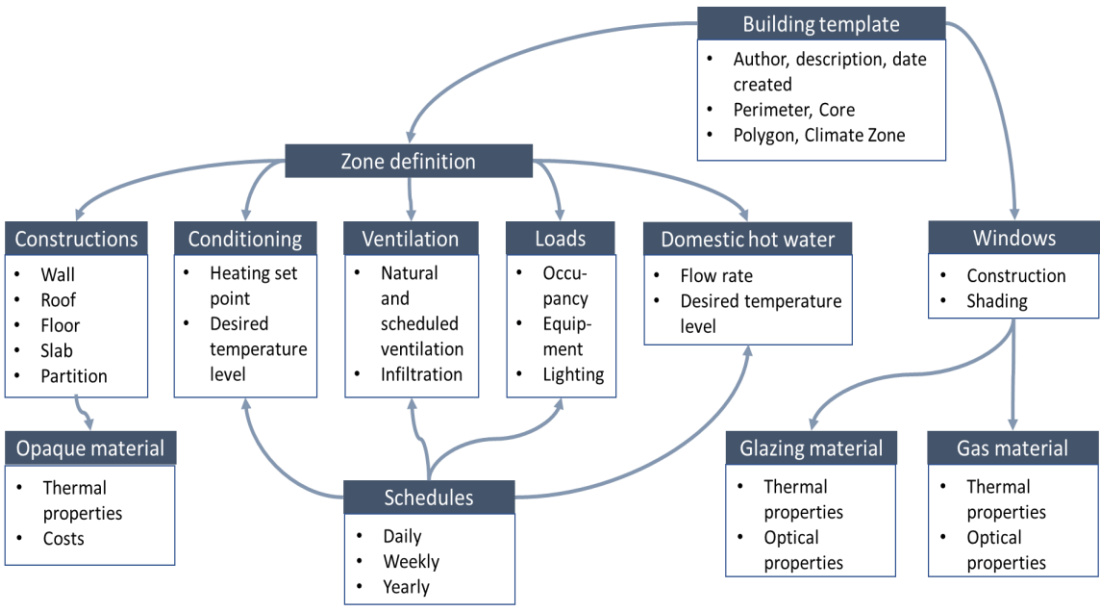

Figure 20: Schematic overview of the building template structure. *Own approach based on Ang et al., 2021: p. 5.*

Via the UMI-toolbar in Rhinoceros, users are provided with the opportunity to view and edit information for every single building type (SDL, 2017b). Via the "Building" tab, building template assignments can be amended and different simulation processes can be selected or disabled for energy simulation of every individual

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building. To change information stored within building templates, users can open the “Template Editor" via the "Project" tab of the toolbar (Ibid).

The “Template editor” is another part of the user interface which translates the user’s calibration of building information into python formats readable by UBEM´s backend (SDL, 2017c). It mimics the interlinked structure of information blocks within the building templates as described above. Therefore, it collects the building information in tabs, which are referencing each other. Each block of a higher hierarchical position references information from blocks of a lower hierarchical position. Conversely, the level of detail of respective information blocks increases, the further low the level of hierarchy within the template structure.

Figures 21 to 28 on the next two pages provide impressions of the “Template editor”. For a more intuitive understanding of the following descriptions, it might be convenient to take a preliminary look first.

The structure of the user interface is the same for all its tabs: There is always a list of template items on the left-hand side, while respective details for these items are displayed on the right-hand side of the editor application window (SDL, 2017e). In the list of items on the left users can select which version of the information block existing they want to view or edit in the detail section on the right. In each detail section of the right side of the editor window, a table is displayed. Here, information categories are described by the "Setting" column. For each of the settings in the column, either information blocks from lower hierarchies can be referenced in the next column “Value”, or information can be manually entered. If information is manually entered in the “Value” column, corresponding units of measurement have to be added in the “Units” column further to the right. This structure of information provision remains constant within the various tabs inside the building template editor. In the header section of the editor, above the item lists on the left-, and detail sections on the right-hand side, basic functionalities are provided (SDL, 2017d). These include saving, adding more templates, or deleting redundant versions from the library.

Practically, if users open the template editor, they are presented with the highest level of hierarchy in the building template structure: The “Building Templates” tab (SDL, 2017f). Here information from lower hierarchy blocks, such as “Zone definition” and “Windows” are combined with information on building structure, partition rate (Degree to which a building is split into rooms, and accordingly involves respective amounts of partition material), the expected lifespan of the building and the default window-to-

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wall-ratio of the respective building type. Figure 21 below provides an impression from the “Building Template”.

As described above, in the “Building Templates” tab, zoning information is referenced from the “Zone Information” tab (SDL, 2017g). Within this tab, again, several sub-information blocks exist. These include the “Zones” sub-tab (SDL, 2017h) by which the following other sub-tabs of “Zone Information” are referenced: “Loads” (SDL, 2017i) for information on heating equipment being employed in the building, “Constructions” (SDL, 2017j) for information on the construction approach to the building, “Conditioning” (SDL, 2017k) reflecting typical values for desired temperature levels and heating threshold temperatures, “Ventilation” (SDL, 2017l) indicating the buildings natural and forced ventilation rates, “Domestic Hot Water” (SDL, 2017m), featuring information on the demand and conditioning of domestic hot water consumed in the building. Beyond, information on internal masses and daylight availability are specified within this information block. Figure 22 provides an impression of the "Zone Information" tab, focussing on the "Zones" sub-tab to provide users with an example.

In addition, the “Zone Information” tab features information on “Windows” (SDL, 2017n), providing information on the construction of windows installed in the building. These are defined by the main “Constructions” tab, described below the upcoming figure section.

There are two "Constructions" tabs. One is the main tab, and another is a sub-tab of the "Zone Information" tab (SDL, 2017j). The latter references information from the main "Constructions" tab, including information on the approach to the construction of facades, groundings, partitions, roofs, and slabs. An example of this sub-tab can be found in figure 23 below. Furthermore, users have the option to indicate whether some of the building parts are adiabatic, meaning there is no natural exchange of gases from within and outside the building possible for part of the construction.

In addition to space heating, heat is consumed for the provision of domestic hot water in most buildings. Users can indicate the need for domestic hot water provision in the "Domestic hot water" tab (SDL, 2017m) by checking the box for the setting "enabled", as in the example of figure 24 below. If the enabling box is checked, the information listed below applies to the building template: "Schedule" referencing usage patterns of domestic hot water within the building, desired supply temperatures, inlet temperatures of water, as well as flow rates for the system.

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TEMPLATE EDITOR: BUILDING TEMPLATES TAB

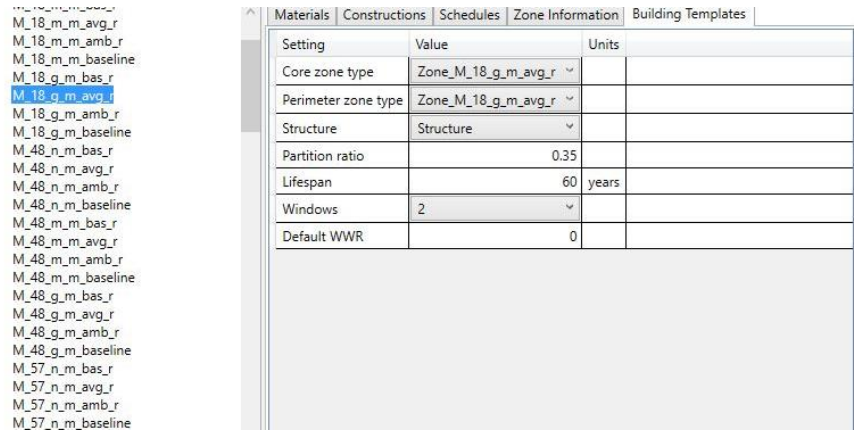

Figure 21: Template editor I: Building templates tab. *Own calibration of SDL, 2017f.*

TEMPLATE EDITOR: ZONE INFORMATION: ZONES TAB

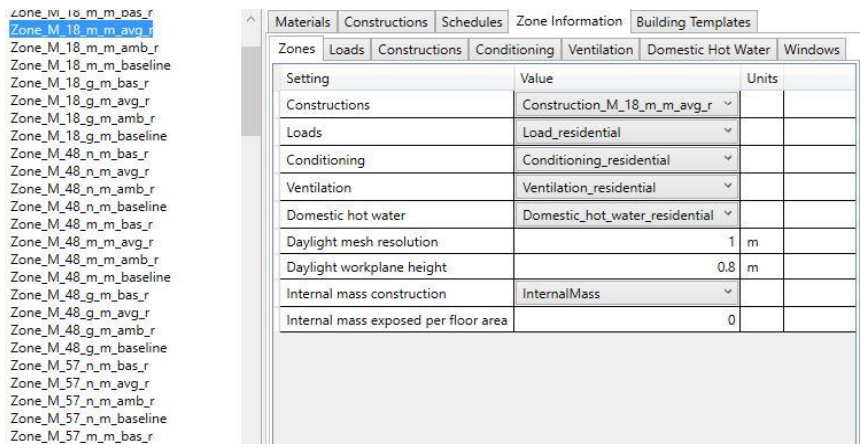

Figure 22: Template editor II: Zone information: Zones tab. *Own calibration of SDL, 2017j.*

TEMPLATE EDITOR: ZONE INFORMATION: CONSTRUCTIONS TAB

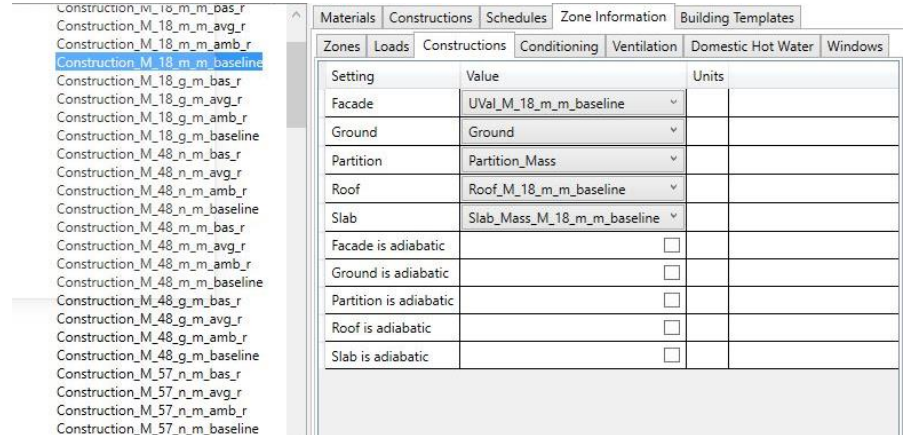

Figure 23: Template editor III: Zone information: Constructions tab. *Own calibration of SDL, 2017.j*

TEMPLATE EDITOR: ZONE INFORMATION: DOMESTIC HOT WATER TAB

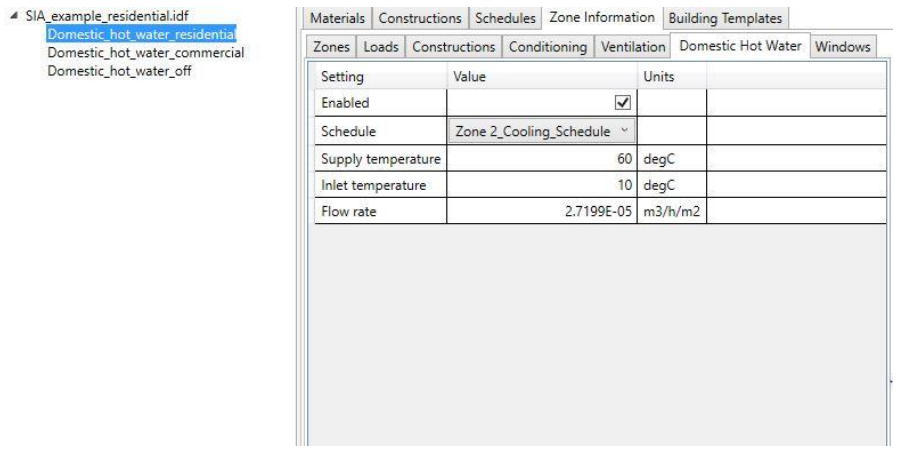

Figure 24: Template editor IV: Zone information: DHW tab. *Own calibration of SDL, 2017m.*

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TEMPLATE EDITOR: SCHEDULES TAB

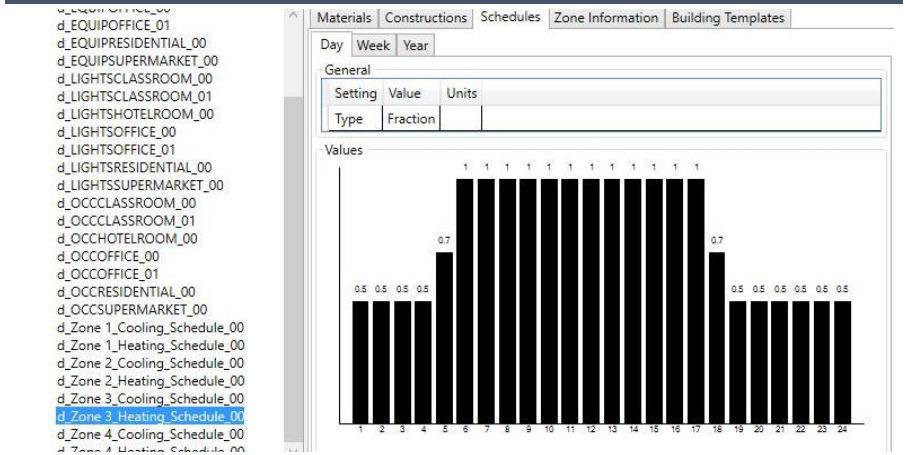

Figure 25: Template editor V: Schedules tab. *Own calibration of SDL, 2017p.*

TEMPLATE EDITOR: MATERIALS: OPAQUE TAB

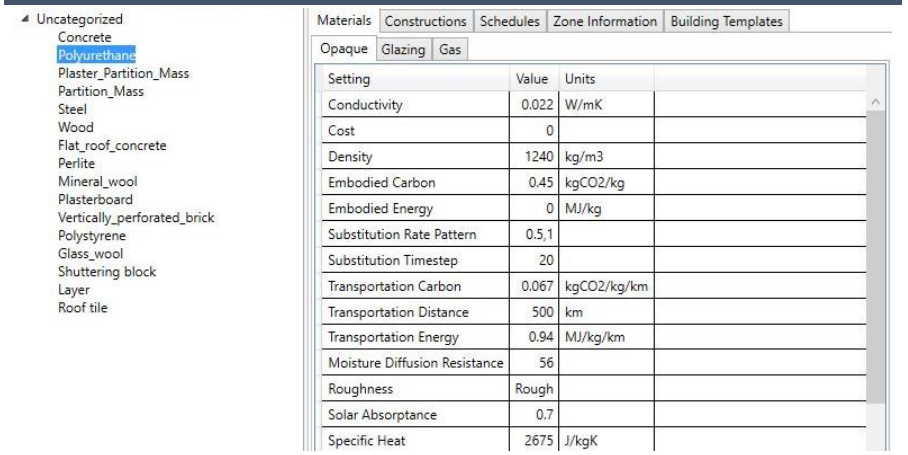

Figure 27: Template editor VII: Materials: Opaque tab. *Own calibration of SDL, 2017q.*

TEMPLATE EDITOR: CONSTRUCTIONS: OPAQUE TAB

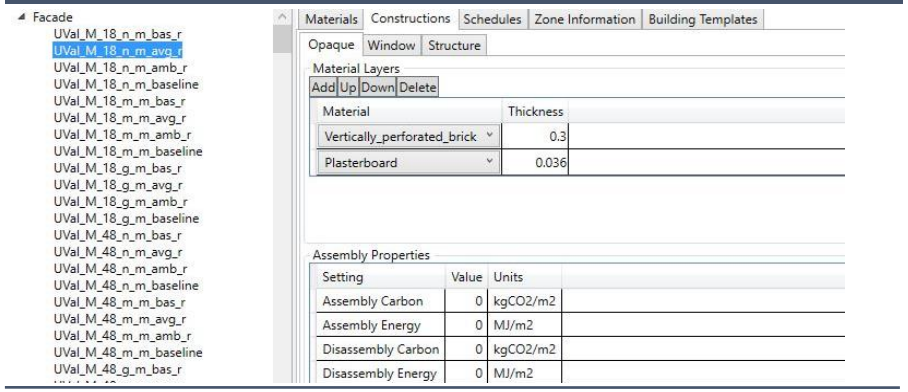

Figure 26: Template editor VI: Constructions: Opaque tab. *Own calibration of SDL, 2017o.*

UBEM IN RHINOCEROS 3D: ASSIGN TEMPLATES TO BUILDINGS

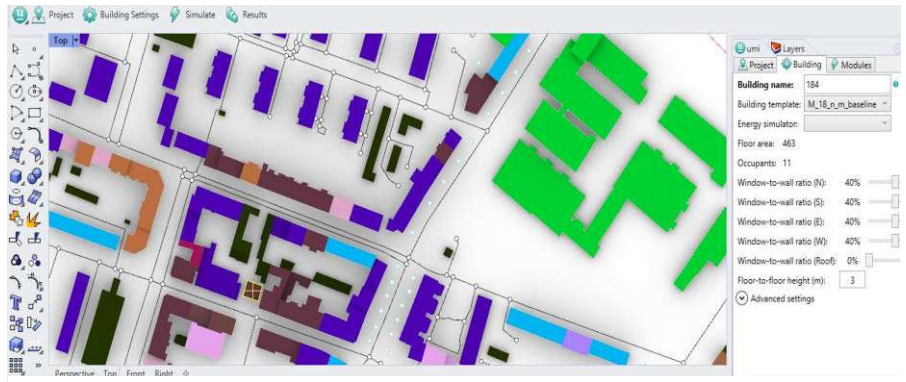

Figure 28: UBEM in Rhinoceros 3D: Assign templates to buildings. *Own application of UBEM.*

Respective patterns of usage are given in the “Schedules” tab (SDL, 2017p). Here, users can differentiate between daily patterns described in the “Day” sub-tab, as well as weekly and yearly patterns, described in the sub-tabs “Week” and “Year”. Yearly patterns are derived by combinations of weekly patterns, which are themselves consisting out of a combination of daily patterns. As shown in figure 25, users can indicate the intensity of usage per hour of the day on a relative scale of 0 to 1, relative to 0 to 100% of the maximum load of the building´s heating equipment. This information is considered when simulating the energy demands of the UBEM.

In the main “Constructions” tab, construction information for building parts, which was referenced by the “Constructions” tab of “Zone Information”, is defined in greater detail (SDL, 2017o). Here users can select building materials, which building parts consist of, and indicate the thickness of constructions. Users can add, move, or delete parts of their building´s construction to change the template if required, or to allow for simulation of energetic refurbishment measures. Additionally, users – optionally – can indicate information on associated costs, embodied energy consumption, and carbon emissions from assembling and disassembling the respective construction. An example of the main “Constructions” tab was provided in figure 26.

On the most detailed level of information, in the “Materials” tab, building materials, being referenced in the main “Constructions” tab are described (SDL, 2017q). This includes thermal conductivity, costs, and density of materials, as well as embodied energy, carbon from natural generation, as well as refining and transportation to the building site. Additionally, users can indicate information on moisture diffusion resistance, solar absorptance, and specific heat of the material. The respective data mask was shown in figure 27.

Once users have gone through the various information tabs within the building templates, they can save their information via the header section of the building template (SDL, 2017e). Completed, or updated building templates need to be uploaded to the UBEM in Rhinoceros via the “Project” tab in the UMI-toolbar, to reflect the latest version of building information.

Loaded building templates can be assigned to individual buildings, by selecting a building shape in the Rhinoceros visualization of the UBEM. This is represented by figure 28. If the building is selected, in the “Building” tab of the UMI-toolbar amongst other indications, a drop-down menu for “Building template” is displayed. Here, users can select a specific template to be assigned to the building (SDL, 2017b).

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Furthermore, in the same tab, users can readjust the window to wall ratios from the UBEM creation process manually on a building-by-building basis, if required.

3.3.3 UBEM simulation process

If users have successfully created and calibrated their UBEM, as well as corresponding building templates, energy simulations can be applied. The UMI-energy plug-in (SDL, 2017r) can be activated from the “Modules” tab in the UMI-toolbar. This module calculates energy consumption, including heating, domestic hot water, and electricity consumption if it is of interest to the user. The simulation runs for all buildings being selected by the user. Hence, users can run the simulation either for the complete model or select just a specific set of buildings for their simulation.

To begin the simulation process, users need to decide which buildings to consider for the simulation process and click on the button "Run Selected” in the energy column of the “Modules” tab of the UMI-toolbar. Subsequently, the energy simulation process is activated in the backend, which is based on the energy plus algorithm by the US department of energy and was described in section 3.1.1. For a more detailed understanding of the algorithm, reading the report “EnergyPlus™ Version 9.6.0 Documentation” by the United States Department of Energy (USDOE, 2021a) is advised. Progress of the backend is indicated by a pop-up window on the right side of the application window of Rhinoceros. Depending on the user´s machine capacity and the volume of buildings to be simulated the simulation process can take between seconds and minutes (Ang et al., 2021: p. 9). Figures 29 provides an impression of the simulation process from one of the UBEM versions being created for the case study district of this thesis.

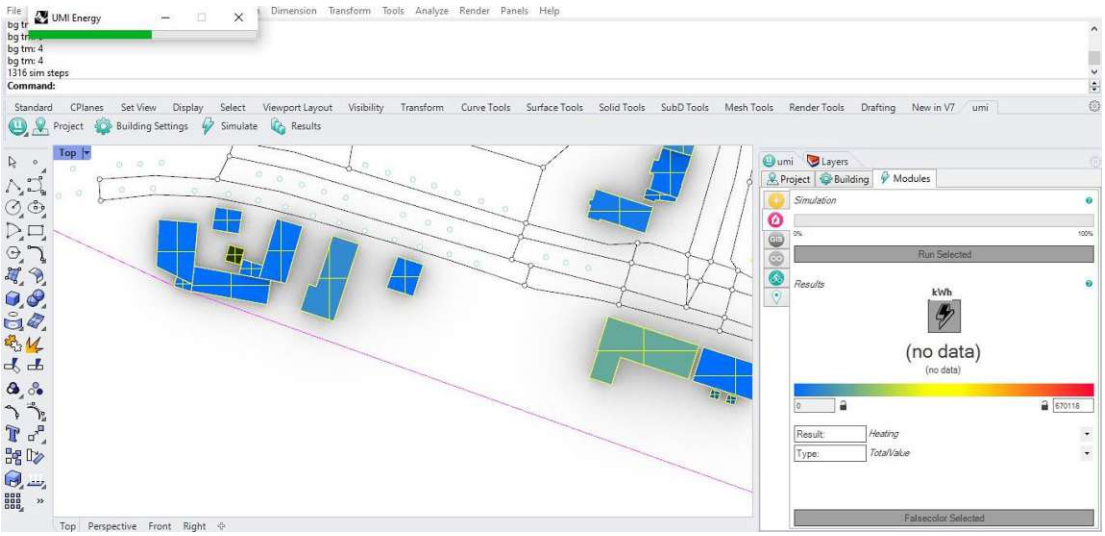

Figure 29: UBEM Energy simulation process. *Own application of UBEM visualized in Rhinoceros 3D (Mc Neel, 2021a).*

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Following the completion of the simulation process, the pop-up window on the progress of the energy simulation automatically disappears. Instead, in the “Modules” tab of the UMI-toolbar, the total energy demand of the UBEM being simulated is displayed. The displayed information is always equal to the heating demand of selected buildings in the UBEM. Accordingly, users can select individual buildings or sets of buildings to review their energy consumption in detail.

Furthermore, the 3D visualization of the UBEM on the left-hand side of the Rhinoceros application window is adapting colours of individual buildings according to the individual building´s energy demand concerning a predefined colour scale of the energy demand in the "Modules" tab. Users can parametrize the scale according to their needs. Colours of buildings will adjust to changes in the parametrization of the scale if users click on the "False-color all" button in the "Modules" tab. Additionally, users can select which indicator of energy consumption to look at. They can choose between heat demand, domestic hot water demand, electricity demand, or total energy demand of the building including all the above (SDL, 2017r).

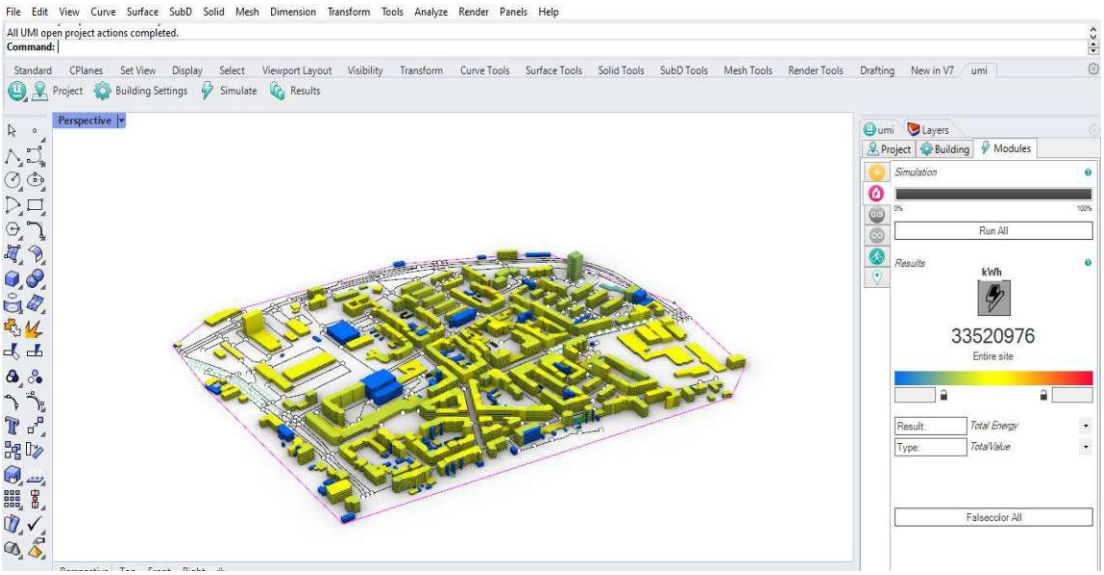

Figure 30: Simulated UBEM. *Own application of UBEM visualized in Rhinoceros. Underlying geo-data: Kiel, 2020f.*

To continue analysis in greater depth or for re-usage as an input to supply-side energy tools, simulation results can be downloaded from the UMI environment. Users need to enter the command “UMI results” into the command line in the header section of the Rhinoceros application window (SDL, 2017s). Consequently, a download process is triggered automatically. Results are received on a building-by-building basis formatted as a CSV file. Impressions of an example can be derived from figure 31.

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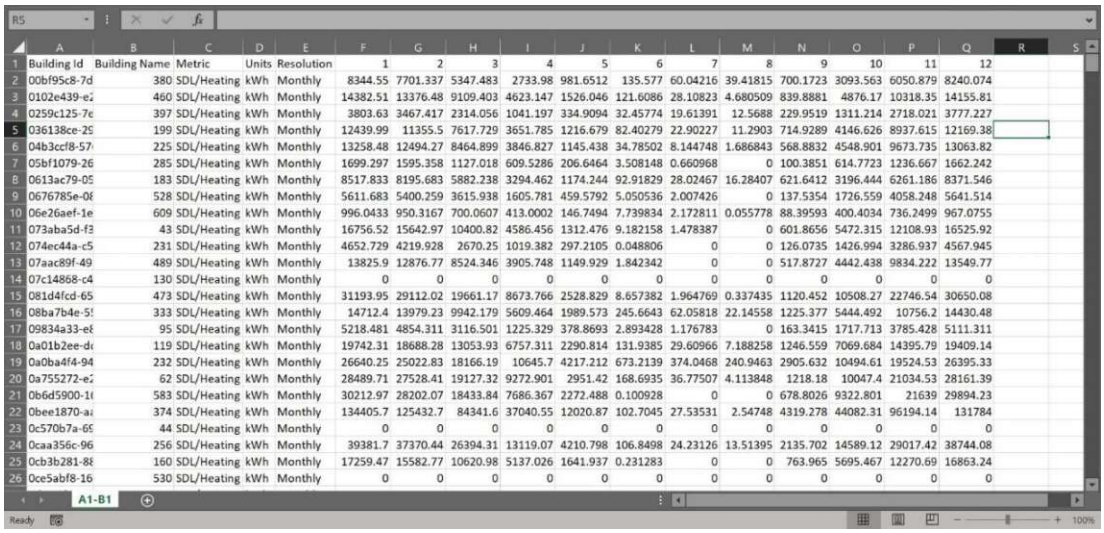

Building Id	Building Name	Metric	Units	Resolution	1	2	3	4	5	6	7	8	9	10	11	12
00bf95c8-7d	380	SDL/Heating	kWh	Monthly	8344.55	7701.337	5347.483	2733.98	981.6512	135.577	60.04216	39.41815	700.1723	3093.563	6050.879	8240.074
0102e439-e2	460	SDL/Heating	kWh	Monthly	14382.51	13376.48	9109.403	4623.147	1526.046	121.6086	28.10823	4.680509	839.8881	4876.17	10318.35	14155.81
0259c125-7e	397	SDL/Heating	kWh	Monthly	3803.63	3467.417	2314.056	1041.197	334.9094	32.45774	19.61391	12.5688	229.9519	1311.214	2718.021	3777.227
036138ce-29	199	SDL/Heating	kWh	Monthly	12439.99	11355.5	7617.729	3651.785	1216.679	82.40279	22.90227	11.2903	714.9289	4146.626	8937.615	12169.38
04b3ccf8-57	225	SDL/Heating	kWh	Monthly	13258.48	12494.27	8464.899	3846.827	1145.438	34.78502	8.144748	1.686843	568.8832	4548.901	9673.735	13063.82
05bf1079-26	285	SDL/Heating	kWh	Monthly	1699.297	1595.358	1127.018	609.5286	206.6464	3.508148	0.660968	0	100.3851	614.7723	1236.667	1662.242
0613ac79-05	183	SDL/Heating	kWh	Monthly	8517.833	8195.683	5882.238	3294.462	1174.244	92.91829	28.02467	16.28407	621.6412	3196.444	6261.186	8371.546
0676785e-0f	528	SDL/Heating	kWh	Monthly	5611.683	5400.259	3615.938	1605.781	459.5792	5.050536	2.007426	0	137.5354	1726.559	4058.248	5641.514
06e26aef-1e	609	SDL/Heating	kWh	Monthly	996.0433	950.3167	700.0607	413.0002	146.7494	7.739834	2.172811	0.055778	88.39593	400.4034	736.2499	967.0755
073aba5d-f3	43	SDL/Heating	kWh	Monthly	16756.52	15642.97	10400.82	4586.456	1312.476	9.182158	1.478387	0	601.8656	5472.315	12108.93	16525.92
074ec44a-c5	231	SDL/Heating	kWh	Monthly	4652.729	4219.928	2670.25	1019.382	297.2105	0.048806	0	0	126.0735	1426.994	3286.937	4567.945
07aac89f-49	489	SDL/Heating	kWh	Monthly	13825.9	12876.77	8524.346	3905.748	1149.929	1.842342	0	0	517.8727	4442.438	9834.222	13549.77
07c14868-c4	130	SDL/Heating	kWh	Monthly	0	0	0	0	0	0	0	0	0	0	0	0
081d4fcd-65	473	SDL/Heating	kWh	Monthly	31193.95	29112.02	19661.17	8673.766	2528.829	8.657382	1.964769	0.337435	1120.452	10508.27	22746.54	30650.08
08ba7b4e-5	333	SDL/Heating	kWh	Monthly	14712.4	13979.23	9942.179	5609.464	1989.573	245.6643	62.05818	22.14558	1225.377	5444.492	10756.2	14430.48
09834a33-e8	95	SDL/Heating	kWh	Monthly	5218.481	4854.311	3116.501	1225.329	378.8693	2.893428	1.176783	0	163.3415	1717.713	3785.428	5111.311
0a01b2ee-d	119	SDL/Heating	kWh	Monthly	19742.31	18688.28	13053.93	6757.311	2290.814	131.9385	29.60966	7.188258	1246.559	7069.684	14395.79	19409.14
0a0ba4f4-94	232	SDL/Heating	kWh	Monthly	26640.25	25022.83	18166.19	10645.7	4217.212	673.2139	374.0468	240.9463	2905.632	10494.61	19524.53	26395.33
0a755272-e2	62	SDL/Heating	kWh	Monthly	28489.71	27528.41	19127.32	9272.901	2951.42	168.6935	36.77507	4.113848	1218.18	10047.4	21034.53	28161.39
0b6d5900-1	583	SDL/Heating	kWh	Monthly	30212.97	28202.07	18433.84	7686.367	2272.488	0.100928	0	0	678.8026	9322.801	21639	29894.23
0bee1870-a	374	SDL/Heating	kWh	Monthly	134405.7	125432.7	84341.6	37040.55	12020.87	102.7045	27.53531	2.54748	4319.278	44082.31	96194.14	131784
0c570b7a-69	44	SDL/Heating	kWh	Monthly	0	0	0	0	0	0	0	0	0	0	0	0
0caa356c-96	256	SDL/Heating	kWh	Monthly	39381.7	37370.44	26394.31	13119.07	4210.798	106.8498	24.23126	13.51395	2135.702	14589.12	29017.42	38744.08
0cb3b281-88	160	SDL/Heating	kWh	Monthly	17259.47	15582.77	10620.98	5137.026	1641.937	0.231283	0	0	763.965	5695.467	12270.69	16863.24
0ce5abf8-16	530	SDL/Heating	kWh	Monthly	0	0	0	0	0	0	0	0	0	0	0	0

Figure 31: UBEM simulation: Export of results. *Own application of SDL, 2017s.*

Results are presented in the form of one building per line. This line includes the building ID, the building name, which is the same as presented in the “Building” tab of the UMI-toolbar, information on metrics, respective units, and timely resolution. Additionally, results for 12 months of a year are given by the indicators of 1-12. The data can be summed either vertically to receive the total for all buildings, horizontally to receive the total for a complete year, or both to receive the total consumption of all buildings over a complete year.

3.3.4 Integration process of UBEM results into the Hotmaps toolbox

The Hotmaps toolbox provides users either with a built-in top-down approach to heat demand per area, as described in section 3.1.2, or allows users to upload their own interpretation of heat demand to the toolbox via its stand-alone calculation module “CM - Customized Heatmaps” (Fallahnejad, 2020a). To simulate supply indications based on the UBEM models being created and simulated before, users need to integrate results from UBEM into the Hotmaps toolbox. This section will focus on the technical approach to data integration, not on the sensitivity to it, which will be described in greater detail in section 4.3.

To integrate results from UBEM into Hotmaps, users need to conduct a joining and formatting exercise via a data-sheet manipulation program, such as Microsoft Excel (MS, 2021a). As described in section 3.3.4, UBEM energy results are provided as a CSV file, which can be viewed and edited in datasheet manipulation programs. Input files to the calculation module “Customized Heatmaps” by the toolbox are equally required in a CSV format (Fallahnejad, 2020a). Hence, data from UBEM result sheets can be reformatted and enhanced to serve as an input to Hotmaps..

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	ID_shp	hotmaps_ID	constructionYear	GFA	demand	X_3035	Y_3035	A1 = Typical values by age	A2 = Visual impression	Reason for A2	A3 = Data from district
1	237	1_1	NRB	2728.40		4330056.13	3467331.21	n_m	n_m	commercial use	n_m
2	238	1_2	N_HR	20.48		4330063.22	3467365.06	n_m	n_m	commercial use	n_m
3	239	1_3	N_HR	0.00		4330071.99	3467373.18	n_m	n_m	commercial use	n_m
4	236	2_1	NRB	79.97		4330062.52	3467262.34	n_m	n_m	commercial use	n_m
5	235	2_2	N_HR	27.07		4330051.68	3467221.88	n_m	n_m	commercial use	n_m
6	241	4_1	NRB	221.57		4330156.9	3467438.98	m_m	n_m	commercial use	m_m
7	253	4_2	Before 1918	815.74		4330165.36	3467484.56	n_m	n_m	old roof; no insulation visible	n_m
8	254	4_3	Before 1918	1160.38		4330173.37	3467498.28	n_m	n_m	old roof; no insulation visible	n_m
9	264	4_4	NRB	2955.71		4330195.37	3467469.59	m_m	m_m	Glass building extensions, new	m_m
10	242	4_5	N_HR	0.00		4330150.44	3467465.15	n_m	n_m	commercial use	n_m
11	247	4_6	NRB	76.30		4330165	3467433.31	m_m	n_m	commercial use	m_m
12	614	5_1	NRB	356.93		4330132.66	3467333.01	m_m	n_m	commercial use	m_m
13	612	5_2	NRB	5792.95		4330141.34	3467331.4	m_m	n_m	commercial use	m_m
14	615	5_3	NRB	705.73		4330157.79	3467338.23	m_m	n_m	commercial use	m_m
15	613	5_4	NRB	2944.67		4330182.28	3467315.93	m_m	n_m	commercial use	m_m
16	240	6_1	NRB	498.47		4330152.54	3467259.05	m_m	n_m	commercial use	m_m
17	260	6_2	NRB	542.15		4330144.43	3467239.64	n_m	n_m	old roof; no insulation visible	n_m
18	535	7_1	NRB	277.88		4330189.73	3467171.13	m_m	n_m	commercial use	m_m
19	530	7_2	N_HR	20.23		4330191.74	3467155.4	n_m	n_m	commercial use	n_m
20	259	8_1	N_HR	477.55		4330237.26	3467679.95	n_m	n_m	commercial use	n_m
21	268	9_1	Before 1978	1196.84		4330222.5	3467522.05	n_m	n_m	commercial use	n_m
22	255	9_2	NT_RB	150.80		4330230.38	3467570.82	m_m	n_m	commercial use	m_m
23	258	9_3	NRB	496.67		4330265.18	3467572.28	m_m	n_m	public building	m_m
24	256	9_4	YH	2278.89		4330264.78	3467510.99	m_m	m_m	modernized roof	m_m
25	400	9_5	YH	1023.69		4330281.42	3467511.55	m_m	m_m	modernized roof	m_m

Figure 32: Masterfile: Information on building stock. *Own approach: Data partly based on UBEM results.*

Users are advised to create a Masterfile, including a list of buildings in their model and UBEM results of various model sensitivities on the demand side in separate datasheets. Figure 32 provides an example from this case study (complete Masterfile in appendix). It contains a list of buildings in the model. Each building is being assigned to a specific ID in column A, while the building name from the original shape-file, hence the building ID from UBEM, appears in column B. For the construction year, codes of building types are assigned. These codes are aligned with the codes for building template codes defined for UBEM. "GFA", in column E provides information on the gross floor area (GFA) per building. Columns G and H include information on the geo-location of the respective building or building part.

Further information in columns I to L is dispensable. They are derived from earlier along with the integrated toolchain when buildings were assigned initial refurbishment status. This information is included to help the user to maintain an overview on which initial refurbishment status was assigned to which specific building.

The most important column is "demand" in column F. Here, users creating the Masterfile via Microsoft Excel, are advised to enter a VLOOKUP formula (MS, 2021b), referencing data from the separate sheets in the same file. Users not using Microsoft Excel should apply functionalities allowing for the same operation to be conducted.

The sheets, from which data is referenced, are holding the results from UBEM energy simulations. They were received as CSV downloads. In a VLOOKUP formula, users need to specify the sheet to be looked at by the program, the value to be found within the sheet specified, and the relative position of the return value to the lookup value in the lookup sheet (MS, 2021b). An example: If a user wants the program to automatically return the value for heat demand from a separate sheet holding results

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for sensitivity A1-B1 into column F “demand” of the list in the Masterfile, he or she needs to specify the separate sheet “A1-B1” as look-up sheet, the building name, “ID_shp” as column holding the look-up values and if the demand values are provided two columns left from the building name on look-up sheet, “2” as the relative position of the return value from the lookup value in the look-up sheet.

Users are advised to keep the same format throughout all their separate sheets holding UBEM results. Thereby, to select results from different sensitivities to be represented in the list of buildings, users just need to specify a different look-up sheet within the VLOOKUP formula in column F “demand”. For example, exchange "A1-B1" from above with "A3-B2" in the formula to automatically receive the complete data for sensitivity A3-B2. This will save effort and time when preparing input files to the Hotmaps toolbox later, as described on the next page.

Also, on the next page, an online tool allowing for determination of the geo-locations of heat demand for integration into Hotmaps will be described. Figure 33 provides an impression.

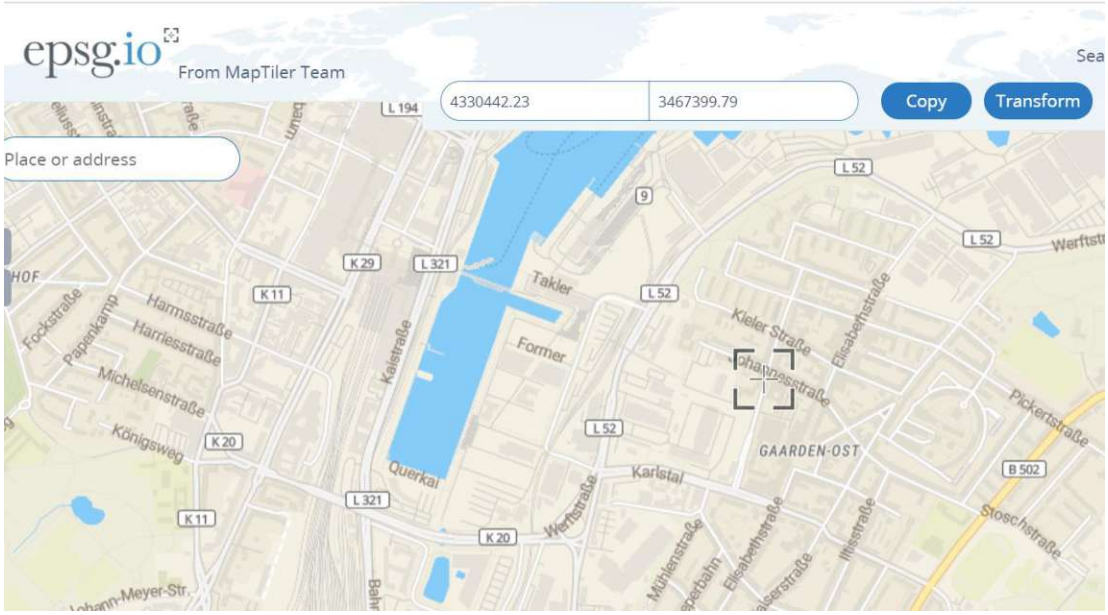

Figure 33: Determination of EPSG:3035 coordinates. *Own application of EPSG.io.*

Coordinates of centre locations of buildings, being held in columns G and H, can be derived from the initial geo-dataset if available in the correct format. Locations are required to be stated in a European Petroleum Survey Group (EPSG) Geodetic Parameter Dataset under the identifier: EPSG:3035. This is a global coordinate reference system, dividing the world´s surface into 4321000 meters easting and 3210000 meters northing (Peifer, 2011: p. 1). If the coordinates of buildings are not

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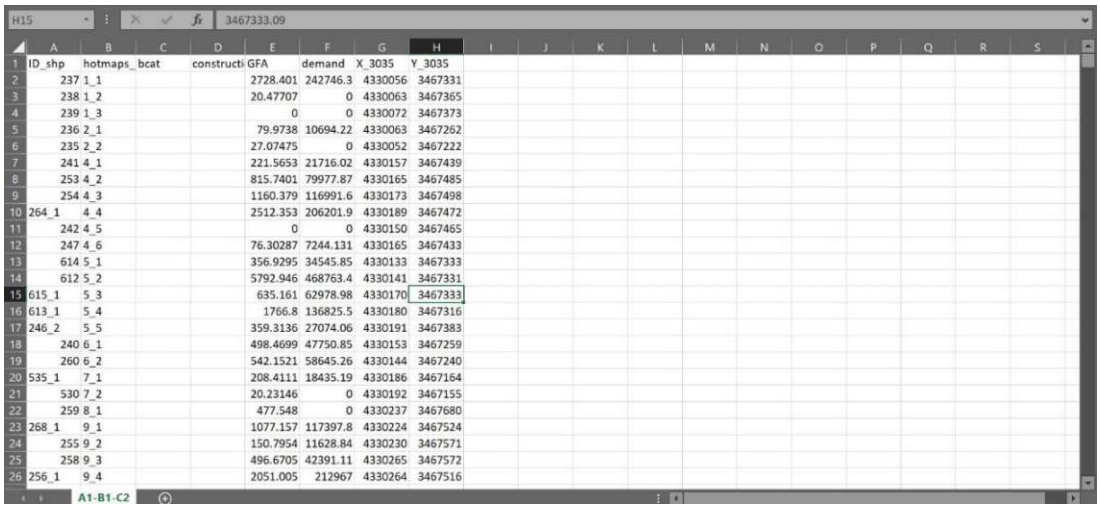
provided by the geo-dataset in EPSG format, users can use open-source online tools, such as epsg.io (EPSG, 2021), which was shown in figure 33 to derive the coordinates of respective buildings.

To include the coordinates, users need to specify the exact location of the building´s central location in the online user interface of the application. Afterward, they can copy the correct EPSG:3035 coordinates from the website and paste them in columns G and H of the relevant line of the building within the list of buildings in the Masterfile.

The Masterfile can serve as central data storage for the integration of data from UBEM into Hotmaps, which is helpful for the process of allocating heat demand manually. This will be described in section 4.3 However, the calculation module “Customized Heatmaps” requires data in a specific format of a CSV file (Fallahnejad, 2020a). Hence, users are advised to create separate input files for each demand-side sensitivity: Each of these will be based on the Masterfile. Every demand-side sensitivity will be called by the VLOOKUP formula, offering the opportunity to copy data for the separate sheets per sensitivity. Subsequently, from the Masterfile dispensable information for the calculation module to perform will be removed.

An example of the format and remaining information from the Masterfile in a separate CSV input-file to the toolbox is provided by figure 34 below: “ID_shp” in column A, and the “hotmaps_ID” in column B are kept unchanged. Columns C and D are not specified. However, except for their headers, these columns can be left blank without any impact on the functionality of Hotmaps (Fallahnejad, 2020a). “GFA”, “demand”, “X_3035”, and “Y_3035” complete the extract from the list of buildings in the Masterfile, to be considered as input-file for the Hotmaps toolbox.



ID_shp	hotmaps_bcat			GFA	demand	X_3035	Y_3035
237	1_1			2728.401	242746.3	4330056	3467331
238	1_2			20.47707	0	4330063	3467365
239	1_3			0	0	4330072	3467373
236	2_1			79.9738	10694.22	4330063	3467262
235	2_2			27.07475	0	4330052	3467222
241	4_1			221.5653	21716.02	4330157	3467439
253	4_2			815.7401	79977.87	4330165	3467485
254	4_3			1160.379	116991.6	4330173	3467498
264_1	4_4			2512.353	206201.9	4330189	3467472
242	4_5			0	0	4330150	3467465
247	4_6			76.30287	7244.131	4330165	3467433
614	5_1			356.9295	34545.85	4330133	3467333
612	5_2			5792.946	468763.4	4330141	3467331
615_1	5_3			635.161	62978.98	4330170	3467333
613_1	5_4			1766.8	136825.5	4330180	3467316
246_2	5_5			359.3136	27074.06	4330191	3467383
240	6_1			498.4699	47750.85	4330153	3467259
260	6_2			542.1521	58645.26	4330144	3467240
535_1	7_1			208.4111	18435.19	4330186	3467164
530	7_2			20.23146	0	4330192	3467155
259	8_1			477.548	0	4330237	3467680
268_1	9_1			1077.157	117397.8	4330224	3467524
255	9_2			150.7954	11628.84	4330230	3467571
258	9_3			496.6705	42391.11	4330265	3467572
256_1	9_4			2051.005	212967	4330264	3467516

Figure 34: Exemplary input file for CM - Customized heatmaps of the Hotmaps toolbox. *Application of Fallahnejad, 2020a.*

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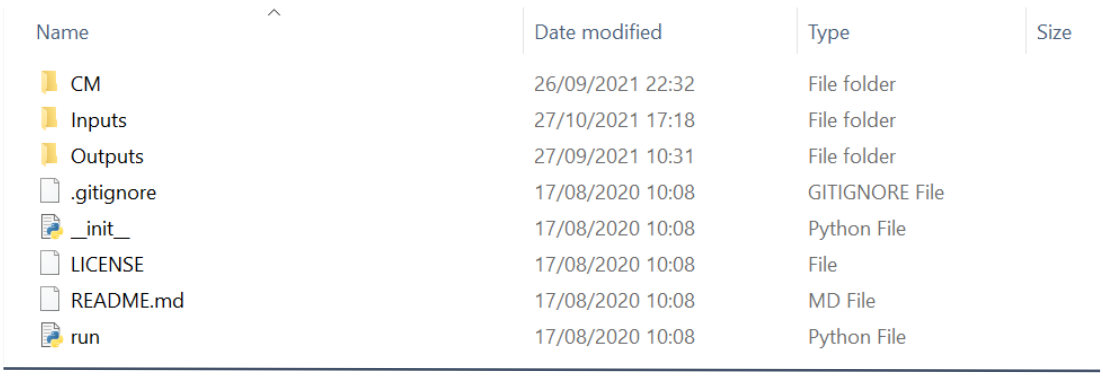
While the example shows the input file for sensitivity A1-B1-C2, such input files need to be created for every sensitivity on the demand side, drawing from the Masterfile, as described above. Completed input files should be stored in a separate folder location on the user´s machine to avoid confusion with the Masterfile.

Having converted data into input files ready to be fed to the calculation modules, users need to download the stand-alone application for the customized calculation module on their machine (Fallahnejad, 2021). An overview of the applications available for the module is provided in figure 35 below.



Name	Date modified	Type	Size
CM	26/09/2021 22:32	File folder	
Inputs	27/10/2021 17:18	File folder	
Outputs	27/09/2021 10:31	File folder	
.gitignore	17/08/2020 10:08	GITIGNORE File	
__init__	17/08/2020 10:08	Python File	
LICENSE	17/08/2020 10:08	File	
README.md	17/08/2020 10:08	MD File	
run	17/08/2020 10:08	Python File	

Figure 35: CM – Customized heatmaps: Application components. *Impression of Fallahnejad, 2021 on user´s machine.*

The download is available at the online wiki and application environment of the toolbox (Hotmaps, 2021). As shown above, the download folder includes phyton scripts performing the calculations necessary to complete the module in the sub-folder "CM", a placeholder for input files in the sub-folder "Inputs", as well as a placeholder for output files in the sub-folder "Outputs".

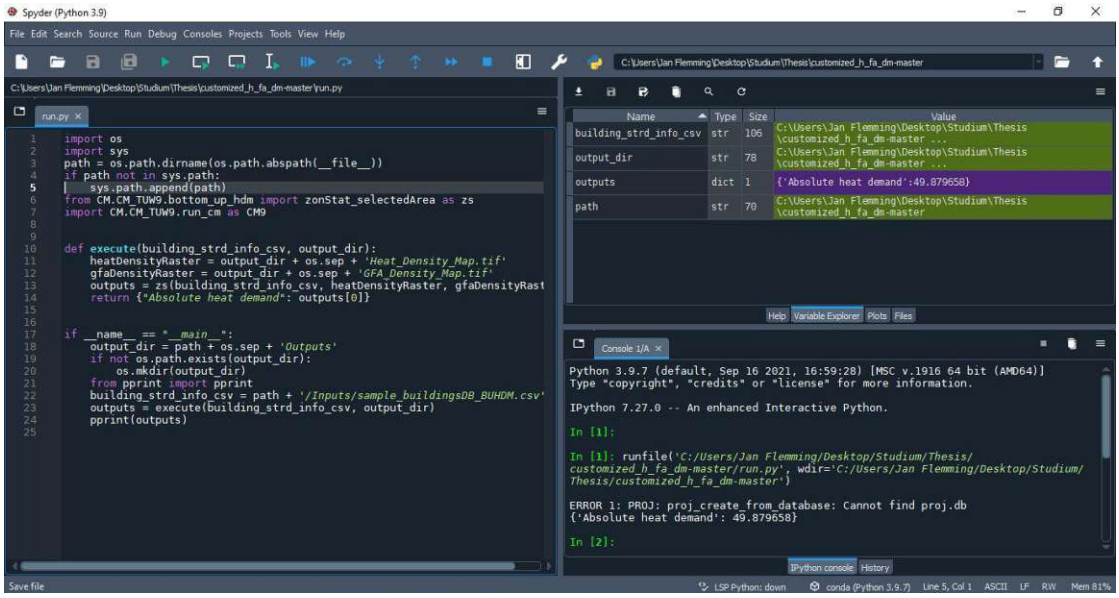


Figure 36: CM – Customized heatmaps: Application script in an IDE. *Own application of Fallahnejad, 2020a.*

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"Run" is a phyton file, serving as the central application to be run by the user in a customized Phyton individual development environment (IDE) (e.g., Anaconda, 2021; Spyder, 2021). This IDE needs to include installed version of the phyton packages: Pandas (data manipulation (Pandas, 2021)), “NumPy” (numerical arrays (NumPy, 2021)), “GeoPandas” (geospatial analysis (GeoPandas, 2021)), and GDAL (geo-spatial abstraction (Warmerdam and Rouault, 2021)). Without these packages being stalled the calculation module cannot return any results as an output. Figure 36 above provided an impression from the “Run” file displayed in an IDE.

To create output files, users need to copy and paste one of their input files at a time into the “Input” subfolder of the calculation module folder. Following this transaction, the module is ready to be executed. Users need to press the “Run” button of their IDE, to perform the python scripts being provided by the calculation module (Fallahnejad, 2020a). Depending on the size of the input file and the capacity of the machine being used by the user, the data transformation process may take from a few seconds up to a few minutes. If the calculation module is executed successfully, two new files are generated and stored in the “Output” sub-folder. These are .tif files, an image format (Aldus Developers Desk (ADD), 1992: pp. 4-5), and represent the heat demand and gross floor areas within the use case area, as specified in the input file. These files should again be saved in a separate folder to avoid confusion and clear the calculation module for future performance.

To visualize and use output files in the toolbox, users need to upload them to the Hotmaps online environment. Therefore, users are required to create an individual user account (Hunacek and Zuber, 2020b). Each user is being provided a limited but for most cases sufficient, data storage capacity on the Hotmaps server to apply customized maps of heat demand and gross floor areas. Figure 37 provides an impression of the toolbox´s user interface, allowing for uploads of customized maps. These need to be selected via the box “Select files” and be confirmed via the button “Upload Layer” to be added to the individual user´s library. The list above the selection section provides an overview of files being stored in the library already.

To visualize and apply customized maps, users can activate their uploaded map material via the “Layers” tab in the toolbox (Hotmaps, 2021). There they can select and deselect each of their customized heat maps, as well as the default heatmap by the toolbox.

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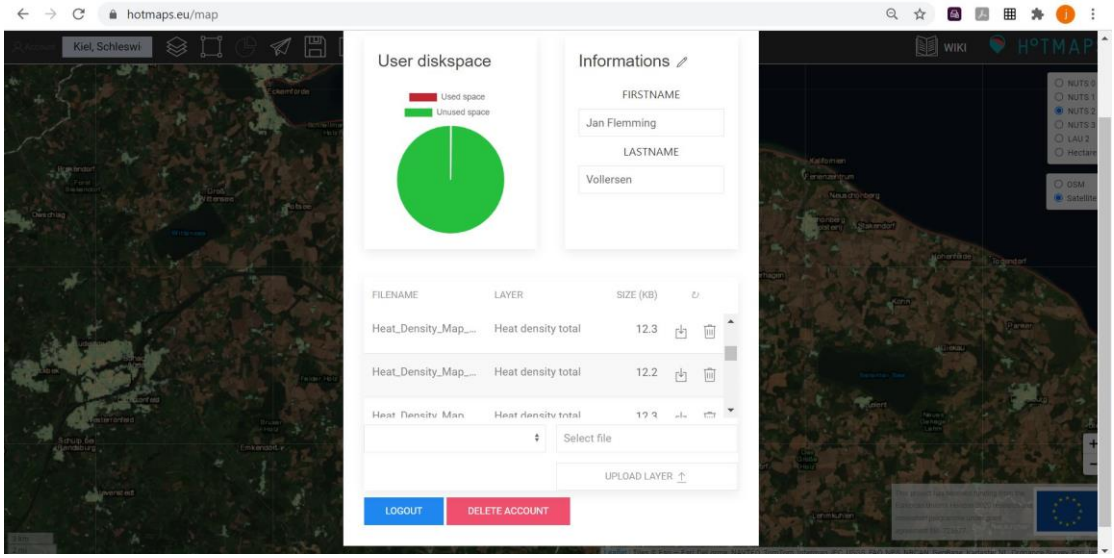

Figure 37: Hotmaps toolbox: Individual user account interface. *Own application of Hunacek and Zuber, 2020b.*

If they zoom into the relevant area covered by their model, they can see a heatmap on a hectare level. This is representing the data from their input files to the calculation module “Customized Heatmaps”, hence information derived from the UBEM results. Figure 38 shows an example of sensitivity A3_C1 being layered over the case study district in the city of Kiel.

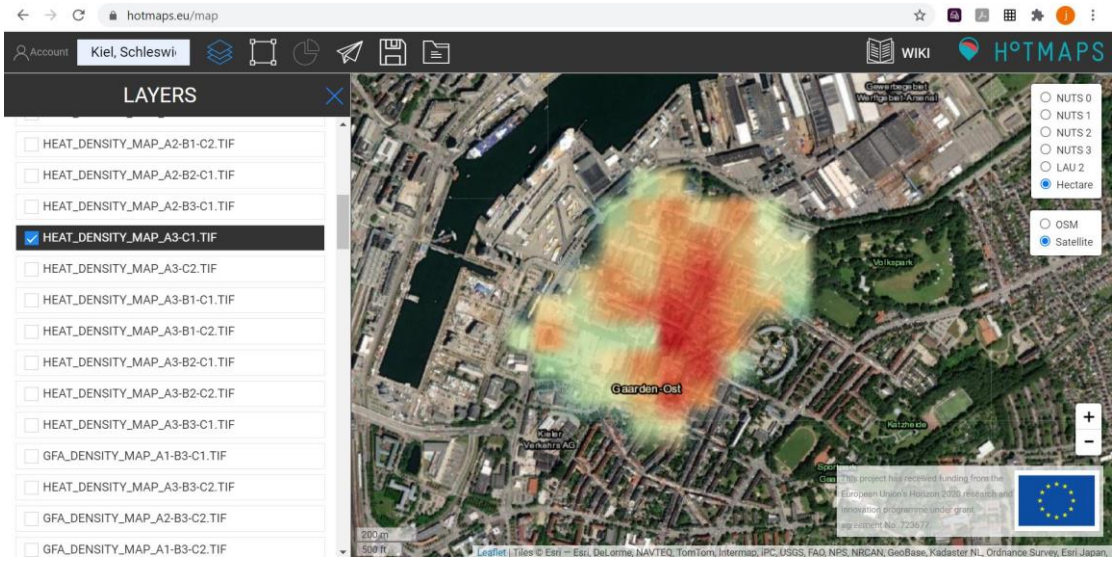

Figure 38: Customized heatmap layers in the Hotmaps toolbox. *Own application of Hunacek and Zuber, 2020b.*

Having successfully integrated information on heat demand estimations from UBEM simulation results into the Hotmaps toolbox, users can continue with the simulation and calculation of supply-side measures and indicators.

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3.3.5 Hotmaps toolbox calibration process

Users having uploaded their customized heatmaps, or using the default top-down approach to heat demand mapping by the toolbox, can use its calculation modules to calculate and simulate supply-side measures. Therefore, they need to activate the "Selection Tool" and select an area within their heatmap, on which they want to perform their simulations (Hasani, 2019a). To calibrate the input parameters of the calculation modules, they can select the "Calculation Modules" column under the "Layers" tab within the toolbox (Hasani, 2019d). In this column, they will find a list of the modules being available for simulation processes, as described in section 3.1.2.

Once they decide to apply one of the calculation modules, a list of adjustable input parameters is presented on the left-hand side of the Hotmaps online application window (Hasani, 2019b). Here, users can calibrate the input parameters to fit their scenarios, which they want to be simulated by the toolbox. Figure 39 shows the Hotmaps calibration pane for the example of the case study district in Kiel Gaarden. Within the black pane on the left-hand side of the screen, the slightly lighter boxes are amendable input fields according to the user's needs.

Some modules furthermore require specifying a map layer on which basis the simulation shall be conducted. In this case, users should select their intended layer from a drop-down menu at the end of the black input calibration pane (e.g., Fallahnejad, 2020a).

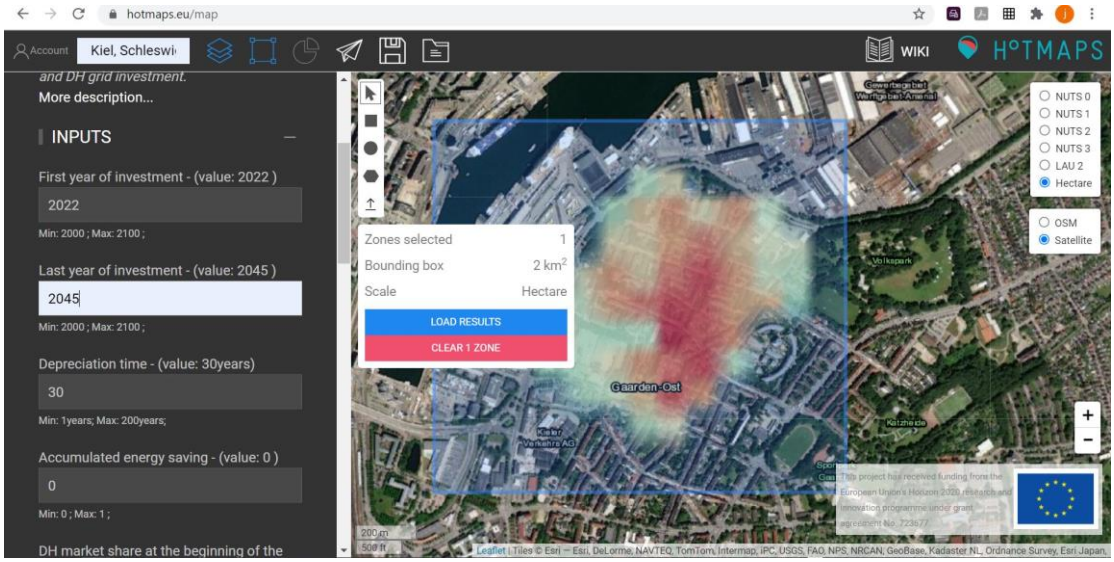

Figure 39: Calculation module calibration for customized heatmap. *Own application of Hasani, 2019a and Hasani,*

3.3.6 Hotmaps toolbox simulation process

Once users have finalized the calibration of the input parameters to the respective calculation module, which they want to be executed, they need to confirm their

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choices by pressing the button “RUN CM”, just below the last item of the input parameter calibration pane.

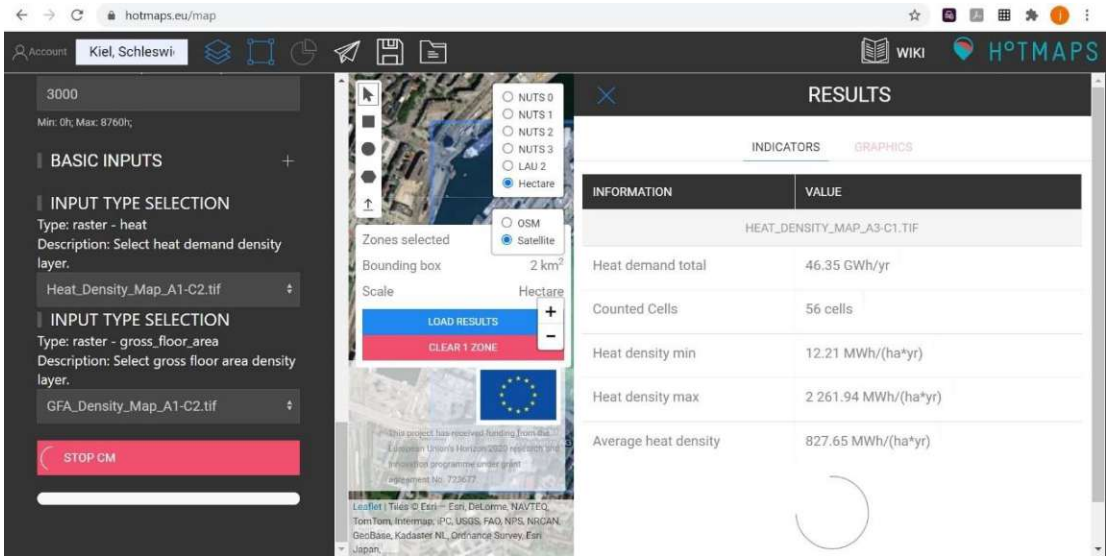

Figure 40: Application of calculation module on customized heatmap. *Application with accordance to Hasani, 2019e.*

Immediately, a white progress bar appears below the button, indicating progress being made by the module in blue colour. In addition, on the right-hand side of the Hotmaps browser window, a “RESULTS” box appears (Hasani, 2019e). It includes the columns “INDICATORS” and “GRAPHICS”. Under the “INDICATORS” tab, “INFORMATION”, such as “Heat demand total”, and various indicators of heat demand density are displayed. Further, specific results from the calculation module are added to both columns as soon as the module has finished its simulation process in the backend. Under “GRAPHICS” results are displayed visually by various charts, while “INDICATORS” purely displays numerical values.

Both result tables can be downloaded as CSV files. Accordingly, for simulation results from most calculation modules, two sets of downloads are available (Hunacek and Zuber, 2020c). These can be used for further in-depth analysis or combined for comparison. Figure 41 is an example of a downloaded result file from the “GRAPHICS” column of the “CM – District Heating Supply Dispatch” calculation module (Hasani, 2020). Column A “serie” shows which indicators are described by the lines and in which unit of measurement. Column B, “label”, indicates which energy carrier option for supply the lines are related to, while column D is not relevant for the interpretation of results, and column C provides the quantitative “value” connected to indicators and units of measurement given by column A.

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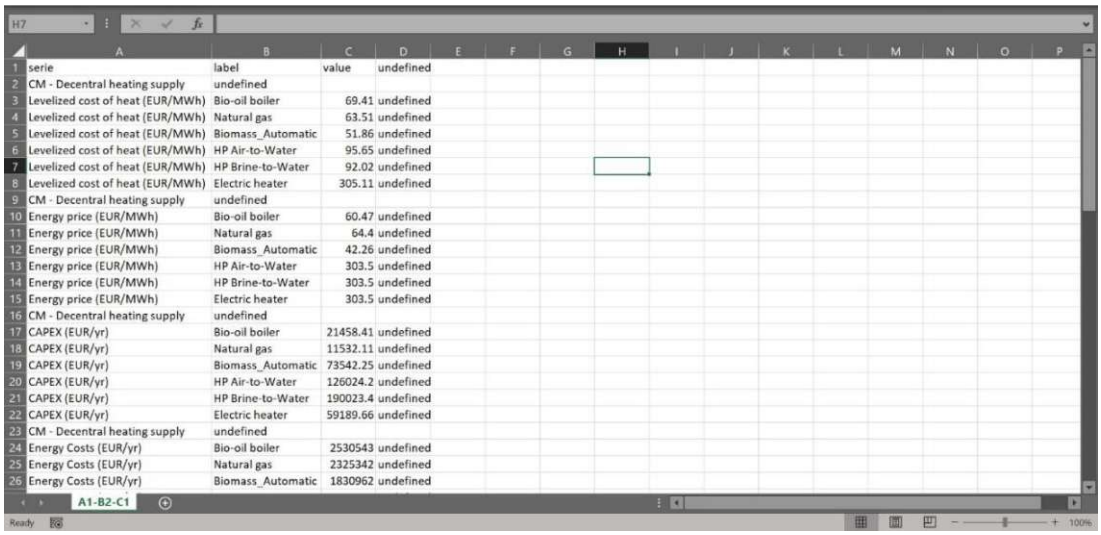

serie	label	value	undefined
CM - Decentral heating supply	undefined		
Levelized cost of heat (EUR/MWh)	Bio-oil boiler	69.41	undefined
Levelized cost of heat (EUR/MWh)	Natural gas	63.51	undefined
Levelized cost of heat (EUR/MWh)	Biomass_Automatic	51.86	undefined
Levelized cost of heat (EUR/MWh)	HP Air-to-Water	95.65	undefined
Levelized cost of heat (EUR/MWh)	HP Brine-to-Water	92.02	undefined
Levelized cost of heat (EUR/MWh)	Electric heater	305.11	undefined
CM - Decentral heating supply	undefined		
Energy price (EUR/MWh)	Bio-oil boiler	60.47	undefined
Energy price (EUR/MWh)	Natural gas	64.4	undefined
Energy price (EUR/MWh)	Biomass_Automatic	42.26	undefined
Energy price (EUR/MWh)	HP Air-to-Water	303.5	undefined
Energy price (EUR/MWh)	HP Brine-to-Water	303.5	undefined
Energy price (EUR/MWh)	Electric heater	303.5	undefined
CM - Decentral heating supply	undefined		
CAPEX (EUR/yr)	Bio-oil boiler	21458.41	undefined
CAPEX (EUR/yr)	Natural gas	11532.11	undefined
CAPEX (EUR/yr)	Biomass_Automatic	73542.25	undefined
CAPEX (EUR/yr)	HP Air-to-Water	126024.2	undefined
CAPEX (EUR/yr)	HP Brine-to-Water	190023.4	undefined
CAPEX (EUR/yr)	Electric heater	59189.66	undefined
CM - Decentral heating supply	undefined		
Energy Costs (EUR/yr)	Bio-oil boiler	2530543	undefined
Energy Costs (EUR/yr)	Natural gas	2325342	undefined
Energy Costs (EUR/yr)	Biomass_Automatic	1830962	undefined

Figure 41: Download of results from calculation module application. *Own application of the Hotmaps toolbox: Hasani 2019c.*

Figure 41 serves as an example of a download of results again from the calculation module “CM – District Heating Supply Dispatch”. Download sheets for results from other calculation modules are structured by the same approach. However, slight differences in format and content due to different topics of the modules remain.

At this point, users should be able to collect, compare, and interpret results from all supply-side calculation modules being available from the Hotmaps toolbox. Furthermore, they should have gained a basic understanding of all relevant applications of UBEM and the Hotmaps toolbox alongside the integrated toolchain, as described in the previous sections. For the coming chapter 4, it will be of interest to apply and embed the methodologies employed for the integrated toolchain to a realistic case study use case. In conjunction with the case study, the impact of described sensitivities alongside the integrated toolchain will be assessed.

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4 CASE STUDY: SENSITIVITY ASSESSMENT OF DATA LINKS FOR A DISTRICT IN KIEL

Following the description of methodologies in chapter 3, this chapter will provide an overview of the application of an integrated toolchain of UBEMs and the Hotmaps toolbox to assess the impact of sensitivities on the model. This will be performed on the case study district and is going to include descriptions of input data, model calibrations, and customized processes considered at the various sensitivity blocks alongside the integrated toolchain.

4.1 Sensitivity Block A: Variations in the initial refurbishment status of buildings

As discussed in section 3.2.2, during sensitivity block A, variations of the assumed initial refurbishment status shall be created to approximate users´ approaches to calibrate their initial UBEM model on the demand side. The following section will describe the data being referenced for the energetic performance of different building types and refurbishment levels. Furthermore, the assignment of initial refurbishment status to individual buildings in the case study district in the city of Kiel will be explained, aligned with sensitivity block A.

4.1.1 Data on initial refurbishment status applied in the case study

In section 2.2, Kiel Gaarden Ost, the case study district within the city of Kiel has been characterized holistically. This section will build on the former and describe three initial refurbishment statuses per building type. For each building type, a table will provide an overview on u-values per building part, as well as a description of refurbishments eventually being adopted already. U-values indicate the rate of thermal transmittance of a material or composition of materials, such as building parts. These values are reciprocal to the conductivity and thickness of values of materials being referenced in the construction of buildings in templates and measured in W/(m^2*K) (Smith, Phillips, and Sweeney, 2014: p. 57). Concerning temperature differences between inside and outside of the building, these values imply how much energy resupply is required by the building to keep the temperature level in the building at a constant level.

All data is oriented at “Gebäudetypologie Schleswig-Holstein” by Arbeitsgemeinschaft Zeitgemäßes Bauen e.V. (ARGE), a local research and consulting group focusing on the built environment in the federal state of Schleswig-Holstein. Their building typology is based on data from several thousand local buildings and aligns with national building codes. Their typology was ordered and approved by the Schleswig

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Holstein ministry of interior, is widely used for energetic estimations, and is referenced in the scientific community (ARGE, 2012).

To enhance readability, the following tables include abbreviations: “Avg.” is short for Average, “TI” is short for thermal insulation, and “HPG” is short for heat protection glass. The number in front of “HPG” quantifies the number of glass layers being integrated with the building´s windows. The term “not modernized” is defined as no energetic refurbishment measures have been applied to the building since it is being built. “Slightly modernized” refers to minimal measures being adopted, while “Modernized” describes the status of a building, which has been refurbished according to outdated energetic standards. These classifications of the modernization status apply to all building types and will be found in all tables.

To reflect the fact that all initial building constructions and refurbishment measures have been implemented long ago, the following descriptions of construction approaches and energetic performances are written in the past tense, while of course, builds do still exist today.

Table 2: Energetic building performance M18 – B0. *Own approach based on: ARGE, 2012: pp. 69-72.*

M18	Not modernized	Slightly modernized	Modernized
Status Quo [Avg. W/(m^2*K)]	2.13	1.65	0.79
Walls [W/(m^2*K)]	1.67	1.67	1.26
Wall refurbishing measure	-	-	30%: 11cm TI*
Roof/Highest floor ceiling [W/(m^2*K)]	2.70	2.70	0.23
Roof refurbishing measure	-	-	12cm TI*
Basement ceiling [W/(m^2*K)]	1.50	0.30	0.23
Basement ceiling refurbishing measure	-	10cm TI*	14cm TI*
Windows [W/(m^2*K)]	2.65	1.94	1.46
Window refurbishing measure	-	60%: 2HPG**	2HPG**

For multifamily houses being built before 1918 (M18), the construction included single-shell masonry of 30cm thickness, clay bricks on a wooden roof truss, wooden structure with floorboards as highest floor ceiling, and bricked basement ceiling. Windows were simple double-layered by default. To achieve a slightly modernized initial refurbishment status, 10cm of thermal insulation were added to the basement ceiling and 60% of windows were exchanged with heat-protecting double-layered windows (2HPG). A modernized status is characterized by 11cm thermal insulation on 30% of the outer walls of the building. Mostly on the building´s less decorated façade towards its backyard. Furthermore, thermal insulation was installed underneath the wooden roof truss elements, the basement ceiling got insulated with 14cm plasterboards and all windows were exchanged with 2HPG.

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Table 3: Energetic building performance M48 – B0. *Own approach based on ARGE, 2012: pp. 77-80.*

M48	Not modernized	Slightly modernized	Modernized
Status Quo [Avg. W/(m²*K)]	1.83	1.03	0.77
Walls [W/(m²*K)]	1.67	1.67	1.15
Wall refurbishing measure	-	-	37.5%: 10cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	2.70	0.33	0.23
Roof refurbishing measure	-	8cm TI*	12cm TI*
Basement ceiling [W/(m²*K)]	0.30	0.30	0.23
Basement ceiling refurbishing measure	-	-	4cm TI*
Windows [W/(m²*K)]	2.65	1.82	1.46
Window refurbishing measure	-	70%: 2HPG**	2HPG**

Multifamily houses being built between 1919 and 1948 (M48) were again characterized by a single-shell masonry of 30cm thickness, concrete roof tiles on a wooden roof truss, wooden top-ceiling, a thick concrete basement ceiling covered by floorboards, and simple double-layered windows. In a slightly modernized building, 8cm of insulation was added below the wooden roof truss, and 70% of windows were exchanged with 2HPG. A modernized state was reached by adding 10cm thermal insulation to 37.5% of the walls, again likely backsides. Additionally, roof trusses and top ceilings were equipped with insulating material, basement ceilings were insulated with 4cm, and all windows were changed to 2HPG.

During the building period between 1949 and 1957 (M57), multifamily houses were characterized by thinner wall constructions of 26cm. Roofs were again constructed as clay tiles on wooden roof trusses.

Table 4: Energetic building performance M57 – B0. *Own approach based on ARGE, 2012: pp. 85-88.*

M57	Not modernized	Slightly modernized	Modernized
Status Quo [Avg. W/(m²*K)]	2.13	1.69	1.07
Walls [W/(m²*K)]	1.79	1.79	1.33
Wall refurbishing measure	-	-	30%: 12cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	2.70	2.70	1.28
Roof refurbishing measure	-	-	4cm TI*
Basement ceiling [W/(m²*K)]	1.36	0.34	0.22
Basement ceiling refurbishing measure	-	8.5cm TI*	14.5cm TI*
Windows [W/(m²*K)]	2.65	1.94	1.46
Window refurbishing measure	-	60%: 2HPG**	2HPG**

However, ceilings were built as concrete layers: 15cm including a 2.5cm insulation layer for the top layer, 16cm for the basement. Windows were again simple double-layered by default. In a slightly refurbished object, 60% of windows were upgraded to 2HPG and 8.5cm insulation was added to the basement ceiling. Modernized version upgraded all windows to 2HPG, insulated the basement ceiling with 14.5cm, added 4cm insulation to the roof construction, and insulated the backyard wall with a 12cm layer of plasterboard.

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Table 5: Energetic building performance M68 – B0. *Own approach based on ARGE, 2012: pp. 93-96.*

M68	Not modernized	Slightly modernized	Modernized
Status Quo [Avg. W/(m²*K)]	1.46	1.16	0.75
Walls [W/(m²*K)]	1.54	1.54	1.09
Wall refurbishing measure	-	-	35%: 12cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.79	0.79	0.23
Roof refurbishing measure	-	-	15.5cm TI*
Basement ceiling [W/(m²*K)]	0.84	0.32	0.22
Basement ceiling refurbishing measure	-	7.25cm TI*	12.75cm TI*
Windows [W/(m²*K)]	2.65	2.00	1.46
Window refurbishing measure	-	55%: 2HPG**	2HPG**

Between 1958 and 1968 (M68), walls of multifamily houses were constructed as 30cm structures of hollow building blocks. Their roofs have been consisting of concrete tiles on wooden trusses, both ceiling types, basement, and floor ceilings were constructed as 15cm concrete layer including 2.5cm insulation for the basement, and 4cm for the top ceiling. Windows are again assumed as simple double-layered for a not modernized status. 55% of those were replaced with 2HPG in a slightly modernized version. Furthermore, the basement ceiling was insulated with an additional 7.25cm layer of insulation. In a modernized version, 35% of the façade was refurbished by adding 12cm layers of insulation. Roof and top ceiling combined received additional insulation of 15.5cm thickness. Basement ceilings were insulated stronger, and all windows reached 2HPG.

Multifamily buildings built between 1969 and 1978 (M78) were constructed with a double-shell wall, including a 19cm outer shell, as well as an 11.5cm inner shell. Between there has been a 6cm air shell. Roofs were constructed including insulation by default. Concrete basement ceilings were topped by 4cm insulation, while all windows were simply double-layered by default. Some owners have added additional 5.5cm insulation to the basement ceiling and exchanged 50% of windows with 2HPG to arrive at a slightly modernized status of the building.

Table 6: Energetic building performance M78 – B0. *Own approach based on ARGE, 2012: pp. 101-104.*

M78	Not modernized	Slightly modernized	Modernized
Status Quo [Avg. W/(m²*K)]	1.34	1.07	0.78
Walls [W/(m²*K)]	1.29	1.29	1.07
Wall refurbishing measure	-	-	30%: 6cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.56	0.56	0.22
Roof refurbishing measure	-	-	10.5cm TI*
Basement ceiling [W/(m²*K)]	0.84	0.37	0.37
Basement ceiling refurbishing measure	-	5.5cm TI*	5.5cm TI*
Windows [W/(m²*K)]	2.65	2.06	1.46
Window refurbishing measure	-	50%: 2HPG**	2HPG**

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In modernized M78 buildings, the air shell in the building´s walls was filled by perlite injections for 30% of the facade. The top ceiling received additional insulation of 10.5cm, while the basement ceiling received the measure as in a slightly modernized version. Also, again, all windows were replaced with 2HPG.

Table 7: Energetic building performance M78 – B0. *Own approach based on ARGE, 2012: pp.109-112.*

M87	Not modernized	Slightly modernized	Modernized
Status Quo [Avg. W/(m^2*K)]	1.03	0.88	0.70
Walls [W/(m^2*K)]	0.81	0.81	0.81
Wall refurbishing measure	-	-	-
Roof/Highest floor ceiling [W/(m^2*K)]	0.35	0.35	0.23
Roof refurbishing measure	-	-	4.5cm TI*
Basement ceiling [W/(m^2*K)]	0.3	0.3	0.3
Basement ceiling refurbishing measure	-	-	-
Windows [W/(m^2*K)]	2.65	2.06	1.46
Window refurbishing measure	-	50%: 2HPG**	2HPG**

A double-shell approach was adopted by the constructors of multifamily houses between 1979 and 1987 (M87) too. However, via perlite inlet and slightly thicker construction, the u-values were better than for M78 houses. Both, roof construction and top ceiling were insulated by 12cm layers each. Basement ceilings were built as a 14cm concrete layer in combination with a 6cm layer of insulation. Windows were simple double-glassed. The only change to a slightly modernized version was the exchange of 50% of windows to 2HPG. In a modernized building, all windows were upgraded, and 4.5cm of insulation was added to the highest floor ceiling.

Table 8: Energetic building performance NRB – B0. *Own approach based on ARGE, 2012: pp. 93-96.*

NRB	Not modernized	Slightly modernized	Modernized
Status Quo [Avg. W/(m^2*K)]	1.46	1.16	0.75
Walls [W/(m^2*K)]	1.54	1.54	1.09
Wall refurbishing measure	-	-	35%: 12cm TI*
Roof/Highest floor ceiling [W/(m^2*K)]	0.79	0.79	0.23
Roof refurbishing measure	-	-	15.5cm TI*
Basement ceiling [W/(m^2*K)]	0.84	0.32	0.22
Basement ceiling refurbishing measure	-	7.25cm TI*	12.75cm TI*
Windows [W/(m^2*K)]	2.65	2.00	1.46
Window refurbishing measure	-	55%: 2HPG**	2HPG**

Non-residential buildings (NRB) are likely of commercial use. Offices and warehouses were constructed as concrete structures, with a tight layer of insulation on walls. Roofs were consisting of 15cm concrete structures holding an 8cm insulation layer. In some cases, thin layers of gravel were integrated as a topping. Basement ceilings were defined by a 14cm concrete basis, combined with 4cm layers of plasterboard. By default, windows were simply double-layered again. In slightly modernized non-residential buildings, basement ceilings were upgraded by additional 7.25cm layers of insulation and 55% of windows were replaced with 2HPG. In modernized buildings,

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35% of the façade was equipped with additional layers of 12cm thermal insulation, both the highest floor- and the basement ceiling received additional insulation layers of 15.5, respectively 12.75cm. All windows were upgraded to 2HPG.

Non-typologized residential buildings (NT_RB) are special buildings, for example, the residential tower building in the northern part of the district. These houses were built as double-shell concrete structures including insulation layers in between. Flat roofs were constructed as continuous concrete structures, including plasterboard layers and gravel as a topping.

Table 9: Energetic building performance NT_RB – B0. *Own approach based on ARGE, 2012: pp. 101-104.*

NT_RB	Not modernized	Slightly modernized	Modernized
Status Quo [Avg. W/(m^2*K)]	1.34	1.07	0.78
Walls [W/(m^2*K)]	1.29	1.29	1.07
Wall refurbishing measure	-	-	30%: 6cm TI*
Roof/Highest floor ceiling [W/(m^2*K)]	0.56	0.56	0.22
Roof refurbishing measure	-	-	10.5cm TI*
Basement ceiling [W/(m^2*K)]	0.84	0.37	0.37
Basement ceiling refurbishing measure	-	5.5cm TI*	5.5cm TI*
Windows [W/(m^2*K)]	2.65	2.06	1.46
Window refurbishing measure	-	50%: 2HPG**	2HPG**

Furthermore, concrete layers of 14cm thickness combined with 4cm insulation layers were designed as basement ceilings. This was upgraded by a 5.5cm additional layer of insulation and 50% of the windows were replaced with 2HPG to arrive at a slightly modernized energetic performance level. A modernized status was derived in buildings by 30% perlite inlets of 6cm between the two wall shells. The top ceiling and roof construction was upgraded with 10.5cm plasterboard insulation, while the basement ceilings were upgraded with 5.5cm insulation. All windows were upgraded to 2HPG.

Table 10: Energetic building performance M87_SVP – B0. *Own approach based on ARGE, 2012: pp.109-112.*

M87_SVP	Not modernized	Slightly modernized	Modernized
Status Quo [Avg. W/(m^2*K)]	1.03	0.88	0.70
Walls [W/(m^2*K)]	0.81	0.81	0.81
Wall refurbishing measure	-	-	-
Roof/Highest floor ceiling [W/(m^2*K)]	0.35	0.35	0.23
Roof refurbishing measure	-	-	4.5cm TI*
Basement ceiling [W/(m^2*K)]	0.3	0.3	0.3
Basement ceiling refurbishing measure	-	-	-
Windows [W/(m^2*K)]	2.65	2.06	1.46
Window refurbishing measure	-	50%: 2HPG**	2HPG**

For the special type of M87 located at the Vineta square (M87_SVP), similar values as for peer groups of buildings are assumed. The building´s structure and construction differed in terms of the roof only: For the special type flat roofs were installed. These

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are interpreted as a concrete structure with plasterboard layers in the respective building template for UBEM.

Table 11: Energetic building performance STC – B0. *Own approach based on ARGE, 2012: pp. 85-88.*

STC	Not modernized
Status Quo [Avg. W/(m^2*K)]	2.13
Walls [W/(m^2*K)]	1.79
Wall refurbishing measure	-
Roof/Highest floor ceiling [W/(m^2*K)]	2.70
Roof refurbishing measure	-
Basement ceiling [W/(m^2*K)]	1.36
Basement ceiling refurbishing measure	-
Windows [W/(m^2*K)]	2.65
Window refurbishing measure	-

The energetic performance of single storey commercial buildings (STC) appears to be approximated by non-modernized M57 buildings. Constructions are defined accordingly.

Table 12: Energetic building performance YH – B0. *Own approach based on ARGE, 2012: pp. 93-96.*

YH	Not modernized
Status Quo [Avg. W/(m^2*K)]	1.46
Walls [W/(m^2*K)]	1.54
Wall refurbishing measure	-
Roof/Highest floor ceiling [W/(m^2*K)]	0.79
Roof refurbishing measure	-
Basement ceiling [W/(m^2*K)]	0.84
Basement ceiling refurbishing measure	-
Windows [W/(m^2*K)]	2.65
Window refurbishing measure	-

Similarly, youth hostel buildings (YH), are approximated by non-modernized M68. Constructions are defined accordingly too.

Table 13: Energetic building performance NB – B0. *Own approach based on GFLG, 1994; GFLG, 2009.*

New builds after 1987 (NB)	Not modernized
Status Quo [Avg. W/(m^2*K)]	0.44
Walls [W/(m^2*K)]	0.22
Wall refurbishing measure	-
Roof/Highest floor ceiling [W/(m^2*K)]	0.22
Roof refurbishing measure	-
Basement ceiling [W/(m^2*K)]	0.3
Basement ceiling refurbishing measure	-
Windows [W/(m^2*K)]	1
Window refurbishing measure	-

New buildings after 1987 (NB) were constructed according to energetic performance levels required by building codes (e.g., GFLG, 1994: p. 2121; GFLG, 2009: p. 954). Within the case study district, all new builds are visually designed in line with their direct neighbour buildings. Hence, walls are constructed from bricks with 20cm layers

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of insulation. Wooden trusses and concrete tiles combined with 9.5cm of thermal insulation form roof structures. The top and basement ceilings comprise concrete layers and plasterboard insulation. Window types are set to three-layered heat protection glasses.

4.1.2 Initial refurbishment status according to typical values for age classes

During the previous section, typical multifamily residential and commercial buildings from several building periods have been characterized and differentiated by modernization status. As discussed in section 3.2.2, depending on the level of detail of data being available, users have different options to allocate initial refurbishment status to the building stock of their study area.

A potential approach adoptable by users not having any specific information on the distribution of initial refurbishment status in their use case area is provided by ARGE in their "Gebäudetypologie Schleswig-Holstein". Here, they present a percentual indication of shares of initial refurbishment status in the building stock, which is again based on several thousand building data from the federal state of Schleswig-Holstein (ARGE, 2012: pp. 130-132):

Most buildings are indicated to be slightly modernized across age classes. There is no age class with a less than 50% share of slightly modernized buildings. Furthermore, modernized building status (22-38% share) outweighs the non-modernized building status (3-9% share) across all building classes, except from multifamily houses built between 1979 and 1987, including its special type located at Vineta square. For these types, according to ARGE´s ratio, 37% of buildings are not modernized, while only 9% are assumed to be modernized.

Table 14: Shares of initial refurbishment status by typical values for age classes. *Based on ARGE, 2012: pp. 130-132.*

Building type	Share of not modernized buildings	Share of slightly modernized buildings	Share of modernized buildings
M18	4%	63%	33%
M48	3%	65%	32%
M57	4%	58%	38%
M68	4%	64%	32%
M78	9%	69%	22%
M87	37%	54%	9%
NRB	4%	64%	32%
STC	4%	58%	38%
NT_RB	9%	69%	22%
M87_SVP	37%	54%	9%
YH	4%	64%	32%

Users referencing publicly available data for initial refurbishment status, such as ARGE in this case study, are assumed to not have any further information on the

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distribution of refurbishment status per building. Hence, they need to adopt a random approach to distributing the above shares per initial refurbishment status onto the individual buildings within their study area. This should be considered as a limitation to the approach.

It is expected that the more abstract indications on a higher level are the more divergent the results for heat demand from the actual demand. Hence, a national split of buildings per type and age class was applied, however, with almost the same values as above (IWU, 2012).

4.1.3 Initial refurbishment status according to visual building impression

Another option for users not having any information on the initial refurbishment status of buildings available is to conduct an individual assessment based on the visual impression of buildings. Therefore, it is advisable to create a list of buildings, including at least three columns: A unique building identifier, an indication of initial refurbishment status to be filled during the assessment, and a column for a short description, or justification of labeling a building an initial refurbishment status. The list can be re-used for the Masterfile as described in section 3.3.4.

If available for their study area, users are advised to conduct both, a desktop research exercise, and a local site visit to assess the building stock. Online applications, such as google.com/maps (Google, 2021) are publicly available and offer 3D visualization of the building stock remotely. Users can derive an indication of the building´s refurbishment status according to visible modernization items, such as new roofs, insulated facades, and alternative heating and climatization equipment being installed. Figure 42 provides an impression of the assessment process of buildings via remote visualizations. Building by building, energetic performance levels are estimated and documented. For later reference and potential correction of indications, users are advised to take screenshots of buildings being assessed and combine them with the list of buildings they assessed (for an example from this case study see appendix). Thereby references, checks, and amendments can always be conducted at a later stage with potentially new insights being available.

For confirmation purposes, users are advised to also visit their study area and double-check indications of the building´s refurbishment on site.

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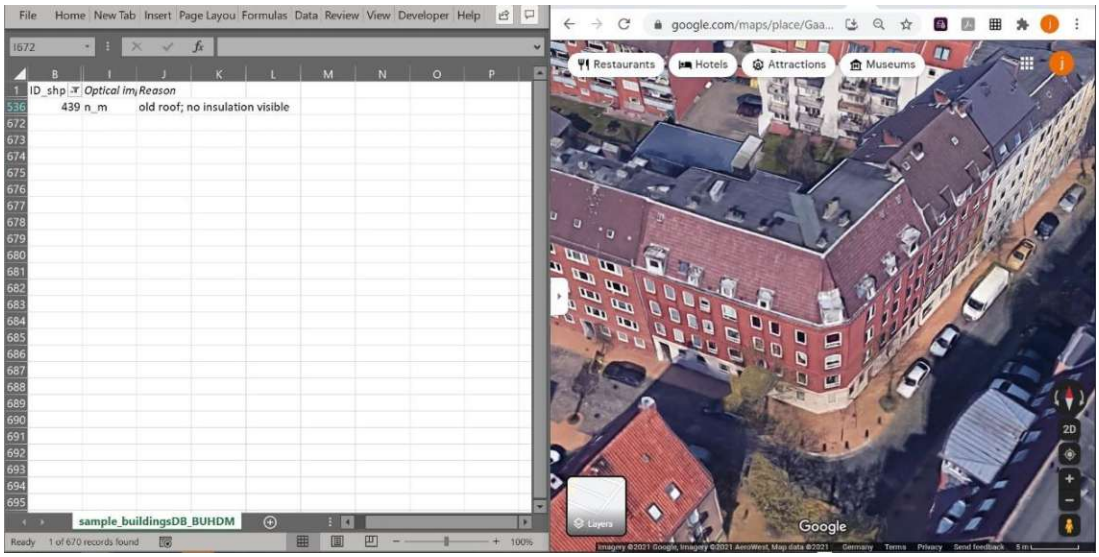

Figure 42: Assigning initial refurbishment status based on visual impression. *Own approach partly based on Google, 2021.*

However, even if for urban areas remote visualizations are mostly available, for rather rural areas the local site visit could be the only means available to assess the visual impression of the building stock.

A limitation of this method, especially in densely built neighborhoods, is that only front facades are visible, and roofs cannot be checked from a street-level perspective. Hence, ideally, a combination of online research and a site visit should be adopted.

4.1.4 Initial refurbishment status according to existing district data

Ideally, users have actual data on the initial refurbishment status of the building stock in their study area available. For the case study district in the city of Kiel, a report on the energetic performance level of its building stock has been published by the city of Kiel and complan Kommunalberatung GmbH in August 2013 (Complan, 2013). This report includes a detailed split up of modernization rates per building type, which is represented in table 15.

Table 15: Shares of initial refurbishment status by existing district data. *Own approach based on Complan, 2013: p. 48-51.*

Building type	Share of not modernized buildings	Share of slightly modernized buildings	Share of modernized buildings
M18	4%	68%	28%
M48	0%	0%	100%
M57	3%	40%	57%
M68	4%	46%	49%
M78	9%	79%	12%
M87	100%	0%	0%
NRB	4%	46%	49%
STC	3%	40%	57%
NT_RB	9%	79%	12%
M87_SVP	100%	0%	0%
YH	4%	46%	49%

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In comparison to the application of ratios on the federal state level based on ARGE, as discussed in section 4.1.2, the distribution of initial refurbishment status across different building types is more diverse: Tendentially, most building classes are either slightly, or even completely modernized. However, for some building types, there is a total concentration on a specific initial refurbishment status. This applies to M48 (100% modernized), M87, and its special type at Vineta square (100% not modernized). For M18 and M78, the majority is slightly modernized, while for all other types the majority (49-57% share of buildings per type) are modernized. Except for M87s, none of the types is indicated to be largely unmodernized.

4.2 Sensitivity Block B: Variations in the refurbishment options for buildings

According to section 3.2.2, the following sections will focus on three levels of refurbishment measures potentially to be applied to the buildings within the case study district: A basic approach, an average approach, as well as an ambitious approach to refurbishment. These are assumed to reflect a realistic set of sensitivities of refurbishment options applied by users.

In the previous sections of 4.1, the initial refurbishment status was discussed. Different initial refurbishment statuses being assigned to buildings during sensitivity block A, need to be considered for defining which refurbishment measures are possible and economically feasible for each building during sensitivity block B. In other words, the initial refurbishment status assigned to a building during sensitivity block A dictates which refurbishment measures are available to it during sensitivity block B. Always provided that a rational orientation of building owners in terms of cost-benefit ratios and longevity of measures is assumed.

For each initial refurbishment status assigned during sensitivity block A, the three alternative refurbishment options mentioned above will be characterized again oriented at options provided by ARGE´s “Gebäudetypologie Schleswig-Holstein” (ARGE, 2012). The information will be translated into building templates. These are to be used for simulations of the overall energetic performance of the case study district, differentiated by all three refurbishment options for the complete building stock: One sensitivity model considering basic refurbishment options for all buildings in the case study district, each according to their initial refurbishment status, another considering average refurbishment options, and another considering ambitious refurbishment options.

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4.2.1 Data on refurbishment options applied in the case study

During the following three sections, refurbishment options will be technically characterized. It is important to note that only additions to the existing building structure are mentioned in the tables below. Any existing refurbishment or default insulation measure is not included in the quantification of refurbishments but was described in 4.1. For example, if a roof construction includes 6cm of thermal insulation by default (B0) and 12cm of the same are added for B1, 2, or 3, only 12cm are shown as a refurbishment measure below.

All options include adding layers of thermal insulation to parts of – or complete – walls, roofs, ceilings, and replacing – at least parts – of the building´s windows with heat protection glasses. Percentual reduction values for u-values are indicated. These are derived from a comparison of average u-values of the complete building between the initial refurbishment status described in section 4.1 and the refurbishment options below. In ARGE´s data costs per refurbishment option are included to allow for cost-benefit indications of refurbishment measures (ARGE, 2012: pp. 69-109). These cost figures are amended using a construction price index for construction and refurbishment of residential and commercial buildings in Germany, issued by the German federal office of statistics to reflect 2021 price levels, given ARGE´s study dates to 2012. Since then, prices for construction and refurbishments have risen by 37.6% (German Federal Office of Statistics (GFOS), 2021). All indications of energetic improvement and costs align with Esser et al., 2019.

Again, as in 4.1, tables are including abbreviations to enhance readability. “Avg.” for average, “TI” for thermal insulation, and “HPG” for heat protection glass.

4.2.2 Basic building refurbishment options

This section will present data on the basic refurbishment options being available to all building types.

For M18 buildings, basic refurbishment measures are mostly applicable to initially non-modernized, or slightly modernized buildings. Due to the high initial u-values of these types, basic refurbishment measures are most effective here. In contrast, most basic measures have been integrated into initially modernized buildings already. Hence, for these, basic options do not create a significant improvement of the building´s energetic performance. Further improvements to initially modernized buildings would be more costly than justifiable for a basic refurbishment option.

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Table 16: Energetic building performance M18 – B1. *Own approach based on ARGE, 2012: pp. 69; 73-74.*

M18	Not modernized	Slightly modernized	Modernized
Basic Refurbishment [Avg. W/(m²*K)]	0.91	0.73	0.73
Walls [W/(m²*K)]	1.23	1.23	1.09
Wall refurbishing measure vs. Status Quo	30%: 16cm TI*	30%: 16cm TI*	40%: 16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15	0.15	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	12cm TI*
Basement ceiling [W/(m²*K)]	0.26	0.26	0.23
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	2cm TI*	-
Windows [W/(m²*K)]	1.99	1.28	1.46
Window refurbishing measure vs. Status Quo	40%: 3HPG***	40%: 3HPG***	-
Avg. Reduction vs. Status Quo [%]	-57%	-56%	-8%
Cost vs. Status Quo [€/m²]	145	145	135

Despite a 50% reduction, the resulting average u-values are still higher for the initially non-modernized building, than for the initially slightly and completely modernized buildings. These, though differently constituted, are achieving almost the same level of energetic performance.

For M48 houses, the difference in the effectiveness of refurbishment measures is more clear: Initially non-modernized buildings improve more significantly (-49%) than initially slightly modernized (-29%) and initially modernized buildings (-17%). Here, basic refurbishment measures are feasible for all different initial refurbishment statuses. However, the extent to which these improve the performance is dependent on the initial potential for improvement.

Table 17: Energetic building performance M48 – B1. *Own approach based on ARGE, 2012: pp. 77; 81-82.*

M48	Not modernized	Slightly modernized	Modernized
Basic Refurbishment [Avg. W/(m²*K)]	0.94	0.73	0.64
Walls [W/(m²*K)]	1.31	1.31	0.79
Wall refurbishing measure vs. Status Quo	25%: 16cm TI*	25%: 16cm TI*	25%: 16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15	0.15	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*	16cm TI*	12cm TI*
Basement ceiling [W/(m²*K)]	0.15	0.15	0.15
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	12cm TI*	8cm TI*
Windows [W/(m²*K)]	2.16	1.32	1.46
Window refurbishing measure vs. Status Quo	30%: 3HPG***	30%: 3HPG***	-
Avg. Reduction vs. Status Quo [%]	-49%	-29%	-17%
Cost vs. Status Quo [€/m²]	190	190	170

The resulting performance levels are still divergent (0.94 to 0.64 W/(m²*K)). However, gaps between the three statuses have decreased.

Due to the relatively similar approach to building construction for M18 and M57, basic options being feasible for application in M57 buildings are comparable to M18. Again, both, the initially non-modernized and the initially slightly modernized buildings can improve their energetic performance level by almost 50%. The initially modernized

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variant´s improvement is less significant, but a roof refurbishment measure can still be realized given the basic approach to cost-benefits.

The resulting thermal performances reflect the shrinking differences between variants, majorly stemming from the different windows being installed.

Table 18: Energetic building performance M57 – B1. *Own approach based on ARGE, 2012: pp. 85; 89-90.*

M57	Not modernized	Slightly modernized	Modernized
Basic Refurbishment [Avg. W/(m²*K)]	1.09	0.92	0.79
Walls [W/(m²*K)]	1.32	1.32	1.33
Wall refurbishing measure vs. Status Quo	30%: 16cm TI*	30%: 16cm TI*	-
Roof/Highest floor ceiling [W/(m²*K)]	0.15	0.15	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	20cm TI*
Basement ceiling [W/(m²*K)]	0.26	0.26	0.22
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	3.5cm TI*	-
Windows [W/(m²*K)]	2.65	1.94	1.46
Window refurbishing measure vs. Status Quo	-	-	-
Avg. Reduction vs. Status Quo [%]	-49%	-46%	-26%
Cost vs. Status Quo [€/m²]	185	165	165

For the building class of 1958 to 1968, basic refurbishment options are less significant in terms of improvement of energetic performance than they were for the building types described above. Again, this is caused by their relatively higher initial performance level. While for the initially non-modernized and initially slightly modernized status quos, performance improvements of over 25% are realized, while for the modernized status quo, only 4% are feasible considering basic refurbishment options. Again, differences between initial performance status are minimized by a basic refurbishment.

Table 19: Energetic building performance M68 – B1. *Own approach based on ARGE, 2012: 93; 97-98.*

M68	Not modernized	Slightly modernized	Modernized
Basic Refurbishment [Avg. W/(m²*K)]	1.03	0.86	0.72
Walls [W/(m²*K)]	1.07	1.07	1.09
Wall refurbishing measure vs. Status Quo	35%: 16cm TI*	35%: 16cm TI*	-
Roof/Highest floor ceiling [W/(m²*K)]	0.15	0.15	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	9.5cm TI*
Basement ceiling [W/(m²*K)]	0.23	0.23	0.19
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	4,75cm TI*	-
Windows [W/(m²*K)]	2.65	2.00	1.46
Window refurbishing measure vs. Status Quo	-	-	-
Avg. Reduction vs. Status Quo [%]	-29%	-26%	-4%
Cost vs. Status Quo [€/m²]	165	165	135

A similar, though even less significant, improvement of energetic performance levels is achieved for M78 buildings.

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Table 20: Energetic building performance M78 – B1. *Own approach based on ARGE, 2012: pp. 101; 105-106.*

M78	Not modernized	Slightly modernized	Modernized
Basic Refurbishment [Avg. W/(m²*K)]	1.00	0.85	0.73
Walls [W/(m²*K)]	0.97	0.97	1.07
Wall refurbishing measure vs. Status Quo	30%: 16cm TI*	30%: 16cm TI*	-
Roof/Highest floor ceiling [W/(m²*K)]	0.16	0.16	0.16
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	13.5cm TI*
Basement ceiling [W/(m²*K)]	0.23	0.23	0.23
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	6.5cm TI*	6.5cm TI*
Windows [W/(m²*K)]	2.65	2.06	1.46
Window refurbishing measure vs. Status Quo	-	-	-
Avg. Reduction vs. Status Quo [%]	-25%	-20%	-7%
Cost vs. Status Quo [€/m²]	165	165	120

Basic refurbishment options enable improvements of above 20% for initially non-modernized and initially slightly modernized buildings while allowing just for roof insulation of initially modernized variants. This measure improves the overall performance by just 7%. The resulting performance levels remain diverse. However, this is the first building class to reach an average u-value of 1 or lower for a non-modernized initial status of refurbishment.

Multifamily houses being built between 1979 and 1987 were constructed with a lot of basic refurbishment options integrated already. Hence, their performance improvement by application of basic refurbishment options is the least effective compared with other building classes. However, still up to 21% improvement are reached by the initially slightly modernized variant. This building class is the only reaching u-values below 1 for all initial variants. The resulting performance levels tendentially align, with a minor tendency of the initially slightly modernized toward alignment with the initially modernized variant. This is caused by allocating the same measures to both, the non-modernized, as well as the slightly modernized. Thereby the effect for the initially slightly modernized variant is larger in relative terms, helping to further approach the initially modernized variant´s level.

Table 21: Energetic building performance M87 – B1. *Own approach based on ARGE (2012): 109; 113.*

M87	Not modernized	Slightly modernized	Modernized
Basic Refurbishment [Avg. W/(m²*K)]	0.84	0.69	0.65
Walls [W/(m²*K)]	0.81	0.81	0.81
Wall refurbishing measure vs. Status Quo	-	-	-
Roof/Highest floor ceiling [W/(m²*K)]	0.12	0.12	0.12
Roof refurbishing measure vs. Status Quo	16.5cm TI*	16.5cm TI*	12cm TI*
Basement ceiling [W/(m²*K)]	0.2	0.2	0.2
Basement ceiling refurbishing measure vs. Status Quo	6cm TI*	6cm TI*	6cm TI*
Windows [W/(m²*K)]	2.24	1.64	1.46
Window refurbishing measure vs. Status Quo	25%: 3HPG***	25%: 3HPG***	-
Avg. Reduction vs. Status Quo [%]	-18%	-21%	-7%
Cost vs. Status Quo [€/m²]	95	95	65

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Non-residential buildings offer moderate potential for basic refurbishment options only. Performances are significantly improved for initially non-modernized and initially slightly modernized variants. The initially modernized variant, however, again allows for roof insulation only. Hence, its performance level is improved only marginally.

Table 22: Energetic building performance NRB – B1. *Own approach based on ARGE, 2012: 93; 97-98.*

NRB	Not modernized	Slightly modernized	Modernized
Basic Refurbishment [Avg. W/(m²*K)]	1.03	0.86	0.72
Walls [W/(m²*K)]	1.07	1.07	1.09
Wall refurbishing measure vs. Status Quo	35%: 16cm TI*	35%: 16cm TI*	-
Roof/Highest floor ceiling [W/(m²*K)]	0.15	0.15	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	9.5cm TI*
Basement ceiling [W/(m²*K)]	0.23	0.23	0.19
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	4,75cm TI*	-
Windows [W/(m²*K)]	2.65	2.00	1.46
Window refurbishing measure vs. Status Quo	-	-	-
Avg. Reduction vs. Status Quo [%]	-29%	-26%	-4%
Cost vs. Status Quo [€/m²]	165	165	135

Costs are in a mid-range of basic refurbishment options compared to multifamily houses.

Non-typologized residential buildings, allow for basic refurbishment across all initial variants, despite no wall refurbishments being feasible for the initially modernized status quo. Also, all variants reach u-values at or below 1, at improvement rates of up to 25%.

Table 23: Energetic building performance NT_RB – B1. *Own approach based on ARGE, 2012: pp. 101; 105-106.*

NT_RB	Not modernized	Slightly modernized	Modernized
Basic Refurbishment [Avg. W/(m²*K)]	1.00	0.85	0.73
Walls [W/(m²*K)]	0.97	0.97	1.07
Wall refurbishing measure vs. Status Quo	30%: 16cm TI*	30%: 16cm TI*	-
Roof/Highest floor ceiling [W/(m²*K)]	0.16	0.16	0.16
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	13.5cm TI*
Basement ceiling [W/(m²*K)]	0.23	0.23	0.23
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	6.5cm TI*	6.5cm TI*
Windows [W/(m²*K)]	2.65	2.06	1.46
Window refurbishing measure vs. Status Quo	-	-	-
Avg. Reduction vs. Status Quo [%]	-25%	-20%	-7%
Cost vs. Status Quo [€/m²]	165	165	120

Differences between non-modernized, slightly modernized, and modernized initial status are moderate and evenly spread.

Basic refurbishment options for the Vineta square special type of M87 are oriented at M87. Accordingly, they offer less potential for significant effects of refurbishments but reach u-values of below 1 for all variants. Compared to other building classes, costs for basic refurbishment measures are marginal.

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Table 24: Energetic building performance M87_SVP – B1. *Own approach based on ARGE (2012): 109; 113.*

M87_SVP	Not modernized	Slightly modernized	Modernized
Basic Refurbishment [Avg. W/(m²*K)]	0.84	0.69	0.65
Walls [W/(m²*K)]	0.81	0.81	0.81
Wall refurbishing measure vs. Status Quo	-	-	-
Roof/Highest floor ceiling [W/(m²*K)]	0.12	0.12	0.12
Roof refurbishing measure vs. Status Quo	16.5cm TI*	16.5cm TI*	12cm TI*
Basement ceiling [W/(m²*K)]	0.2	0.2	0.2
Basement ceiling refurbishing measure vs. Status Quo	6cm TI*	6cm TI*	6cm TI*
Windows [W/(m²*K)]	2.24	1.64	1.46
Window refurbishing measure vs. Status Quo	25%: 3HPG***	25%: 3HPG***	-
Avg. Reduction vs. Status Quo [%]	-18%	-21%	-7%
Cost vs. Status Quo [€/m²]	95	95	65

Single story commercial units were built with limited consideration of the building´s operational energy consumption levels. Hence, these buildings offer significant potential for energy consumption savings by applying basic refurbishment options already.

Table 25: Energetic building performance STC – B1. *Own approach based on ARGE, 2012: pp. 85; 89-90.*

STC	Not modernized
Basic Refurbishment [Avg. W/(m²*K)]	1.09
Walls [W/(m²*K)]	1.32
Wall refurbishing measure vs. Status Quo	30%: 16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*
Basement ceiling [W/(m²*K)]	0.26
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*
Windows [W/(m²*K)]	2.65
Window refurbishing measure vs. Status Quo	-
Avg. Reduction vs. Status Quo [%]	-49%
Cost vs. Status Quo [€/m²]	185

Table 26: Energetic building performance YH – B1. *Own approach based on ARGE, 2012: 93; 97-98.*

YH	Not modernized
Basic Refurbishment [Avg. W/(m²*K)]	1.03
Walls [W/(m²*K)]	1.07
Wall refurbishing measure vs. Status Quo	35%: 16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*
Basement ceiling [W/(m²*K)]	0.23
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*
Windows [W/(m²*K)]	2.65
Window refurbishing measure vs. Status Quo	-
Avg. Reduction vs. Status Quo [%]	-29%
Cost vs. Status Quo [€/m²]	165

The local youth hostel was built considering moderate energetic building standards. Therefore, basic refurbishment options are feasible for all building parts. Accordingly, the average energetic performance level can be improved by 29% for the building type. Costs are again mid-ranging compared to multifamily houses.

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4.2.3 Average building refurbishment options

Average refurbishment options for multifamily houses being built before 1918 are significantly more effective than the basic options characterized in the previous section. Up to 76% improvement of energetic performance levels is possible for non-modernized initial status. Compared to basic refurbishment options performance levels are improved by approximately 20 additional percentage points.

Table 27: Energetic building performance M18 – B2. *Own approach based on ARGE, 2012: pp. 69; 74-75.*

M18	Not modernized	Slightly modernized	Modernized
Average Refurbishment [Avg. W/(m²*K)]	0.51	0.58	0.62
Walls [W/(m²*K)]	0.65	0.65	0.65
Wall refurbishing measure vs. Status Quo	70%: 16cm TI*	70%: 16cm TI*	70%: 16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15	0.15	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	12cm TI*
Basement ceiling [W/(m²*K)]	0.26	0.26	0.23
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	2cm TI*	-
Windows [W/(m²*K)]	1	1.28	1.46
Window refurbishing measure vs. Status Quo	3HPG***	40%: 3HPG***	-
Avg. Reduction vs. Status Quo [%]	-76%	-65%	-22%
Cost vs. Status Quo [€/m²]	290	270	185

The average refurbishment options shown in table 27 enable u-values between 0.62 and 0.51 W/(m²*K). U-values for initially non-modernized buildings are lower than for initially slightly or completely modernized buildings. This is due to the requirement of economic feasibility. While for the initially non-modernized variant, there is a clear case of cost-benefit for replacing all windows with three-layered heat protection glasses (3HPG), for parts of the windows in the initially slightly modernized variant, and all windows in the initially modernized variant, this is not the case for the initially modernized buildings. Replacing their 2HPG with 3HPG holds less additional benefit from a cost-benefit perspective than required. Therefore, the measure is not applied to the initially better-modernized variant as part of average refurbishment options.

Table 28: Energetic building performance M48 – B2. *Own approach based on ARGE, 2012: pp. 77; 82-83.*

M48	Not modernized	Slightly modernized	Modernized
Average Refurbishment [Avg. W/(m²*K)]	0.51	0.59	0.52
Walls [W/(m²*K)]	0.76	0.76	0.31
Wall refurbishing measure vs. Status Quo	62.5%: 16cm TI*	62.5%: 16cm TI*	57.5%: 16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15	0.15	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*	16cm TI*	12cm TI*
Basement ceiling [W/(m²*K)]	0.15	0.15	0.15
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	12cm TI*	8cm TI*
Windows [W/(m²*K)]	1.00	1.32	1.46
Window refurbishing measure vs. Status Quo	3HPG***	30%: 3HPG***	-
Avg. Reduction vs. Status Quo [%]	-72%	-42%	-33%
Cost vs. Status Quo [€/m²]	350	320	245

The same phenomenon applies to buildings from the building class of M48: After applying an average refurbishment, the lowest u-values are achieved by initially not

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modernized buildings. However, their energetic performance is almost the same as for the initially modernized variant. On a relative scale, initially non-modernized variant´s performance levels are improved most significantly by 72%, compared to 33% improvement for the initially modernized buildings. However, this is reflected in significant cost differences as well: While the owners of initially modernized buildings need to spend 245€/m^2 to implement an average refurbishment option, owners of initially non-modernized buildings need to spend approximately 43% more (350€/m^2).

Multifamily houses from the 1950es (M57) reach less significant improvements in energetic performance levels than the previous two older building classes. This holds on both, an absolute and a relative scale. Achieved u-values reach from 0.81 to 0.66 W/(m^2*K). This equals relative improvements from 38% to 62%.

Table 29: Energetic building performance M57 – B2. *Own approach based on ARGE, 2012: pp. 85; 90-91.*

M57	Not modernized	Slightly modernized	Modernized
Average Refurbishment [Avg. W/(m^2*K)]	0.81	0.76	0.66
Walls [W/(m^2*K)]	0.68	0.68	0.82
Wall refurbishing measure vs. Status Quo	70%: 16cm TI*	70%: 16cm TI*	32.5%: 16cm TI*
Roof/Highest floor ceiling [W/(m^2*K)]	0.15	0.15	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	20cm TI*
Basement ceiling [W/(m^2*K)]	0.26	0.26	0.22
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	3.5cm TI*	-
Windows [W/(m^2*K)]	2.16	1.94	1.46
Window refurbishing measure vs. Status Quo	60%: 3HPG***	-	-
Avg. Reduction vs. Status Quo [%]	-62%	-55%	-38%
Cost vs. Status Quo [€/m^2]	330	300	235

The average refurbishment options for M68 buildings can be interpreted in the same way: Better initial substances allow for lower relative benefits of refurbishments measures. Hence, less is considered economically feasible for an average refurbishment option. U-values following implementation are again better for the initially non-modernized, than for the initially slightly modernized variant. The reason for that are again better opportunities for thermal insulation on a cost-benefit basis. On a relative basis from 18 to 50% performance improvements are achieved. In line with diminishing benefits, costs of the proposed measures decrease, reflecting the constant optimum for cost-benefit for refurbishments.

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Table 30: Energetic building performance M68 – B2. *Own approach based on ARGE, 2012: pp. 93, 98-99.*

M68	Not modernized	Slightly modernized	Modernized
Average Refurbishment [Avg. W/(m²*K)]	0.73	0.76	0.61
Walls [W/(m²*K)]	0.64	0.64	0.66
Wall refurbishing measure vs. Status Quo	67.5%: 16cm TI*	67.5%: 16cm TI*	32.5%: 16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15	0.15	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	9.5cm TI*
Basement ceiling [W/(m²*K)]	0.23	0.23	0.19
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	4,75cm TI*	-
Windows [W/(m²*K)]	1.91	2.00	1.46
Window refurbishing measure vs. Status Quo	55%: 3HPG***	-	-
Avg. Reduction vs. Status Quo [%]	-50%	-35%	-18%
Cost vs. Status Quo [€/m²]	305	280	215

Average refurbishments of M78 buildings achieve even lower rates of improvement during the implementation of average refurbishment measures on a relative scale, reaching between 16 and 48%. Again, the resulting u-values are the highest for initially slightly modernized buildings, stemming from less attractive economic cases for additional refurbishment measures to the buildings.

Table 31: Energetic building performance M78 – B2. *Own approach based on ARGE, 2012: pp. 101; 106-107.*

M78	Not modernized	Slightly modernized	Modernized
Average Refurbishment [Avg. W/(m²*K)]	0.69	0.75	0.66
Walls [W/(m²*K)]	0.55	0.55	0.78
Wall refurbishing measure vs. Status Quo	65%: 16cm TI*	65%: 16cm TI*	35%: 16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.16	0.16	0.16
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	13.5cm TI*
Basement ceiling [W/(m²*K)]	0.23	0.23	0.23
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	6.5cm TI*	6.5cm TI*
Windows [W/(m²*K)]	1.83	2.06	1.46
Window refurbishing measure vs. Status Quo	50%: 3HPG***	-	-
Avg. Reduction vs. Status Quo [%]	-48%	-30%	-16%
Cost vs. Status Quo [€/m²]	300	275	245

The least effective average refurbishment option applies to initially modernized M87 buildings. Here only 7 percentage points of energetic performance can be improved compared to the basic refurbishment options.

Table 32: Energetic building performance M87 – B2. *Own approach based on ARGE, 2012: pp. 109; 114..*

M87	Not modernized	Slightly modernized	Modernized
Average Refurbishment [Avg. W/(m²*K)]	0.53	0.59	0.65
Walls [W/(m²*K)]	0.81	0.81	0.81
Wall refurbishing measure vs. Status Quo	-	-	-
Roof/Highest floor ceiling [W/(m²*K)]	0.12	0.12	0.12
Roof refurbishing measure vs. Status Quo	16.5cm TI*	16.5cm TI*	12cm TI*
Basement ceiling [W/(m²*K)]	0.2	0.2	0.2
Basement ceiling refurbishing measure vs. Status Quo	6cm TI*	6cm TI*	6cm TI*
Windows [W/(m²*K)]	1	1.23	1.46
Window refurbishing measure vs. Status Quo	3HPG***	50%: 3HPG***	-
Avg. Reduction vs. Status Quo [%]	-48%	-33%	-7%
Cost vs. Status Quo [€/m²]	180	155	105

Hence, for M87 buildings also after applying average refurbishment measures, the

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energetic performance level of initially modernized buildings is still worse than those of initially non-modernized and initially slightly modernized buildings.

Table 33: Energetic building performance NRB – B2. *Own approach based on ARGE, 2012: pp. 93, 98-99.*

NRB	Not modernized	Slightly modernized	Modernized
Average Refurbishment [Avg. W/(m²*K)]	0.73	0.76	0.61
Walls [W/(m²*K)]	0.64	0.64	0.66
Wall refurbishing measure vs. Status Quo	67.5%: 16cm TI*	67.5%: 16cm TI*	32.5%: 16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15	0.15	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	9.5cm TI*
Basement ceiling [W/(m²*K)]	0.23	0.23	0.19
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	4,75cm TI*	-
Windows [W/(m²*K)]	1.91	2.00	1.46
Window refurbishing measure vs. Status Quo	55%: 3HPG***	-	-
Avg. Reduction vs. Status Quo [%]	-50%	-35%	-18%
Cost vs. Status Quo [€/m²]	305	280	215

Non-residential buildings allow for similar relative improvements of energetic performance, however on a lower absolute level of between 0.76 to 0.61 W/(m²*K). However, these refurbishments are relatively more cost-intensive than those for the residential buildings, given an equal improvement of energetic performance levels is desired.

Average refurbishments applied to non-typologized residential buildings increase the energetic performance level between 16 and 48%. Compared to the other initial variants, the slightly modernized variant is less attractive to consider for an average refurbishment option, given the relatively high remaining u-values not being represented in lower cost by the same ratio.

Table 34: Energetic building performance NT_RB – B2. *Own approach based on ARGE, 2012: pp. 101; 106-107.*

NT_RB	Not modernized	Slightly modernized	Modernized
Average Refurbishment [Avg. W/(m²*K)]	0.69	0.75	0.66
Walls [W/(m²*K)]	0.55	0.55	0.78
Wall refurbishing measure vs. Status Quo	65%: 16cm TI*	65%: 16cm TI*	35%: 16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.16	0.16	0.16
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	13.5cm TI*
Basement ceiling [W/(m²*K)]	0.23	0.23	0.23
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	6.5cm TI*	6.5cm TI*
Windows [W/(m²*K)]	1.83	2.06	1.46
Window refurbishing measure vs. Status Quo	50%: 3HPG***	-	-
Avg. Reduction vs. Status Quo [%]	-48%	-30%	-16%
Cost vs. Status Quo [€/m²]	300	275	245

Again, special types of M87 at Vineta square align with their standard M87 peers: As for the basic refurbishment options of M87_SVP, only limited potential for measures of significant effect exists, especially for buildings being modernized initially.

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Table 35: Energetic building performance M87_SVP – B2. *Own approach based on ARGE, 2012: pp. 109; 114.*

M87_SVP	Not modernized	Slightly modernized	Modernized
Average Refurbishment [Avg. W/(m²*K)]	0.53	0.59	0.65
Walls [W/(m²*K)]	0.81	0.81	0.81
Wall refurbishing measure vs. Status Quo	-	-	-
Roof/Highest floor ceiling [W/(m²*K)]	0.12	0.12	0.12
Roof refurbishing measure vs. Status Quo	16.5cm TI*	16.5cm TI*	12cm TI*
Basement ceiling [W/(m²*K)]	0.2	0.2	0.2
Basement ceiling refurbishing measure vs. Status Quo	6cm TI*	6cm TI*	6cm TI*
Windows [W/(m²*K)]	1	1.23	1.46
Window refurbishing measure vs. Status Quo	3HPG***	50%: 3HPG***	-
Avg. Reduction vs. Status Quo [%]	-48%	-33%	-7%
Cost vs. Status Quo [€/m²]	180	155	105

Table 36: Energetic building performance STC – B2. *Own approach based on ARGE, 2012: pp. 85; 90-91.*

STC	Not modernized
Average Refurbishment [Avg. W/(m²*K)]	0.81
Walls [W/(m²*K)]	0.68
Wall refurbishing measure vs. Status Quo	70%: 16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*
Basement ceiling [W/(m²*K)]	0.26
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*
Windows [W/(m²*K)]	2.16
Window refurbishing measure vs. Status Quo	60%: 3HPG***
Avg. Reduction vs. Status Quo [%]	-62%
Cost vs. Status Quo [€/m²]	330

Single story commercial units again offer vast potential for refurbishment given their weak initial energetic performance levels. In direct comparison to the initial status quo, these can be improved by more than 60%, reaching a u-value of clearly below 1. The youth hostel also achieves u-values of below 0.75, assuming an average energetic refurbishment being applied. By partly adding 3HPG to the building´s composition, the energetic performance level is increased by 50%.

Table 37: Energetic building performance YH – B2. *Own approach based on ARGE, 2012: pp. 93, 98-99.*

YH	Not modernized
Average Refurbishment [Avg. W/(m²*K)]	0.73
Walls [W/(m²*K)]	0.64
Wall refurbishing measure vs. Status Quo	67.5%: 16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*
Basement ceiling [W/(m²*K)]	0.23
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*
Windows [W/(m²*K)]	1.91
Window refurbishing measure vs. Status Quo	55%: 3HPG***
Avg. Reduction vs. Status Quo [%]	-50%
Cost vs. Status Quo [€/m²]	305

4.2.4 Ambitious building refurbishment options

In the previous two sections, especially for initially modernized variants, basic and average refurbishment measures had a limited effect of improvement on the energetic performance levels. Some measures were identified to be too costly to be considered

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for these refurbishment options. This was due to the assumed principle of users to maintain a sensible cost-benefit ratio for measures applied.

Ambitious refurbishment options will consider all measures being required to achieve the German “Energie-Einspar-Verordnung" (ENEV) building standard as of 2009: This implies the equivalent of 85% of the primary energy consumption of reference buildings defined by the standard. In effect, all buildings need to reach an average u-value of 0.4 W/(m^2*K) for buildings smaller than 350m^2 usable floor area, and 0.5 W/(m^2*K) for buildings with larger floor areas usable (GFLG, 2021: p. 962). Multifamily and non-residential buildings considered in the case study are mostly larger than 350m^2. The measures to reach such low values of thermal transmittance will be identified as costly and are therefore considered ambitious from a cost-benefit perspective.

If costs would be neglected, there would be further potential to improve the energetic performance level of buildings, ultimately reaching the status of passive- (Passivhaus Institut (PHI), 2021), or plus-energy houses (German Federal Ministry for Interior (GFMI), 2018). However, this is not considered feasible from a cost-benefit perspective in the short to medium term. Hence, these are not considered within the scope of the thesis.

The oldest class of buildings, M18, as for the basic and average options, offers large potential for energetic refurbishments to be integrated. Compared to the average options, most measures are adopted by the initially modernized buildings, while the initially slightly-, and non-modernized buildings improve their energetic performance level marginally only. Costs, however, increase substantially compared to average refurbishment options.

Table 38: Energetic building performance M18 – B3. *Own approach based on ARGE, 2012: pp. 69; 75-76.*

M18	Not modernized	Slightly modernized	Modernized
Ambitious Refurbishment [Avg. W/(m^2*K)]	0.41	0.47	0.46
Walls [W/(m^2*K)]	0.21	0.21	0.20
Wall refurbishing measure vs. Status Quo	16cm TI*	16cm TI*	70%: 20cm TI*; 30%: 16cm TI*
Roof/Highest floor ceiling [W/(m^2*K)]	0.15	0.15	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	12cm TI*
Basement ceiling [W/(m^2*K)]	0.26	0.26	0.23
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	2cm TI*	-
Windows [W/(m^2*K)]	1	1.28	1.28
Window refurbishing measure vs. Status Quo	3HPG***	40%: 3HPG***	40%: 3HPG***
Avg. Reduction vs. Status Quo [%]	-81%	-71%	-42%
Cost vs. Status Quo [€/m^2]	415	380	370

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Similar effects apply to multifamily houses being built before 1948. Again, a sharp cost increase is caused by reaching – except the initially modernized variant – only marginal improvements compared to the average refurbishment options.

Table 39: Energetic building performance M48 – B3. *Own approach based on ARGE, 2012: pp. 77; 83-84.*

M48	Not modernized	Slightly modernized	Modernized
Ambitious Refurbishment [Avg. W/(m²*K)]	0.38	0.45	0.45
Walls [W/(m²*K)]	0.21	0.19	0.19
Wall refurbishing measure vs. Status Quo	16cm TI*	62.5%: 20cm TI* 37.5cm 16cm TI*	62.5%: 20cm TI* 37.5cm 16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15	0.15	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*	16cm TI*	12cm TI*
Basement ceiling [W/(m²*K)]	0.15	0.15	0.15
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	12cm TI*	8cm TI*
Windows [W/(m²*K)]	1.00	1.32	1.32
Window refurbishing measure vs. Status Quo	3HPG***	30%: 3HPG***	30%: 3HPG***
Avg. Reduction vs. Status Quo [%]	-79%	-56%	-41%
Cost vs. Status Quo [€/m²]	535	490	480

Substantial improvements in energetic performance can be realized by applying ambitious refurbishment measures to M57 buildings. Here, measures previously being considered too costly are incorporated increasing the energetic performance level by 58%. Refurbishment costs of ambitious measures are high compared to former refurbishment options.

Also, for multifamily houses built between 1958 and 1968, high costs occur for ambitious refurbishment measures. In line with other age classes, the initially modernized variant is improving its energetic performance level most significantly compared to average refurbishment´s implications.

Table 40: Energetic building performance M57 – B3. *Own approach based on ARGE, 2012: pp. 85; 91-92.*

M57	Not modernized	Slightly modernized	Modernized
Ambitious Refurbishment [Avg. W/(m²*K)]	0.41	0.47	0.45
Walls [W/(m²*K)]	0.21	0.21	0.17
Wall refurbishing measure vs. Status Quo	16cm TI*	16cm TI*	20cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15	0.15	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	20cm TI*
Basement ceiling [W/(m²*K)]	0.26	0.26	0.22
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	3.5cm TI*	-
Windows [W/(m²*K)]	1	1.28	1.28
Window refurbishing measure vs. Status Quo	3HPG***	40%: 3HPG***	40%: 3HPG***
Avg. Reduction vs. Status Quo [%]	-81%	-72%	-58%
Cost vs. Status Quo [€/m²]	510	470	460

Overall, between 41 and 73% improvement rates compared to the initial status are achieved.

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Table 41: Energetic building performance M68 – B3. *Own approach based on ARGE, 2012: pp. 93; 99-100.*

M68	Not modernized	Slightly modernized	Modernized
Ambitious Refurbishment [Avg. W/(m²*K)]	0.40	0.46	0.44
Walls [W/(m²*K)]	0.21	0.21	0.17
Wall refurbishing measure vs. Status Quo	16cm TI*	16cm TI*	20cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15	0.15	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	9.5cm TI*
Basement ceiling [W/(m²*K)]	0.23	0.23	0.19
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	4,75cm TI*	-
Windows [W/(m²*K)]	1	1.25	1.25
Window refurbishing measure vs. Status Quo	3HPG***	45%: 3HPG***	45%: 3HPG***
Avg. Reduction vs. Status Quo [%]	-73%	-60%	-41%
Cost vs. Status Quo [€/m²]	480	435	435

A more insulated initial substance allows for attractive improvement rates in M78 (41 to 70%). These are significantly better than in the building class´ average refurbishment set of options. Refurbishment costs, however, are increasing by approximately 50% compared to B2.

Table 42: Energetic building performance M78 – B3. *Own approach based on ARGE, 2012: pp. 101; 107-108.*

M78	Not modernized	Slightly modernized	Modernized
Ambitious Refurbishment [Avg. W/(m²*K)]	0.41	0.46	0.46
Walls [W/(m²*K)]	0.23	0.23	0.23
Wall refurbishing measure vs. Status Quo	16cm TI*	16cm TI*	16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.16	0.16	0.16
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	13.5cm TI*
Basement ceiling [W/(m²*K)]	0.23	0.23	0.23
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	6.5cm TI*	6.5cm TI*
Windows [W/(m²*K)]	1	1.23	1.23
Window refurbishing measure vs. Status Quo	3HPG***	50%: 3HPG***	50%: 3HPG***
Avg. Reduction vs. Status Quo [%]	-70%	-57%	-41%
Cost vs. Status Quo [€/m²]	460	420	410

If ambitious measures are considered, for M87 buildings the resulting energetic performance levels of initially modernized buildings are worse than for initially non-, and slightly modernized buildings.

Table 43: Energetic building performance M87 – B3. *Own approach based on ARGE, 2012: pp. 109; 115.*

M87	Not modernized	Slightly modernized	Modernized
Ambitious Refurbishment [Avg. W/(m²*K)]	0.41	0.46	0.52
Walls [W/(m²*K)]	0.30	0.30	0.30
Wall refurbishing measure vs. Status Quo	65%: 12cm TI*	65%: 12cm TI*	65%: 12cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.12	0.12	0.12
Roof refurbishing measure vs. Status Quo	16.5cm TI*	16.5cm TI*	12cm TI*
Basement ceiling [W/(m²*K)]	0.2	0.2	0.2
Basement ceiling refurbishing measure vs. Status Quo	6cm TI*	6cm TI*	6cm TI*
Windows [W/(m²*K)]	1	1.23	1.46
Window refurbishing measure vs. Status Quo	3HPG***	50%: 3HPG***	-
Avg. Reduction vs. Status Quo [%]	-61%	-47%	-26%
Cost vs. Status Quo [€/m²]	270	235	205

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Additional investments in 3HPG are considered too costly, while ENEV-standards are reached, due to the relatively effective initial energetic status.

Non-residential buildings being addressed with ambitious refurbishments reach improvement rates of between 41 and 73%. Resulting u-values range between 0.4 and 0.46 W/(m²*K). They thereby fulfill the requirement by ENEV.

Table 44: Energetic building performance NRB – B3. *Own approach based on ARGE, 2012: pp. 93; 99-100.*

NRB	Not modernized	Slightly modernized	Modernized
Ambitious Refurbishment [Avg. W/(m²*K)]	0.40	0.46	0.44
Walls [W/(m²*K)]	0.21	0.21	0.17
Wall refurbishing measure vs. Status Quo	16cm TI*	16cm TI*	20cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15	0.15	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	9.5cm TI*
Basement ceiling [W/(m²*K)]	0.23	0.23	0.19
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	4,75cm TI*	-
Windows [W/(m²*K)]	1	1.25	1.25
Window refurbishing measure vs. Status Quo	3HPG***	45%: 3HPG***	45%: 3HPG***
Avg. Reduction vs. Status Quo [%]	-73%	-60%	-41%
Cost vs. Status Quo [€/m²]	480	435	435

Table 45: Energetic building performance NT_RB – B3. *Own approach based on ARGE, 2012: pp. 101; 107-108.*

NT_RB	Not modernized	Slightly modernized	Modernized
Ambitious Refurbishment [Avg. W/(m²*K)]	0.41	0.46	0.46
Walls [W/(m²*K)]	0.23	0.23	0.23
Wall refurbishing measure vs. Status Quo	16cm TI*	16cm TI*	16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.16	0.16	0.16
Roof refurbishing measure vs. Status Quo	24cm TI*	24cm TI*	13.5cm TI*
Basement ceiling [W/(m²*K)]	0.23	0.23	0.23
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*	6.5cm TI*	6.5cm TI*
Windows [W/(m²*K)]	1	1.23	1.23
Window refurbishing measure vs. Status Quo	3HPG***	50%: 3HPG***	50%: 3HPG***
Avg. Reduction vs. Status Quo [%]	-70%	-57%	-41%
Cost vs. Status Quo [€/m²]	460	420	410

Similar implications are achieved by applying ambitious refurbishments to non-typologized residential buildings. Here, the resulting energetic performances of initially slightly modernized and modernized buildings are equal, while non-modernized buildings perform slightly better.

According to the previous refurbishment options for M87_SVP, the special type of M87 is again aligned with M87.

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Table 46: Energetic building performance M87_SVP – B3. *Own approach based on ARGE, 2012: pp. 109; 115.*

M87_SVP	Not modernized	Slightly modernized	Modernized
Ambitious Refurbishment [Avg. W/(m²*K)]	0.41	0.46	0.52
Walls [W/(m²*K)]	0.30	0.30	0.30
Wall refurbishing measure vs. Status Quo	65%: 12cm TI*	65%: 12cm TI*	65%: 12cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.12	0.12	0.12
Roof refurbishing measure vs. Status Quo	16.5cm TI*	16.5cm TI*	12cm TI*
Basement ceiling [W/(m²*K)]	0.2	0.2	0.2
Basement ceiling refurbishing measure vs. Status Quo	6cm TI*	6cm TI*	6cm TI*
Windows [W/(m²*K)]	1	1.23	1.46
Window refurbishing measure vs. Status Quo	3HPG***	50%: 3HPG***	-
Avg. Reduction vs. Status Quo [%]	-61%	-47%	-26%
Cost vs. Status Quo [€/m²]	270	235	205

Refurbishment costs for commercial units are increased by approximately 40%, while the energetic performance improves by approximately 30% compared to the average refurbishment options. Overall, u-values of 0.41 W/(m²*K) are achievable.

Table 47: Energetic building performance STC – B3. *Own approach based on ARGE, 2012: pp. 85; 91-92.*

STC	Not modernized
Ambitious Refurbishment [Avg. W/(m²*K)]	0.41
Walls [W/(m²*K)]	0.21
Wall refurbishing measure vs. Status Quo	16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*
Basement ceiling [W/(m²*K)]	0.26
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*
Windows [W/(m²*K)]	1
Window refurbishing measure vs. Status Quo	3HPG***
Avg. Reduction vs. Status Quo [%]	-81%
Cost vs. Status Quo [€/m²]	510

Table 48: Energetic building performance YH – B3. *Own approach based on ARGE, 2012: pp. 93; 99-100.*

YH	Not modernized
Ambitious Refurbishment [Avg. W/(m²*K)]	0.40
Walls [W/(m²*K)]	0.21
Wall refurbishing measure vs. Status Quo	16cm TI*
Roof/Highest floor ceiling [W/(m²*K)]	0.15
Roof refurbishing measure vs. Status Quo	24cm TI*
Basement ceiling [W/(m²*K)]	0.23
Basement ceiling refurbishing measure vs. Status Quo	12cm TI*
Windows [W/(m²*K)]	1
Window refurbishing measure vs. Status Quo	3HPG***
Avg. Reduction vs. Status Quo [%]	-73%
Cost vs. Status Quo [€/m²]	480

Akin improvement rates and cost increases are realized by ambitious refurbishment options being applied to the buildings serving as a youth hostel: Costs are increased by approximately 40%, energetic performance level improved by around a third. U-values of 0.4 W/(m²*K) are achievable.

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4.3 Sensitivity Block C: Variations in allocation of heat demand to hectare level

This section elaborates on the application of different options to allocate heat demand to hectare level, as to be assessed by sensitivity block C. As described in section 3.2.3 users might adopt two different approaches to allocating heat demand from a building-by-building level in UBEM to a hectare level for supply-side simulations in the Hotmaps toolbox:

1. Option C1: Geo-referencing heat demand results at the building´s central location
2. Option C2: Virtually splitting buildings at the hectare borders, and consequently referencing heat demand at the central locations of the resulting partial buildings.

For orientation, figure 43 shows the case study district overlayed with a hectare raster:

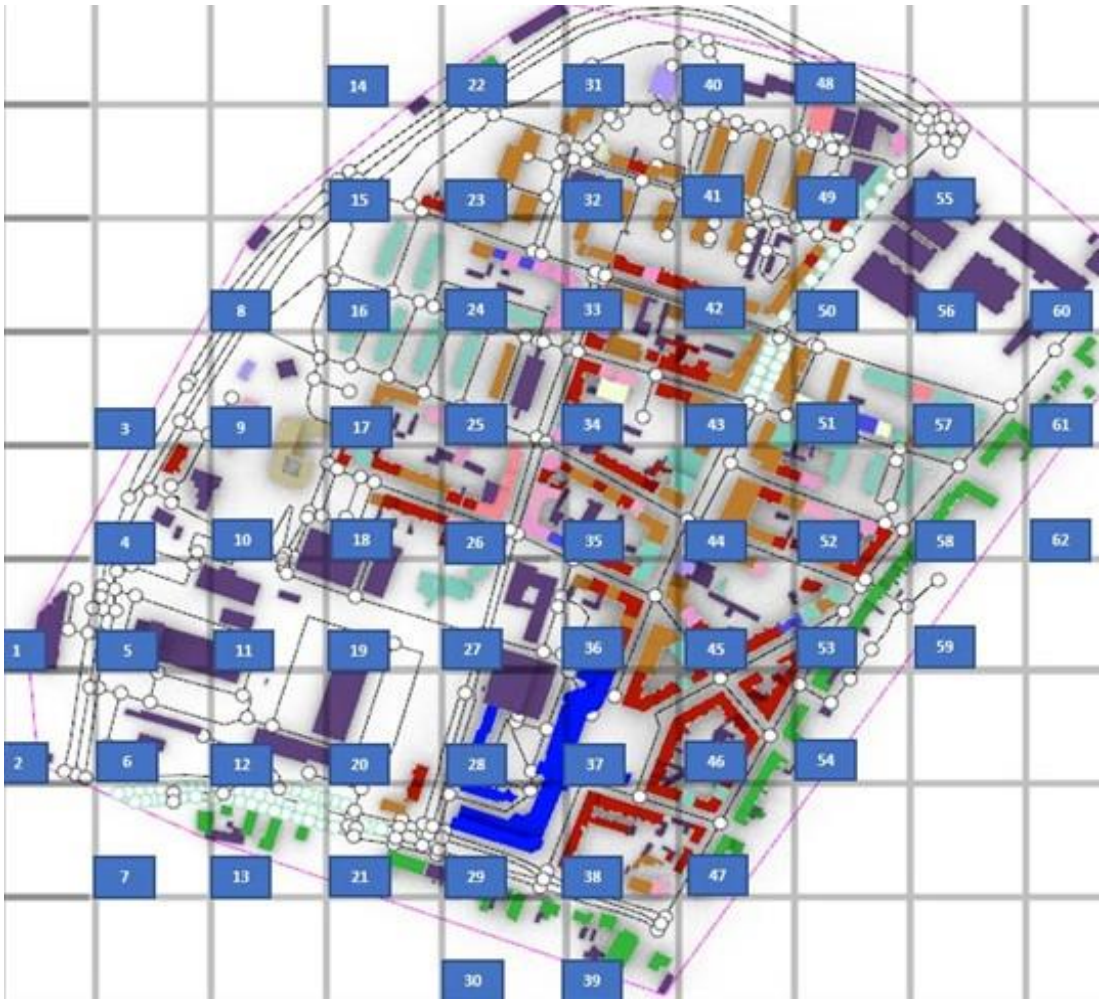

Figure 43: Control and navigation map of case study district on hectare level. *Own approach considering Peifer, 2011.*

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To differentiate heat demand by hectare, users need to identify which buildings belong to which hectare according to the EPSG:3035 framework (Peifer, 2011), which is used by the toolbox. Therefore, users can use the above overlay of an EPSG hectare raster as a control and navigation map of buildings for the case study district. All hectares, in which buildings are located, are assigned a unique hectare identifier in the numeric format: Hectare IDs of 1 to 62.

Furthermore, each building within the individual hectares is assigned an additional sub-identifier. This is provided in the format of “Hectare-ID_Building-ID”. For example, in hectare 42, 17 buildings are located. Accordingly, the buildings within the hectare are assigned the identifiers “42_1” to “42_17”. Thereby, every building in the case study district can be differentiated by hectare, and buildings located on the edges of hectares can directly be identified. For more detailed versions of the control and navigation map see appendix.

4.3.1 Heat demand allocation according to the building´s centre

The default approach to the allocation of heat demand to the hectare level is oriented at the location of the building´s centre. This approach is adopted by the calculation module “Customized Heatmaps” of the Hotmaps toolbox (Fallahnejad, 2020a).

As described in section 3.3.4, 100% of a building´s heat demand and gross floor area is allocated towards the specific hectare, in which the centre of the building is located. In consequence, for buildings being located on the edge of hectares information is allocated to one of these hectares only. All other hectares, on which the building may have shares of gross floor area and heat demand, are not considered for allocation of heat demand.

Figure 44 provides a detailed view of a part of the control map being created for option C1. This is an extract of figure 43 including the layer of building identifiers.

Heat demand and gross floor area are geo-referenced at the coordinates of the building´s central location and considered as input to the Masterfile of buildings, being described in section 3.3.4. Based on this list, input files for the calculation module of customized data into the Hotmaps toolbox are generated. The dark raster lines indicate the edges of hectares according to EPSG.3035 (Peifer, 2011). Buildings are highlighted by their sub-identifier in yellow. This number represents the building within its hectare. This is relevant to translate information from the map into the Masterfile and vice versa. Thereby verifications and amendments can be conducted later.

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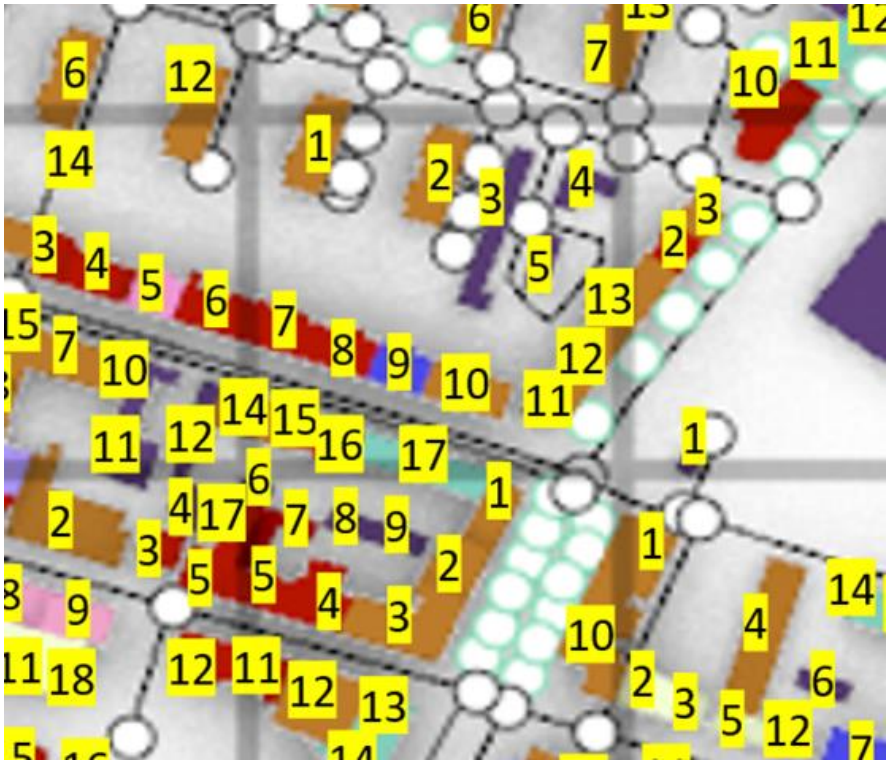

Figure 44: Detailed extract of the control map for allocation according to C1. *Own approach considering Peifer, 2011.*

Initially, the control map is used to ensure all buildings and their demand data were assigned to the right hectare by the module, as users can identify in which hectare the centre of a building is located.

Examples are buildings 6 and 12 in the upper left-hand corner of figure 44: These are primarily located in the up-most left-hand hectare, though having some of their gross floor area and heat demand on the hectare below. Following the methodology for option C1, heat demand for both buildings, 6 and 12, are allocated by 100% towards the up-most left-hand side hectare in figure 44. The hectare below does not receive any share of gross floor area or heat demand from buildings 6 and 12.

4.3.2 Heat demand allocation according to building´s floor area per hectare

The second alternative to allocate gross floor areas and heat demand to the hectare level is to orient the allocation strictly at the actual share of the building´s ground coverage within the respective hectares. Therefore, buildings being located on the edge of hectares are virtually split at the edges of the hectare raster given by EPSG:3035. Hence, two virtual buildings are created from fractions of the former single complete building. The two or more newly created virtual buildings receive their share of the complete building data according to their ground coverage in the

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respective hectares measured in percent. These shares are applied for allocating heat demand and gross floor area from the complete building to the virtual buildings and with them to hectares.

In contrast to option C1, not the centre locations of the complete building, but the centre locations of the new virtual buildings are considered as coordinates for geo-referencing. Again, these coordinates are used to complete columns G and H in the Masterfile of buildings (see section 3.3.4). The Masterfile subsequently is considered as an input to the “CM - Customized Heatmaps” calculation module, integrating custom datasets into the Hotmaps toolbox.

However, if virtual fractions of a building are considered as buildings too, there are more buildings in the model, than in the case of option C1. Hence, the initial Masterfile needs to be duplicated to allow for additional lines, without discarding the set-up for option C1. These additional lines are filled with information on virtual buildings, being created as independent parts of the formerly complete buildings, as they are located on neighboring hectares.

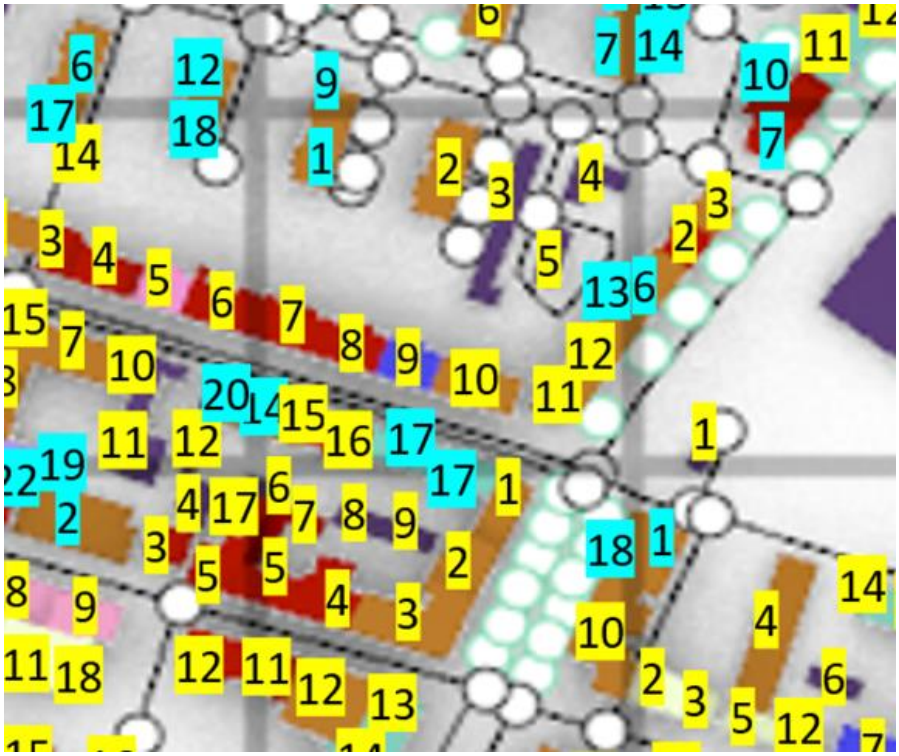

Figure 45: Detailed extract of the control map for allocation according to C2. *Own approach considering Peifer, 2011.*

Consequences of this alternative approach to allocating gross floor areas and heat demand to hectares are visualized in figure 45. It is an alternative approach to the control map from the previous section. All buildings being located on the edges of

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hectares are highlighted by a light blue background. According to the methodology of option C2, as described above, they are divided into independent parts. In contrast, buildings not being located on hectare edges, remain with a yellow indicator, and are allocated to hectares completely.

Buildings 6 and 12 from the up-most left-hand hectare are again referenced as an example: In contrast to option C1, these buildings are not entirely allocated to their primary hectare. Instead, their heat demand and gross floor area are allocated according to ground coverage on the respective hectares. Hence, the primary hectare only receives its primary share of heat demand and gross floor areas. The remaining shares of gross floor areas and heat demand are allocated to the hectare below. Within this hectare, the virtual buildings 17 and 18 are created by this approach. In the duplicated Masterfile for option C2, buildings 17 and 18 are added as new line items. All four line-items, buildings 6, 12, 17, and 18 receive their share of gross floor area and heat demand according to their share of ground coverage within their specific hectare.

For creating the duplicate of the Masterfile, users are advised to adhere to the following process description: After the technical duplication of the Masterfile via the user´s datasheet program, all buildings in scope of virtual division are marked in light blue – just as in the control map for option C2 above. Subsequently, the list is processed from top to bottom: Every blue line is checked for its building part´s share of ground coverage within the primary hectare. This is noted in an additional column named “Share”. For the previous example of building 6 on the up-most left-hand side, 80% share of the complete building´s heat demand and gross floor area is allocated to the initial line. For the remaining 20%, a new line is created. This new line represents the new virtual building 17 in the hectare below. Once both lines are created, named and shares of ground coverage are correctly indicated, the light blue highlight of the initial line can be removed.

4.3.3 Potential for process automation as customized calculation module

The above process for allocating gross floor areas and heat demand according to the actual ground coverage per building might be complex and error-prone.

For example: If in the Masterfile building 6 is split into two parts, users need to add a line item for the new virtual building part in the section of the other hectare, which may be a few tenths or hundreds of lines below or above. Additionally, users may not lose

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sight over which virtual buildings comprise a real building, to ensure not more or less than 100% of the building´s share of gross floor area and heat demand are allocated. Depending on the density of buildings and the number of buildings located on hectare edges, this process needs to be iterated many hundred times. Users need to strictly follow the process described in the previous section to avoid confusion of lines, as well as confusion of connections between different line items. Also, they are advised to never trust the first version of the duplicated master list of buildings without rechecking the correct allocation of data per hectare with the control map, partly shown in figure 45.

Automation could simplify the file amendment process for users. In the geo-dataset used as input to create the UMI files, coordinates for the individual building shapes are included (ESRI, 1998). Also, via the EPSG:3035 raster coordinates, all coordinates within different hectares can be identified, because the coordinates are structured in a continuous number format (Peifer, 2011). If both coordinate reference systems, the user´s geo-data input-file for UBEM and the EPSG:3035 coordinate reference system can be aligned via a python application, such as the backend process "Process GIS files" (Ang et al., 2021: p. 4), described in section 3.1.1, both could be compared to identify which buildings are in which hectares. Accordingly, building shapes being located across several hectares could be divided to create the virtual buildings automatically.

The automated module should identify all building shapes located on two or more hectares. Next, building contours connecting building corners on different hectares need to be selected. On these contours, the coordinate exactly located on the edge of the hectare needs to be identified by a match with the respective x_3035-, or y_3035-coordinate of the EPSG raster. As the coordinate of the raster line is fixed, the interception point on the building contour could easily be identified. This coordinate of intersection would serve as a new building corner coordinate for the two new virtual buildings.

The approach is visualized in figure 46 on the next page. In the example, a building with the coordinates 0.5/0.45, 1.4/0.9, 1.6/0.55, and 0.7/0.1 with corners located on two sides of the hectare border at the rater line at horizontal 1 is split into two virtual buildings. The required new building corner coordinates (1/0.75 and 1/0.25) are identified by the interception points of the contours with the hectare raster border.

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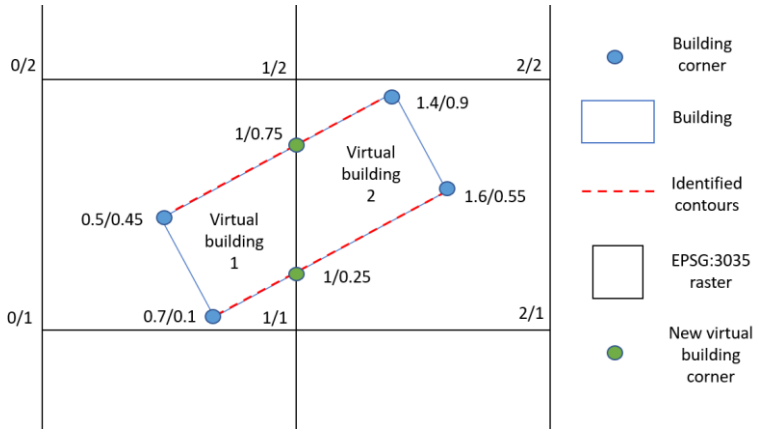

Figure 46: Schematic visualization of automatic demand allocation logic for new CM. *Own approach.*

The operation in the calculation module can be conducted by a matching function for coordinates between geo-datasets. This should be fed the EPSG raster and the geo-dataset of the use case to identify the required interception points automatically. The automated module should be applied to the user´s geo-datasets before the UMI files are created. Therefore, the complete UBEM creation, calibration, and simulation process on the demand side will be conducted separately and independent from the decision, whether the original shapefile for C1 or a C2-adjusted shapefile will be used.

4.4 Comparison of heat demand from blocks A-C and the Hotmaps toolbox

Following the successful completion of creation, calibration, simulation of the UBEM of the case study district in Kiel, as well as the integration of demand-side results into the Hotmaps toolbox, it is of interest to compare the results from the bottom-up approach via UBEM with the default top-down approach provided by the toolbox. This includes the indicators of total heat demand, average heat density, maximum heat density, and minimum heat demand.

4.4.1 Comparison of total heat demand

UBEM results include heat demand indications per building and month. These are summarized and integrated into the Hotmaps toolbox, as described in section 3.3.4. Thereby, the total heat demand per year can be indicated for the complete model. It is of interest to compare it with the top-down approach from the toolbox (Müller et al., 2019) and to other model sensitivities. The results are measured in Gigawatt-hours per year (GWh/yr). Beyond the quantifiable indication of GWh/yr, visual comparisons can be conducted either based on the visualizations from UBEM or the Hotmaps toolbox. Total heat demand is the major indicator to evaluate the effectiveness of

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refurbishment measures (DENA, 2021). Therefore, savings of refurbishment sensitivities are compared to the models based on initial refurbishment status.

4.4.2 Comparison of heat density

Heat density indicators are relevant to indicate suitability for district heating application (Djørup et al., 2019a: p. 20). Depending on market conditions and cost assumptions, higher or lower shares of the case study area are considered feasible to be supplied by district heating on economic terms.

Average values of heat density for a district are rough indicators of the overall suitability of the area. They do not provide sufficient information on whether district heating infrastructure is feasible on an individual hectare level (Djørup et al., 2019a: p. 18). Indications of maximum heat density allow for estimations of the maximum capacities of district heating infrastructure needed within a hectare (Ancona et al., 2014: p. 1227). Minimum heat density in turn enables the user to identify hectares, which are not feasible for district heating supply, as their heat demand is not sufficient to be considered on economic terms (Aydemir et al., 2020: p. 287).

In contrast, on a district-, instead of an individual hectare-level, conclusions from maximum and minimum heat density are vague. They might reflect outliers on both ends of the spectrum only. Proper feasibility for district heating applications needs to be assessed via the Hotmaps toolbox, as described in the next section.

However, for this case study, all heat density measures are of interest, as their comparison may show differences caused by the different allocation methods of heat demand gross floor areas during sensitivity block C. Alike the total heat demand, all heat density measures are compared on a visual, and a quantitative basis.

4.5 Sensitivity Block D: Impact on supply side indicators

To evaluate refurbishment options beyond their energetic effectiveness, the scope of the case study is extended from the demand side evaluation of changes in heat demand to the supply side evaluation of cost-efficiencies of refurbishment measures. To realize cost-benefit optimal solutions for the required low carbon building stock of the future, combinations of building refurbishment and renewable, highly efficient heat supply technology are required (GFMEC, 2015: p. 10). Hence, a set of scenarios of the future development of future market conditions, district and decentral heating parameters are calculated as sensitivities based on the results from sensitivity blocks A-C.

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An overarching sensitivity independent from all lenses to be evaluated below is the assumed emission factor for electricity. While green electricity´s carbon footprint amounts to a fraction of the footprint of grey electricity only (Verband der Automobilindustrie e.V. (VDA), 2019: pp. 192-195), its availability and local potentials to be converted into heat are limited, hence costly (HIC Hamburg Institut Consulting GmbH (HIC) and Forschungsgesellschaft für Energiewirtschaft mbH (FFE), 2021: p. 43). While the target of a minimum 95% reduction of carbon dioxide emissions from heating in the case study district (Kiel, 2019b) is likely based on direct emissions – and therefore reached by all electrons independent from its origin, there will be a check on whether the target can be achieved considering lifecycle emission factors for grey, green electricity, and green hydrogen.

4.5.1 Economic assessment of district heating options

The feasibility of district heating infrastructure for the case study district is dependent on the definition of criteria required to be met for economic feasibility (Djørup et al., 2019a: p. 19). Put differently, a defined target share of district heating in the case study district influences the economics of district heating infrastructures. These economics are assessed via the calculation module “CM - District Heating Potential: Economic Assessment” provided by the Hotmaps toolbox (Fallahnejad, 2020b).

As described in section 3.3.4, calculation modules can be executed based on all heat demand layers available to the users in their individual Hotmaps account. Furthermore, input parameters to the simulations can be calibrated according to the individual user scenarios, as described in 3.3.5.

The module “CM – District heating economic assessment” simulating district heating infrastructure poses many options for sensitivities of input parameters (Fallahnejad, 2020b). However, as this case study focuses on the impact of different approaches to the demand side of urban heat planning and simulation tools, the set of sensitivities assessed on the supply side is deliberately limited to a set of representative extremes.

Hence, for the economic assessment of district heating infrastructure, most default input parameters provided by the Hotmaps toolbox remain unchanged (Fallahnejad et al., 2018: p. 143-147). This includes cost data for infrastructure: For all sensitivities, a "Construction cost constant" of 212€/m of district heating network, a "Construction cost coefficient" of 4,464€/m^2 gross floor area, and a "Construction cost ceiling" of 25€/MWh of levelized construction cost is assumed. Furthermore, all sensitivities are calculated assuming an interest rate of 4%. Again, for all sensitivities, “Accumulated

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energy saving" is set to 0, as energy-saving from energetic refurbishments on the demand site are considered by the sensitivity blocks A-C already. Depreciation times are kept at 30 years, while the investment period has been amended from default applicable to all sensitivities: The “First year of investment” is defined as 2022; The “Last year of investment” is defined as 2045, when the target of minimum 95% reduction of carbon dioxide emissions from heating processes shall be reached the latest.

Sensitivities to the economic assessment of district heating potential for the case study district are defined by the market shares of district heating. The following three cases are distinguished:

Table 49: Market share sensitivities for the economic assessment of DH networks. *Own calibration of Fallahnejad, 2020b.*

Sensitivity	Market share at the beginning	Market share at the end
N1 = Network sensitivity 1	62.51%	100.00%
N2 = Network sensitivity 2	62.51%	80.00%
N3 = Network sensitivtiy 3	40.00%	80.00%

For N1 and N2, the market shares at the beginning of the investment period are oriented at the share of district heating supply from the district report from the city of Kiel and complan Kommunalberatung GmbH from 2013 (Complan, 2013: p. 59). For N3, a lower market share is considered to reflect the uncertainty of users potentially not having any information on existing infrastructure. For the market shares at the end of the investment period, a value of 80% is assumed realistic by N2 and N3, while the 100% share assumed for N1 is contemplated an extreme.

4.5.2 Assessment of district heating supply costs

If district heating infrastructure is economically feasible, these networks need to be supplied with energy in form of heat. The Hotmaps toolbox provides users with the calculation module of “CM – District heating supply dispatch” (Hasani, 2020). As for the economic assessment of potential infrastructure, evaluation of supply conditions offers countless opportunities for sensitivities of supply-side parameters. However, again, the set of sensitivities is limited to a set of representative scenarios, to benefit the scope of the case study. These scenarios are oriented at heating and cooling strategies for the pilot city Frankfurt am Main, Germany (Prohaska et al., 2020: p. 40).

Inputs to the calculation module are structured in four groups: “Inputs”, “Basic Inputs”, “Advanced Inputs (Level 1)”, and “Advanced Inputs (Level 2)” (Fallahnejad, 2020b).

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In the “Inputs” section, available thermal output capacity indicators – for a back-pressure combined heat and power (CHP) plant, a waste incineration plant, a heating boiler, a heat pump, and a solar thermal unit are defined according to local potentials.

As the case study district is located at the Baltic Sea, there is a large potential for water-sourced heat pumps using “Kieler Förde”, the local bay of the Baltic described in 1.2. Additionally, in a neighboring park there is potential for another heat pump using shallow geothermal potentials as heat source. Furthermore, in the south-western corner of the district, on the edges of the commercial area used as logistic centre by the German postal service there is potential for an air-sourced heat pump using ambient air as heat potential. There is neither potential for use of industrial excess heat, nor a waste incineration plant near the district. Biomass applications require large space for storage and handling, as well as they are considered difficult to place within densely populated urban areas. Hence, every demand for additional heating capacities beyond the capacities of heat pumps needs to be supplied either via heat boilers or CHPs. For this case study a cascade of different CHP sizes is considered according to different levels of demand from refurbishment options B0, B1, B2, and B3. Figure 47 provides an overview of installed heating capacities.

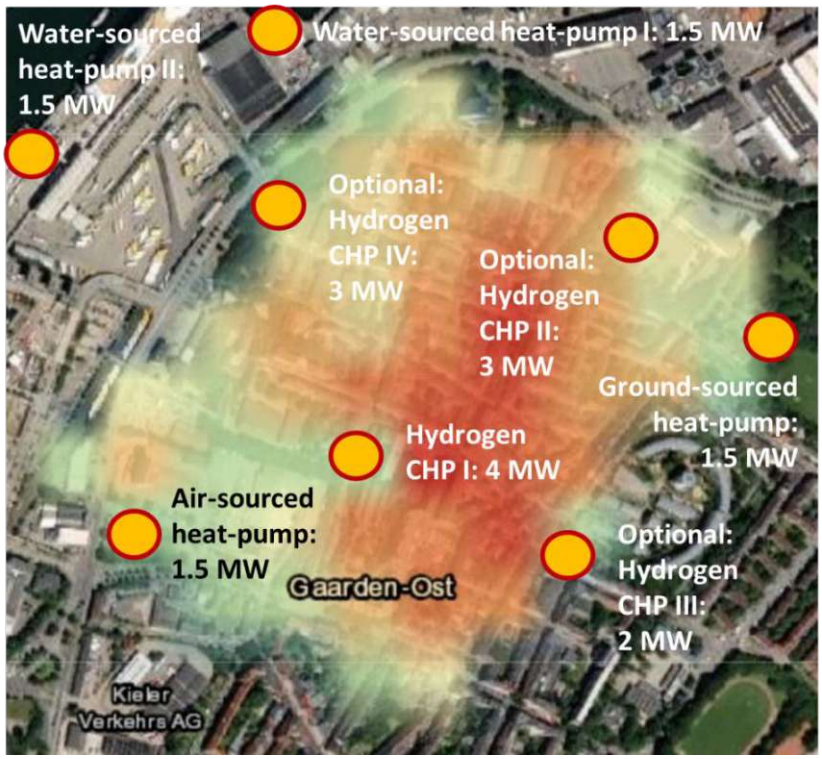

Figure 47: Map of heat supply installation options: HP potentials and CHP cascades. *Own approach.*

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For the specified capacities to be recognized by the toolbox, it is important to select the simulation mode “dispatch” instead of “invest” in the entry mask of “Input”. Furthermore, the district heating demand is not specified in the data entry mask, as this is provided by the customized input files being uploaded to the user´s account. These are selected at the end of the data entry mask. Other amendments within the “Inputs” section are the interest rate and the CO_2 (carbon dioxide) price applicable to emissions from district heating facilities. In alignment with the previous section, the interest rate is amended to 4%. For the carbon price, four sensitivities apply according to the scenarios described below.

Table 50: Carbon prices for all district heating supply scenarios. *Own visualization based on Prohaska et al., 2020: p. 40.*

Sensitivity	Carbon Price [€/ton CO_2e]
DH1 = District heating supply 1	183
DH2 = District heating supply 2	139
DH3 = District heating supply 3	199
DH4 = District heating supply 4	296

"Basic Inputs" includes information on thermal, and electrical efficiencies, as well as coefficients of performance (COP)s for heat pumps. In addition, lifetimes of equipment and energy carriers used for different supply options are determined. Within the scope of this case study application, no changes to the default settings provided by the toolbox are considered (Hasani, 2020). Hence, the thermal efficiencies of backpressure CHPs remain at 60%, while their electrical efficiencies remain at 20%. COPs of heat pumps are defined as 3, resulting in 300% heat generation from the respective input of electricity. "Lifetime” for back pressure CHPs and heat pumps is assumed to be 25 years. Considering the aim of 95% reduction of carbon emissions, only low carbon energy carriers are considered for energy supply streams. This includes green hydrogen for the back-pressure CHPs and electricity for heat pumps.

Subsequently, in the input section “Advanced Inputs: (Level 1), emission factors and prices of potential energy carriers are defined. Values for electricity represent the overarching sensitivity of lifecycle emissions of electricity, differentiating between renewable (Intergovernmental Panel on Climate Change (IPCC), 2011: p. 17) and conventional generation (German Federal Environmental Agency (GFEA), 2021: p. 15). Emission factors for green hydrogen are derived considering their origin of renewable electricity (Deutscher Industrie- und Handelskammertag e.V. (DIHK), 2020: p. 7; Fuel Cells and Hydrogen Joint Technology Initiative (FCH JU), 2016: p. 7). Direct emissions of electricity and hydrogen are zero. All emission factors are provided by table 51:

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Table 51: Carbon emission factors (lifecycle and direct) for all district heating supply scenarios.
Own table based on IPCC, 2011: p. 17; GFEA, 2021: p. 15; DIHK, 2020: p.7.

Energy carrier	LC Carbon emission factor [t CO2e/MWh]	Direct carbon emissions [t CO2e/MWh]
Electricity	Conventional: 0.366 ; Green: 0.05	0
Hydrogen	0.075	0

While the development of prices for energy carriers remains uncertain, some studies propose scarcity of supply as a future scenario (e.g., Bundesverband Erneuerbare Energie e.V. (BEE), 2021: p. 7). Additionally, there are views that cities and sectors might generate competition for renewable energy resources on a global level (HIC and FFE, 2021: p. 43). Markets could react with rising prices (Asmundson, 2020: p. 2). For the case study the uncertainty about future prices of energy carriers is represented by the scenarios shown in table 52. Electricity prices are varied in alignment with Prohaska et al., 2020. Accordingly, hydrogen prices (German Federal Parliament (GFP), 2020: p. 9) were adjusted to reflect variations in electricity prices between scenarios as electricity is considered as a basis for green hydrogen production (Ajanovic and Haas, 2021: p. 10519).

Table 52: Energy carrier prices for all DH supply scenarios. *Own visualization of Prohaska et al, 2020; GFP, 2020: p.9*

Energy carrier	Price [€/MWh]			
Sensitivities	District heating supply 1	District heating supply 2	District heating supply 3	District heating supply 4
Electricity	68	72	86	103
Hydrogen	120	120	135	155

The toolbox´s provided optionality to adjust the simulation´s level of detail in terms of the resolution of heat dispatch profiles – especially via a stand-alone module (Energy Economics Group (EEG), 2019) – is neglected for the scope of this case study. However, users shall be aware of the opportunity to not only simulate dispatches on an aggregated level but to derive detail dispatch profiles differentiating between different load situations. This is necessary to verify whether supply scenarios are realistic to be supplied either by electricity generation and renewable energy resources and potentials within the case study district - or whether these need to be imported via sufficient capacities of transmission lines, pipelines, or other logistic infrastructures into the case study district (Connolly et al., 2015: p. 6).

The input section “Advanced Inputs: (Level 2)” provides with optionality to calibrate investment cost, ramping cost, and operational expenses (OPEX) for equipment being installed to supply the district heating network (Hasani, 2020).

The toolbox´s default data is amended in terms of investment costs for heat pumps. Water-sourced heat pumps are considered more costly than air-sourced, or brine-

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sourced heat pumps (Pieper et al., 2018: p. 366). The following table 53 provides investment cost parameters applied for the case study.

Table 53: Investment costs of heating equipment for all DH supply scenarios. *Calibration partly based on Hasani, 2020.*

Equipment	Investment cost [€/MW]
Back-pressure CHP	800,000
Heat pump	1,500,000

Ramping costs are not amended from the Hotmaps toolbox default settings: Accordingly, the backpressure CHP plants incur 100€/MWh of levelized ramping cost. In alignment with investment costs, OPEX indications have been amended to reflect higher costs for water- and ground-sourced heat pumps. Parameters for the case study application are shown in table 54.

Table 54: Operative costs of heating equipment for all district heating supply scenarios. *Calibration based on Hasani, 2020.*

Equipment	OPEX fix [€/MW*yr]	OPEX variable [€/MWh]
Back-pressure CHP	46,000	4.5
Heat pump	68,000	1.0

4.5.3 Assessment of decentral heating supply costs

According to the district heating network sensitivities as described in section 4.5.1, not the entire district will be supplied by district heating infrastructure. Consequently, some decentral heating infrastructure will be needed in these scenarios. In addition, the extreme case of 100% decentral heat provision is simulated to create a complete range of results between extreme scenarios.

“CM – Decentral heating supply” is a calculation module by the Hotmaps toolbox enabling the assessment of economic indicators and carbon emissions for decentral heating options (Hasani, 2019c). Inputs for the calculation module are again structured as “Inputs” and “Basic Inputs”. To keep the scope of the case study on the integration of demand data into the toolbox, inputs to the calculation module are not amended except from the interest rate, which is aligned with the previous calculation modules defined at 4%.

Consequently, in the input section “Basic Inputs”, the below emission factors of table 55 are referenced. The only amendments to the data are the carbon emission factors for conventional and green electricity, which are aligned with the values for the district heating supply.

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Table 55: Carbon emission factors for all decentral supply scenarios. *Calibration based on Hasani, 2019; GFEA, 2021: p.15.*

Energy carrier	Carbon emission factor [t CO2e/MWh]
Natural gas	0.20124
Biomass solid	0.312
Electricity	Conventional: 0.366 ; Green: 0.05
Light fuel oil	0.2664

4.5.4 Assessment of cost measures for comparison and decision-making

Total refurbishment costs are calculated by multiplying refurbished gross floor areas with the respective costs per square meter of the chosen refurbishment option. However, to compare the cost effectiveness of refurbishment measures independent from the size of the refurbished areas, levelized refurbishment costs are derived by dividing the total refurbishment costs by the total energy demand saved over a defined lifetime of the refurbishment measure.

$$LCOR = \frac{C_R}{E_S * L} \quad \textbf{[53]}$$

With: LCOR= Levelized costs of refurbishments [€/MWh], C_R = Cost of the refurbishments [€], E_S = Energy savings achieved by the refurbishments [MWh/yr], L = Lifetime of the refurbishments [yr]; Source: Filippi Oberegger et al., 2020: p.6.

For the average lifetime of refurbishment measures, 50 years are considered. This is a conservative approach as other authors proposed a lifetime of 60 years (e.g., Schwartz, Raslan, and Mumovic, 2018: pp. 232-233).

Both, district, and decentral heating options require heat supply, which incurs costs. These can be stated in levelized form, using MWh consumed by the loads of the network as the quotient of the following equation 54:

$$LCOH = \frac{C_{HS}}{E} \quad \textbf{[54]}$$

With: LCOH= Levelized costs of heat supply [€/MWh], C_{HS} = Cost of heat supply [€/yr], E = Energy supplied by the heating system set-up [MWh/yr], Source: Cui et al., 2016: p. 223.

For district heating set-ups, furthermore network infrastructure is required, which incurs costs. Again, these costs can be stated in levelized form, using MWh consumed by the loads of the network as the quotient of the following equation 55:

$$LCON = \frac{C_N}{E} \quad \textbf{[55]}$$

With: LCON= Levelized costs of network infrastructure [€/MWh], C_N = Cost of network infrastructure [€/yr], E = Energy supplied by the heating system set-up [MWh/yr], Adapted from LCOH: Cui et al., 2016: p. 223.

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Accordingly, the total heating costs for district heating options consist of both, LCOH for district heating, as well as LCON for the respective district heating network. This can be used to compare levelized costs of district heating with levelized refurbishment costs and levelized costs of decentral heat supply on a fair basis. The approach is shown by equation 56 below:

$$LCODH = LCOH + LCON \quad [56]$$

With: LCODH= Levelized costs of district heating [€/MWh], LCOH= Levelized costs of heat supply [€/MWh], LCON= Levelized costs of network infrastructure [€/MWh]. Own approach.

To furthermore evaluate the long-term economic feasibility of energetic refurbishment options, a comparison of total heating costs over the lifetime of potential refurbishment measures needs to be conducted. This shall indicate whether from an economic perspective it is advisable to invest in energetic refurbishment. The condition should be fulfilled if the levelized cost of refurbishment is lower than the total heating costs over lifetime. Their calculation is shown by equation 57 below:

$$C_{THL} = \frac{C_R + C_{NL} + C_{SL}}{L} \quad [57]$$

With: C_{THL} = Total heating costs over lifetime [€], C_R = Cost of refurbishments [€], C_{NL} = Cost of eventual district heating networks over lifetime [€], C_{SL} = Cost of heat supply over lifetime [€], and L = Lifetime of the refurbishments [yr]; Source: Own approach oriented at Gustafsson, Myhren, and Dotzauer, 2018: p. 3.

Total heating costs over a lifetime are assumed to be the central decision-making criteria for most decision-makers. However, while strictly economic decisions might be imperative in the short-term, they might unintentionally hinder a more prosperous long-term economic performance: If short-term oriented economic decision-making would lead to unsustainable development in the longer term, this could harm environmental and social framing conditions required for a prospering economy (Ibrahim and Kennedy, 2016: p. 2). Hence, the sustainability impact of lower carbon emissions can be considered for decision-making by the indicator of carbon abatement costs. Here, carbon reduction and monetary savings are equally valued, as shown in equation 58.

$$\frac{\Delta C_{THL}}{\Delta_{CO2e}} \quad [58]$$

With: ΔC_{THL} = Difference in total heating costs over lifetime [€], Δ_{CO2e} = Carbon reduction [t CO_2e]; Source: Own approach based on Ibrahim and Kennedy, 2016: p. 11.

Carbon abatement cost shall be the long-term decision-making metric applied in this case study.

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5 RESULTS

For the case study district in the city of Kiel, all data presented in chapter 4 were used to create, calibrate, and apply UBEMs and the Hotmaps toolbox with sensitivities alongside the toolchain as described in chapter 3. This chapter will provide results from these simulations.

5.1 Sensitivity blocks A-C: Impact on demand side indicators

The aims of sensitivity blocks A-C were described in sections 3.2.1 – 3.2.5. Sensitivity block A focused on three different approaches to creating a base model for the case study district, as the user might have different levels of detail on the energetic status quo of the buildings available. Figure 48 provides a visual representation of results, combined with a quantitative indication of total heat demand, measured in GWh/yr.

Figure 48: Results of heat demand simulation for A1-B0, A2-B0, and A3-B0. *Own applications of UBEM. Underlying geo-data: Kiel, 2020f.*

The results show that the data-based approaches of orientation at the distribution of initial refurbishment levels (B0) on federal state level (A1), and on district level (A3) are more closely aligned to each other than to the individual assessment by the user (A2). This indicates that the distribution of initial refurbishment status per building type in the case study district does not differ from the average on the federal state level significantly. A2, the user´s assessment based on visual impression indicates a substantially higher heat demand. This difference in the results

of assessing the building´s energetic performance status can be an ambiguous differentiator from the data-based approaches A1 and A3 if the real demand remains unknown. To qualify which version is closer to reality, results are compared to the district report (Complan, 2013: p. 59), which claims to be based on metered data. The report focuses on total energy consumption and therefore includes electricity consumption, but not all buildings, which are considered for this case study. However, when comparing the values for the congruent buildings in the centre of the district and normalizing the estimates accordingly, it indicates a yearly heat demand of 45 GWh/yr, thereby coming closest to A3.

In sensitivity block B, different refurbishment options to the base models from A were considered. Figure 49 shows a visualization of its results on the next page:

Total heat demand results for the refurbishment options basic refurbishment (B1, B2, and B3) are derived from the combination of respective building templates, which were presented in chapter 4. Consequently, the results for the sensitivity block improvements of the energetic performance of the overall building stock are aligned with the energetic performance improvements recognized by the building templates. However, since district results consist of a mixture of building types, they do not align exactly with reduction levels of single templates.

An interesting perspective is the improvement for A2: Though having a higher total heat demand in the initial model (B0), it achieves the lowest total heat demand for the average (B2) and ambitious (B3) refurbishment options. By 15.3 GWh/yr (B3), coming from 52.5 GWh/yr (B0), a reduction of the total heat demand of approximately 71% is achieved by the application of ambitious refurbishment measures, compared to the initial status quo. In contrast, for A1 and A3, only 20.2, respectively 20.3 GWh/yr of total heat demand are achieved by ambitious refurbishment measures (B3). This translates into a 57%, respectively 56% reduction of total heat demand compared to the initial energetic status quo (B0).

Cost-benefit optimization for the refurbishment measures explains this phenomenon: As there is greater potential for improvements of energetic performance for weak initial refurbishment status, in exemplum non-modernized buildings. These buildings can be addressed with measures improving the performance level at relatively low costs. These low-cost, but high benefit solutions ("quick-win measures") are integrated into the modernized – and partly into the slightly modernized – initial variants already.

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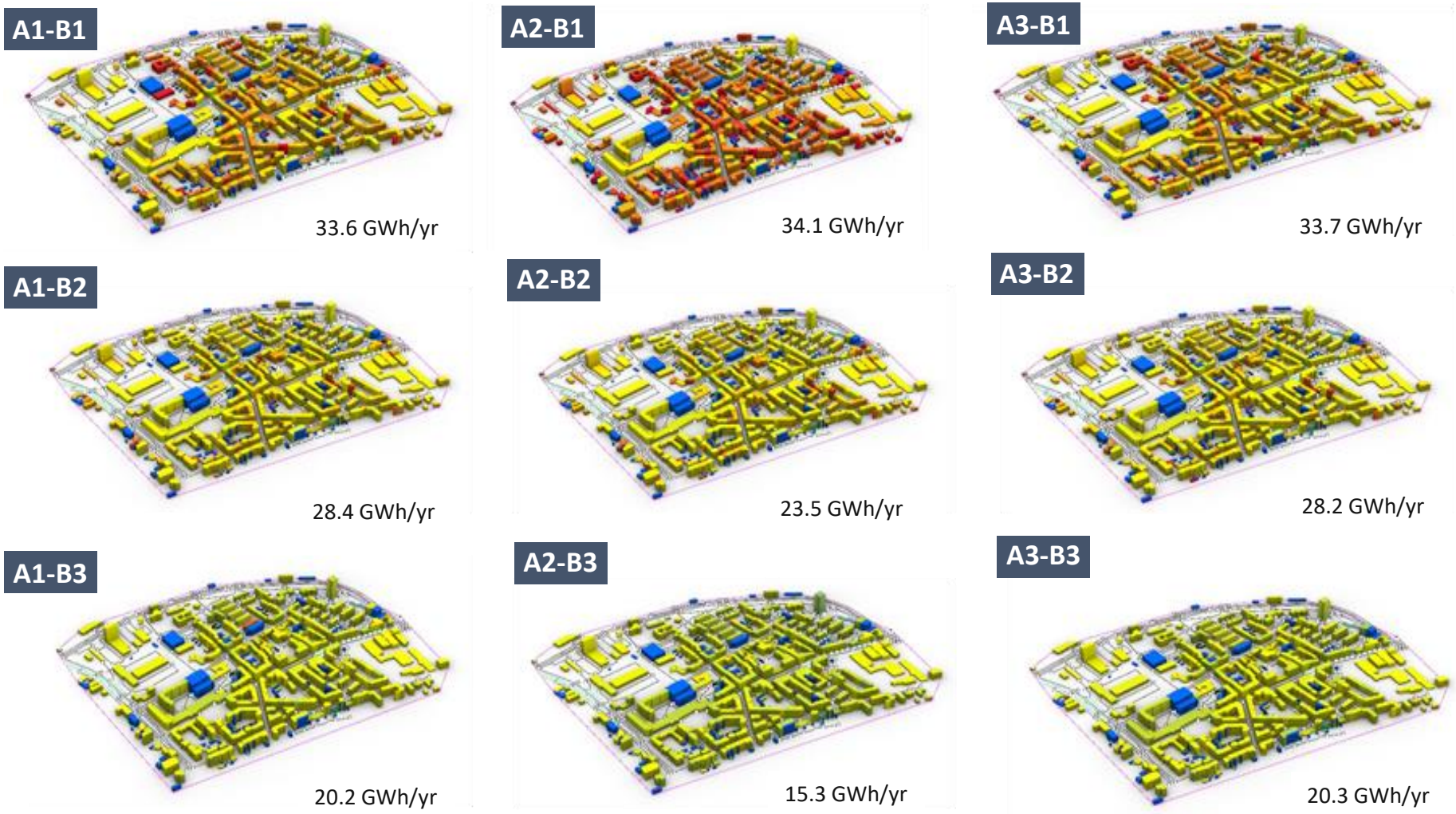

Figure 49: Results of heat demand simulation for refurbishment options B1, B2, and B3, applied on A1, A2, and A3. *Own applications of UBEM. Underlying geo-data: Kiel, 2020f.*

Hence, these initial variants need to be addressed with more costly, less effective measures. In addition, their initial status prevents more effective measures from being implemented. For example, an existing 2 HPG window in a modernized initial status quo is not cost-benefit optimal to be replaced with a 3 HPG, because the energetic benefit from one additional layer of glass is too small to justify the additional cost. In contrast, in the case of a non-modernized building, the benefit from replacing a simple double-layered window with a 3 HPG window is much larger. This is allowing for more costs while maintaining the required cost-benefit level.

The same effects are visualized in figure 50. The scatterplot compares the levelized cost of refurbishment options (LCOR) in €/MWh saved, with the total heat demand per refurbishment option in GWh/yr. The different levels of refurbishment options and initial status quo (B0,1,2,3) are circled, while the development of the three initial refurbishment status variants is indicated via lines. According to the lines, it becomes apparent that the higher share of non-modernized buildings in variant A2 leads to higher total heat demands in B0, the initial refurbishment status, and B1, the basic refurbishment option. However, from the average refurbishment option, B2, onwards, A2 achieves lowest total heat demands. The reason again: More optionality for higher-cost measures in initially non-modernized buildings, because the relatively higher benefit allows for more costly measures while keeping within required cost-benefit ratios.

Despite the occurrence of higher total costs of refurbishment, these are divided by a higher reduction of heat demand, leading to lower levelized costs. Overall, there is a clear relationship between lower total heat demand and lower levelized refurbishment costs. Put differently, more ambitious measures cause higher total refurbishment costs, but these are divided by a larger reduction of heat demand, leading to lower costs of refurbishment per MWh saved. This is emphasized by unmodernized buildings, allowing for more costly measures of greater effect.

Furthermore, figure 50 on the next page confirms, that there are no differences between C1 and C2 versions.

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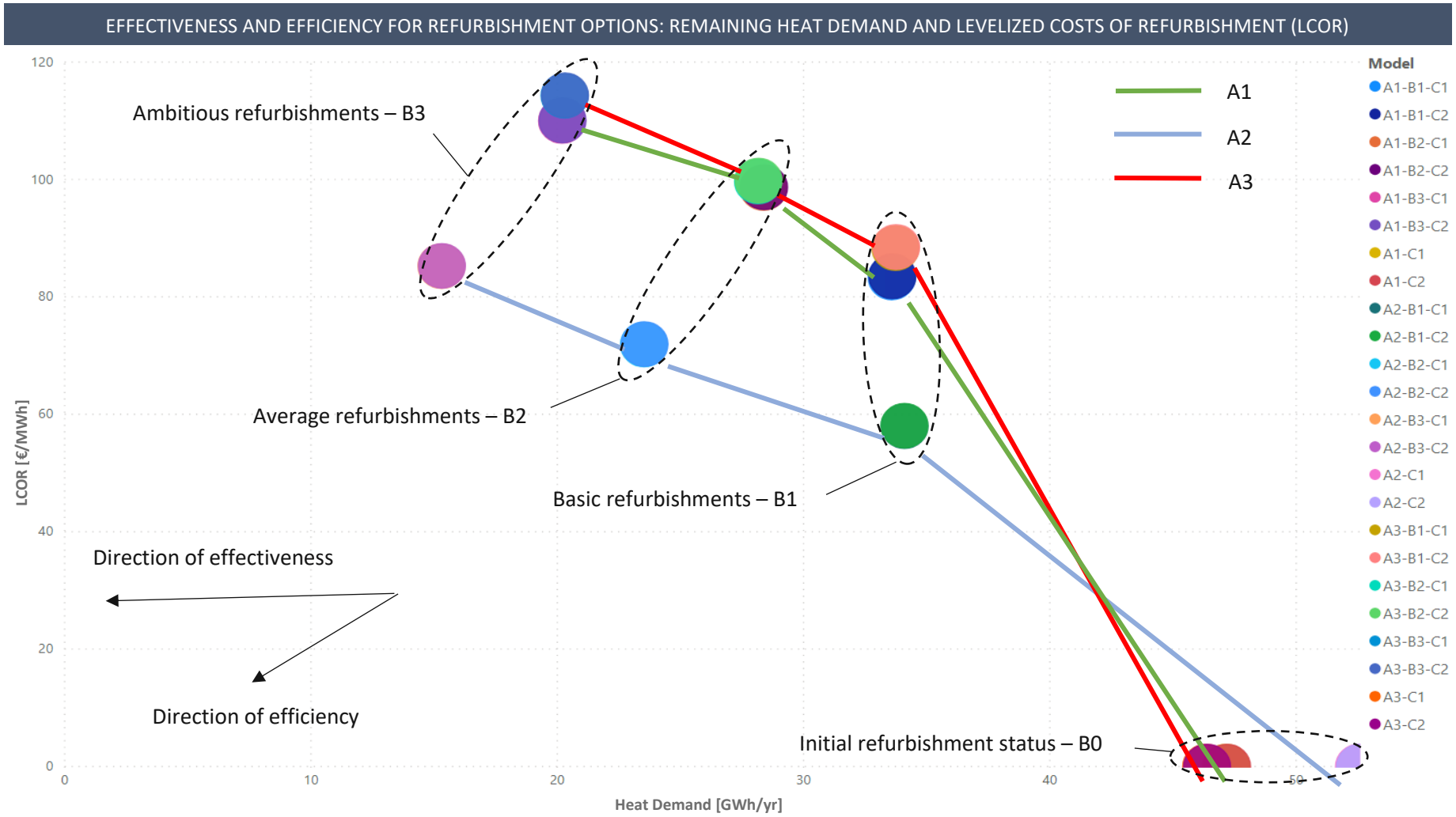

Figure 50: LCOR: Effectiveness and efficiency of refurbishment options. *Own approach. GWh/yr based on UBEM results. Refurbishment costs derived from ARGE, 2012 and applicable GFA.*

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5.2 Comparison of heat demand from blocks A-C and the Hotmaps toolbox

More interesting for the different approaches of allocating heat demand to hectare level is to check whether there is a substantial difference in heat densities between C1 and C2 options. In addition, a comparison with the default heat demand provided by the Hotmaps toolbox is of interest. Figure 51 provides a visual comparison of heatmaps from the Hotmaps default setting, and the sensitivity blocks A-C.

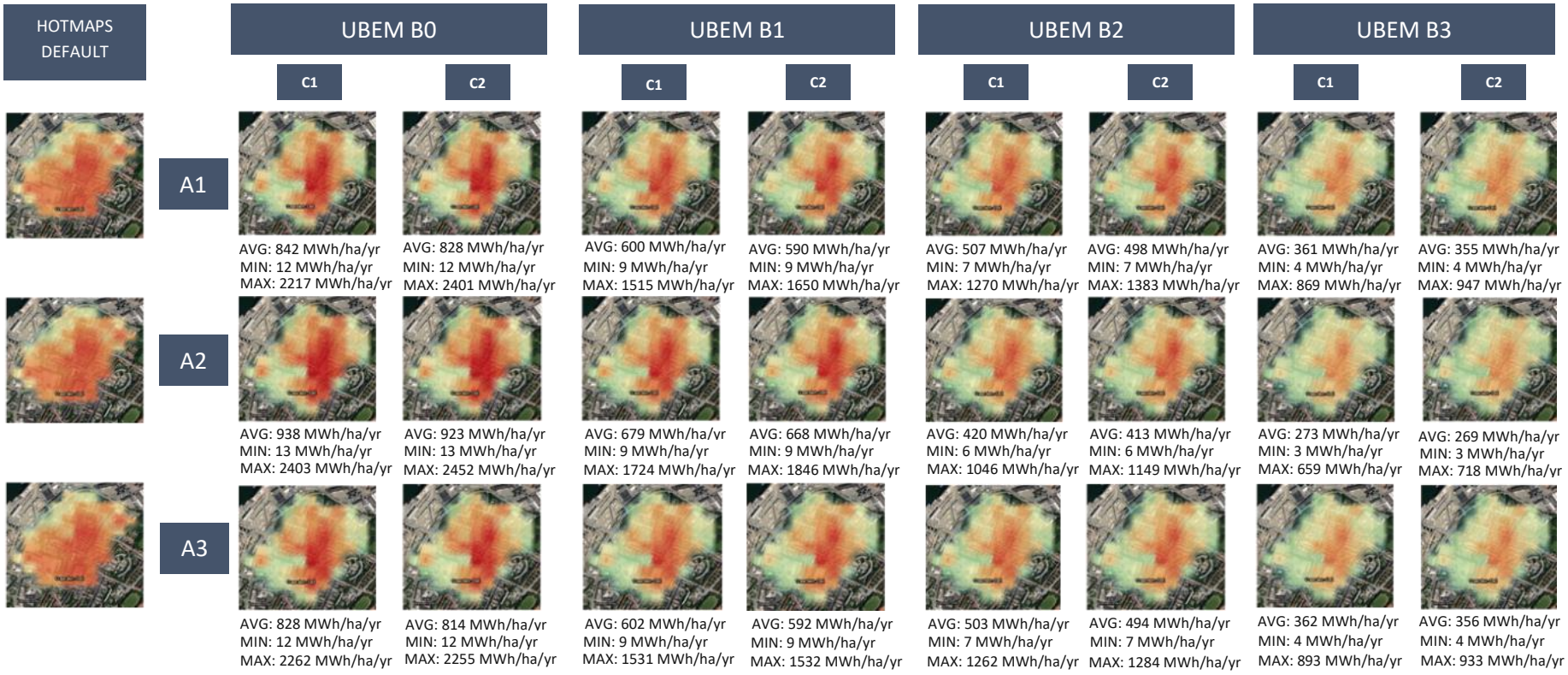

Figure 51: Comparison of resulting heat demand maps from sensitivity steps A-C and the Hotmaps toolbox´ default heatmap. *Own application of Fallahnejad, 2020a.*

All visuals below show the same area of the case study district and its surroundings on the same color scale. Dark red for high heat demand at the location, light green for low heat demand at the location. The maps are arranged in a matrix form, each indicating their A-, B- and C-variant and their average (AVG), minimum (MIN), and maximum (MAX) heat density.

Between the UBEM sensitivities and the Hotmaps toolbox default heatmap, there are differences in the spatial allocation of heat demand. Hence, while the toolbox indicates a higher heat demand overall, it is evenly spread across the case study district. For the UBEM sensitivities, however, heat demand is concentrated on the central hectares of the district, while less populated zones in the southwest and northeast show indications of lower heat demand.

This holds for all sensitivities of UBEM. It might reflect the difference between the top-down and bottom-up approach to defining heat demand per hectare: While the toolbox considers heat demand information of a higher level and breaks it down to the individual hectares, according to procedures described in section 3.1.2, by the UBEM, individual buildings are considered based on their type and size to compute heat demand. This leads to a sharper resolution of heat demand per hectare.

Differences of heat densities between C1 and C2 options to the allocation of heat demand need to be differentiated between average, minimum, and maximum heat densities:
From an average heat density perspective, the C2 option indicates slightly lower heat densities in all cases. This is caused by hectares, which are located at the edges of the case study district. In the C2 version, they have received their real shares of heat demand from buildings which are located on the borders to more central hectares. In C1, these hectares have received no heat demand. Hence, there are more hectares considered by C2, than by C1, increasing the quotient for calculating average heat densities and thereby reducing the results for average heat density. In terms of minimum heat densities, there are no differences between C1 and C2 versions. This is caused by a specific hectare, in which a small number of buildings are located. None of these buildings is located on the edges of the hectare. Hence, there is no change in minimum heat densities across sensitivities. The shares of the heat demand of buildings, which is allocated to hectares on the edges, not being considered for allocation in C1 versions, are higher than the heat demand of this specific hectare. Accordingly, values of minimum heat density are not influenced by different heat

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demand allocation approaches in C2. In contrast, maximum heat densities are higher in C2 versions for almost all sensitivities. However, there is one exception and further inconsistencies in terms of the size of the differences between C1 and C2 versions. In the initial refurbishment status of A3, the C1 version has a higher heat density than the C2 version. The inconsistencies are caused by different initial refurbishment status being assigned to individual buildings in the most heat-dense hectare of the district. Accordingly, different refurbishment measures are assigned. In consequence, in all sensitivity cases, different amounts of heat demand are allocated to neighboring hectares in C2 versions. In summary, in C2 versions, heat demands are tendentially shifted from the dense central hectares towards the less populated peripheries.

5.3 Sensitivity blocks A-D: Impact on supply side indicators

Beyond heat demand reductions on the demand side, refurbishment measures need to be evaluated including the heat supply indicators. This is because supply solutions orient at demand conditions. Thereby, sensitivities on the demand side might have impacts – knock-on-effects – on the supply side. Relevant sensitivities on the supply side of the case study were described in sections 4.5.1, 4.5.2, and 4.5.3: Sensitivities on network market shares, different options for district heat supply, and decentral supply for the district.

All refurbishment measures need to reach a 95% reduction of direct carbon emissions from the building stock (Kiel, 2019b). As hydrogen and electricity do not create direct emissions, this target is reached by all options. However, for the lifecycle perspective, relevant benchmarks are calculated from demand indications of A1, A2, A3, considering the current fuel mix from the district report (Complan, 2013: p. 59). All scenarios were calculated with the “CM – District Heating Supply Dispatch” and “CM – Decentral heating” of the toolbox. The various supply sensitivities are measured in tons of carbon emissions per year and are visualized in column charts in figure 52 below, each distinguished between different options for electricity supply: From a grey grid or a green grid, as described in sections 5.4.2 and 5.4.3

The Hotmaps toolbox considered large-scale heat pumps (limited at 6 MW local potential), combined with hydrogen-fed CHPs as the supply set up for the district heating network cases. The decentral supply options are assumed to be supplied by a mix of residential heat pumps and hydrogen-fed heat boilers. Important to note is that for network sensitivities covering only 80% of supply, the remaining 20% are assumed to be covered by the decentral supply options.

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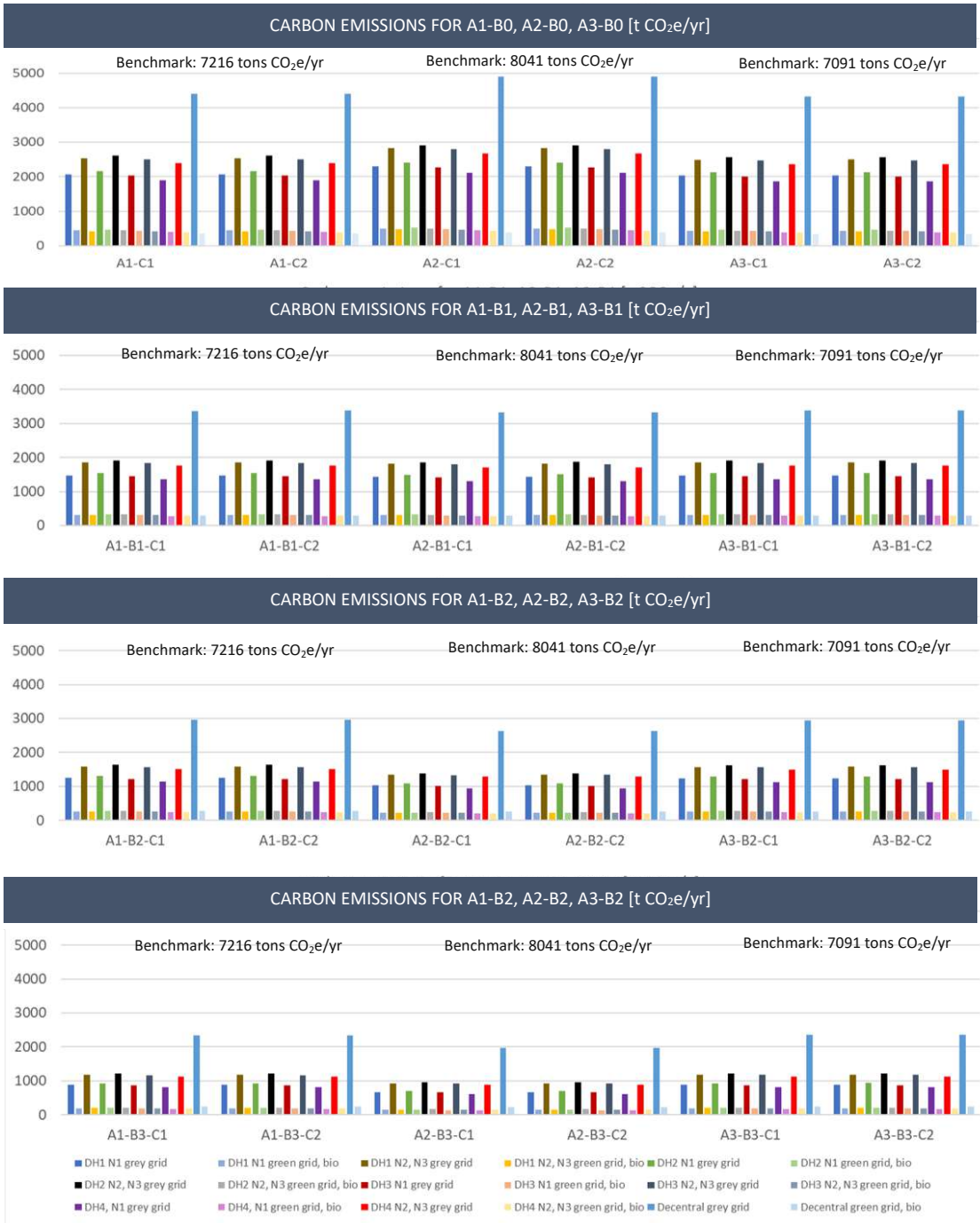

Figure 52: Carbon emissions for refurbishment and heat supply options. *Own application of Hasani, 2020; Fallahnejad, 2020b.*

While for direct emissions all scenarios reach a 95% reduction of lifecycle carbon emissions, for a lifecycle perspective the following maximum values cannot be exceeded: 361 tons CO_2e/yr for A1, 402 tons CO_2e/yr for A2, 356 tons CO_2e/yr.

Unfortunately, none of the conventional electricity grid supply options for electricity reaches the required reduction rates. Therefore, only renewable electricity grid options are feasible. These renewable electricity grid supply options for initial

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refurbishment status B0 allow for the following ranges of carbon emissions depending on the individual sensitivity cases:

For B0, the A1, A2, and A3 district heating supply options range between 383 to 520 tons CO_2e/yr. Its decentral supply equivalent ranges between 345 to 392 ton CO_2e/yr. Accordingly, not all versions of the initial refurbishment status are considered fit for purpose by default, if emissions are considered on a lifecycle basis. In some cases, owners will need to refurbish their buildings, independent from the development of carbon intensity of supply to reach the target. District heat supply options for B1 versions achieve between 276 and 334 ton CO_2e/yr. Equivalent decentral supply options reach 345 to 395 ton CO_2e/yr. Here, all supply options achieve a 95% reduction of lifecycle carbon emissions. This holds for all further refurbishment steps: For B2 versions, district heating options reduce their carbon emissions to between 199 to 281 ton CO_2e/yr, while decentral heating options reduce to between 257 and 272 ton CO_2e/yr. The largest reductions of carbon emissions compared to the benchmarks are achieved by the B3 ambitious refurbishment options: Emissions from district heating supply options amount to 129 – 209 ton CO_2e/yr, their equivalent decentral supply options to 216 – 238 ton CO_2e/yr.

In the following figures 53, 54, and 55, levelized costs of heat supply (LCOH), levelized costs of network infrastructure (LCON), and levelized costs of district heat supply (LCODH), including both, LCOH and LCON, will be visualized for district heating options. All of these measures will be shown for all initial refurbishment status (A1-A3), the refurbishment options (B0-B3), and the alternative approaches to areal distribution (C1-C2).

In figure 53 LCOH will be shown on the next page. LCOH reflects the total costs for the heat generation capacity (investment costs, maintenance, etc.) and its operational expenditures (O&M-, fuel-, CO_2-costs, etc.) in relation to the utilization of the capacities in full load hours per year (Cui et al., 2016: p. 223). It is measured in €/MWh. Inputs were described in chapter 4. However, the sensitivities consider different market conditions for energy carriers, carbon costs (DH1 – DH4), and capacities of district heating supply plants according to the different demand levels of refurbishments (B0-B3). In general, the case study district is supplied by large-scale heat pumps and hydrogen-fed CHPs. The latter are required in situations of peak demand. Then they are used to maintain a balance between demand and supply, while supply from heat pumps might be insufficient (Bloess et al., 2018: p. 1618).

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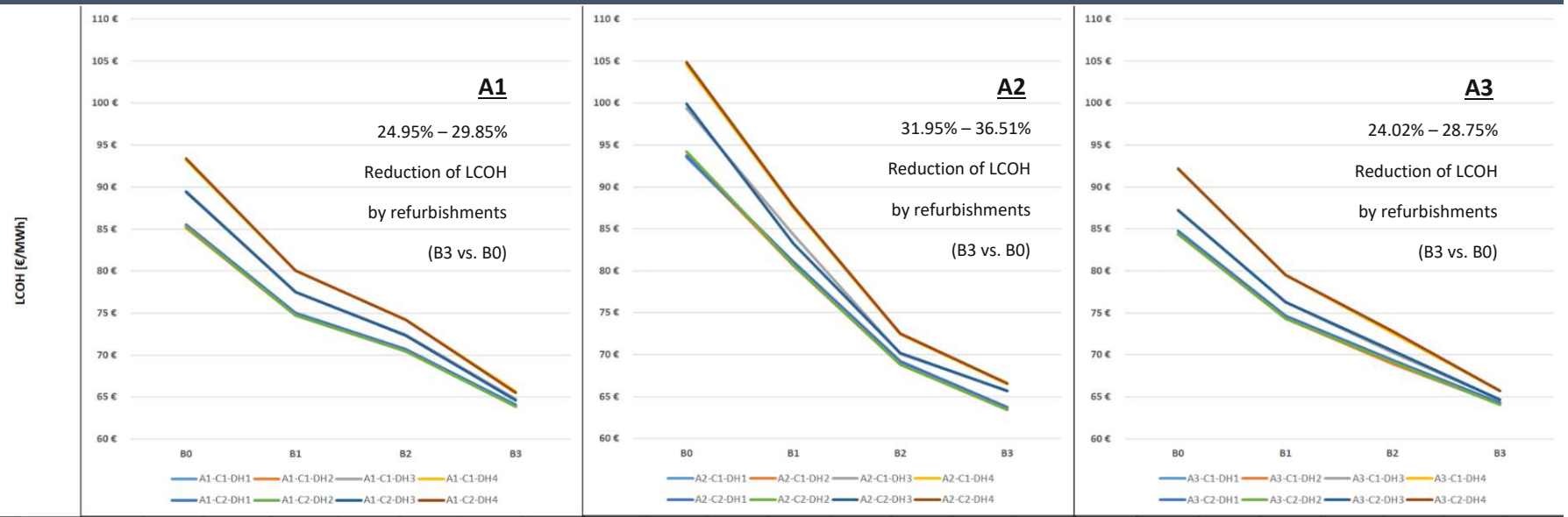
The following values have been calculated with the “CM – District Heating Supply Dispatch” provided by the Hotmaps toolbox. Tables below the graphics show the exact results from the calculations module.

LEVELIZED COSTS OF HEAT SUPPLY (LCOH) FOR VARIOS SENSITIVITIES OF DISTRICT HEATING SUPPLY OPTIONS [€/MWh]



Refur-	B0	85.54 €	85.15 €	89.50 €	93.26 €	85.50 €	85.27 €	89.40 €	93.39 €	93.52 €	93.75 €	99.40 €	104.55 €	93.69 €	94.20 €	99.90 €	104.89 €	84.76 €	84.39 €	87.26 €	92.21 €	84.74 €	84.37 €	87.25 €	92.21 €
bish-	B1	75.00 €	74.72 €	77.54 €	80.08 €	74.99 €	74.71 €	77.54 €	80.08 €	80.93 €	80.59 €	84.27 €	87.53 €	81.07 €	80.73 €	83.28 €	87.68 €	74.64 €	74.37 €	76.27 €	79.53 €	74.64 €	74.37 €	76.27 €	79.54 €
ment	B2	70.70 €	70.48 €	72.40 €	74.24 €	70.67 €	70.45 €	72.37 €	74.22 €	69.12 €	68.82 €	70.15 €	72.43 €	69.18 €	68.87 €	70.22 €	72.50 €	69.15 €	68.93 €	70.28 €	72.57 €	69.37 €	69.15 €	70.50 €	72.80 €
levels	B3	64.06 €	63.91 €	64.77 €	65.68 €	63.99 €	63.85 €	64.63 €	65.52 €	63.64 €	63.54 €	65.72 €	66.50 €	63.70 €	63.48 €	65.65 €	66.59 €	64.26 €	64.12 €	64.65 €	65.70 €	64.30 €	64.06 €	64.69 €	65.74 €
DH Sensitivities		DH1	DH2	DH3	DH4	DH1	DH2	DH3	DH4	DH1	DH2	DH3	DH4	DH1	DH2	DH3	DH4	DH1	DH2	DH3	DH4	DH1	DH2	DH3	DH4
Sensitivities A/C		A1-C1				A1-C2				A2-C1				A2-C2				A3-C1				A3-C2			

Figure 53: Levelized costs of heat supply for various sensitivities of district heating supply options. *Own application of Hasani, 2020.*

The results shown in figure 53 above indicate decreasing LCOH for higher levels of refurbishment. This is due to the relatively lower demand for heat in the refurbished versions of the case study district. Considering the limitation of local heat potentials for large-scale heat pumps to a maximal capacity of 6 MW, as described in section 4.5, it becomes apparent that the higher the heat demand of the respective model of the

case study district, the more capacity and heat provision will be required from comparatively less efficient CHPs, converting relatively costly hydrogen into heat, and thereby driving LCOH up.

The results suggest: The more ambitious the refurbishment measures being applied, the lower the remaining heat demand, the lower the associated LCOH for the case study district. This is especially true for versions of A2, where heat demand is highest for the versions of initial refurbishment status (LCOH up to 104.89€/MWh). Even if by the application of refurbishments, the differences decline (Lowest LCOH levels: A1: 63.85€/MWh; A2: 63.48€/MWh; A3:64.06€/MWh), the initial refurbishment status has an influence on LCOH.

In contrast, the differences between the LCOH of C1 and C2 versions are marginal. Hence, the alternative approach to allocating heat demand from building- to hectare-level does not have a significant impact on LCOH.

As mentioned above, LCON have been derived from the results of the "CM – Economic Assessment" provided by the Hotmaps toolbox. This calculation module provides annuity values for network costs, which can be converted into levelized form by considering the respective heat provision per year. The results shown in figure 54 on the next page indicate again a significant impact of initial refurbishment status:

As the initial heat demand is larger in A2-versions, compared to A1-, and A3-versions, the slightly higher total costs reflected by the annuities can be divided by a larger number of MWh to derive the LCON, leading to the lowest LCON at 11.77€/MWh. In contrast, for A1-, and A3-version, the LCON for initial refurbishment status is higher, due to lower levels of demand.

As described in section 5.1, initially less modernized buildings allow for more effective refurbishment measures to be applied economically. A2-versions include a higher share of less modernized buildings. Hence, here the ambitious refurbishment measures lead to the lowest demand levels. Accordingly, the network infrastructure is least utilized in this B3 scenario, leading to the highest LCON of all sensitivities at up to 30.11€/MWh.

As for LCOH, C-sensitivities have a marginal impact on LCON-levels only. However, as C2 versions cover more hectares (section 5.1), networks are slightly larger. Hence, also effects of refurbishments are larger.

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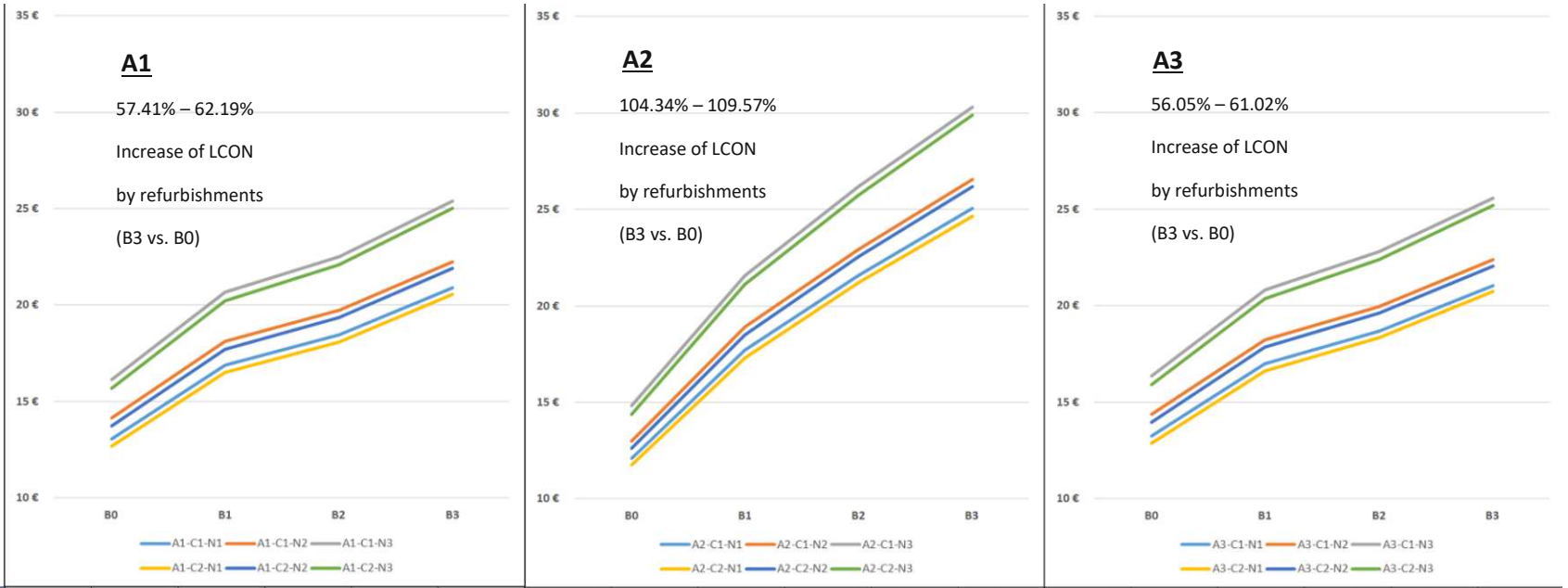
LEVELIZED COSTS OF NETWORK INFRASTRUCTURE (LCON) FOR VARIOS SENSITIVITIES OF DISTRICT HEATING SUPPLY OPTIONS [€/MWh]



Refur-bish-ment levels	B0	13.05 €	14.15 €	16.14 €	12.68 €	13.75 €	15.69 €	12.11 €	12.99 €	14.82 €	11.77 €	12.61 €	14.39 €	13.25 €	14.36 €	16.38 €	12.88 €	13.96 €	15.93 €
	B1	16.87 €	18.10 €	20.66 €	16.49 €	17.71 €	20.22 €	17.70 €	18.90 €	21.57 €	17.31 €	18.50 €	21.12 €	17.01 €	18.24 €	20.82 €	16.63 €	17.85 €	20.38 €
	B2	18.44 €	19.72 €	22.51 €	18.08 €	19.35 €	22.08 €	21.57 €	22.93 €	26.17 €	21.19 €	22.55 €	25.73 €	18.70 €	19.97 €	22.80 €	18.34 €	19.61 €	22.38 €
	B3	20.90 €	22.25 €	25.41 €	20.57 €	21.91 €	25.02 €	25.04 €	26.54 €	30.31 €	24.67 €	26.18 €	29.88 €	21.04 €	22.41 €	25.59 €	20.74 €	22.07 €	25.20 €
N Sensitivities		N1	N2	N3	N1	N2	N3	N1	N2	N3	N1	N2	N3	N1	N2	N3	N1	N2	N3
Sensitivities A/C		A1-C1			A1-C2			A2-C1			A2-C2			A3-C1			A3-C2		

Figure 54: Levelized costs of network infrastructure for various sensitivities of district heating supply options. *Own approach based on application of Fallahnejad, 2020b.*

For district heating options, both heat supply (LCOH) and network infrastructure (LCON) are necessary system components. The respective levelized cost of district heating (LCODH) is calculated as the sum of LCOH and LCON (equation 56 in 5.4.5). Results are shown in figure 55:

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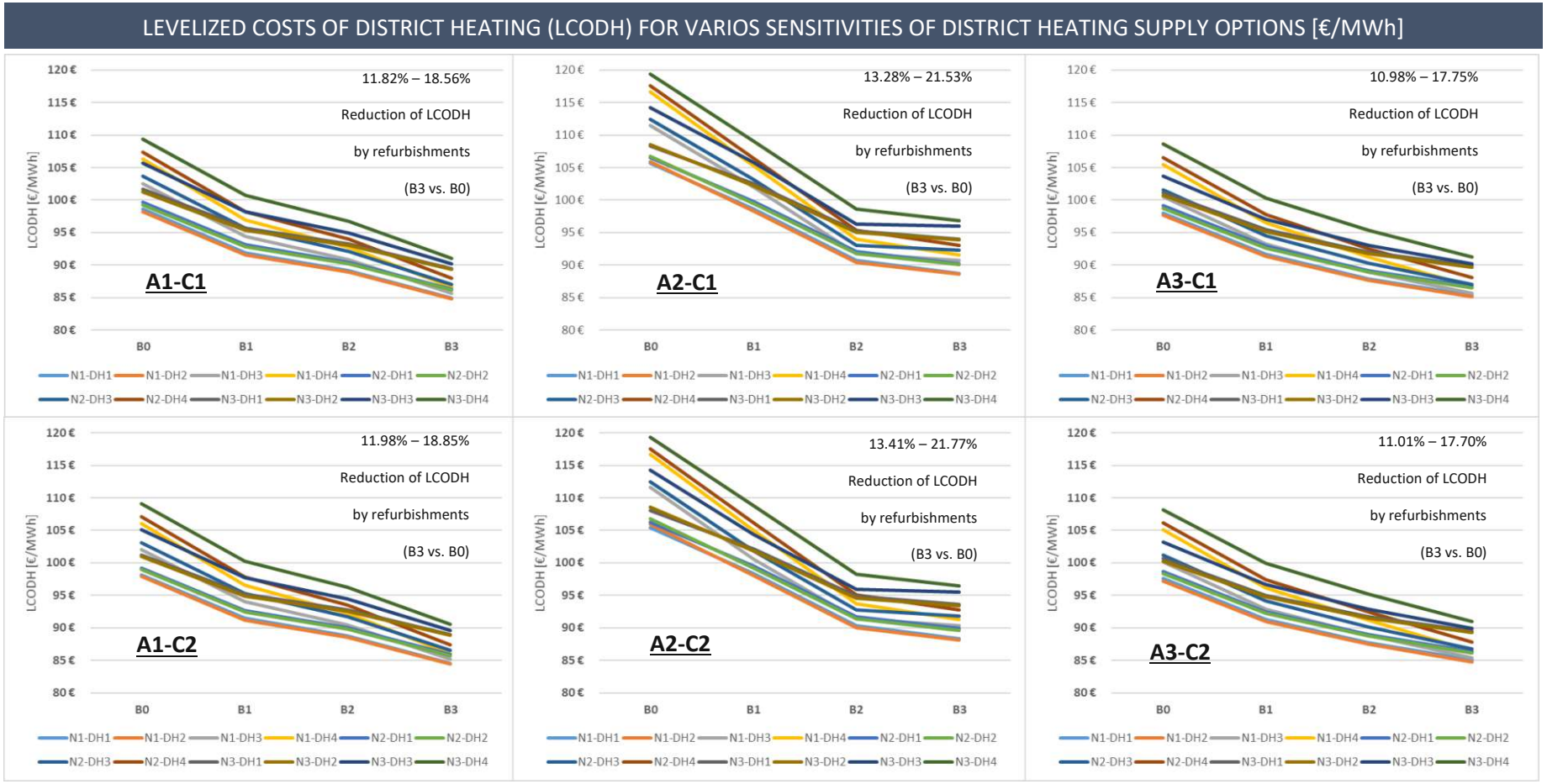

Figure 55: Levelized costs of district heating for various sensitivities of district heating supply options. *Own approach based on applications of Fallahnejad, 2020b; Hasani, 2020.*

The visualizations of results in figure 55 showed that levelized costs of district heating decrease if refurbishments are applied. B0 values are

highest across all versions of A and C sensitivities. Amongst all options, the LCODH for A2-C1 in combination with N3 and DH4 are the highest at 119.37€/MWh. Values for A1 and A3 are slightly lower at 109.40€/MWh and 108.59€/MWh. In line with the LCOH, the costs decrease most significant in A2-version. However, the larger decrease of demand and LCOH, leads to higher values of LCON. In effect, the combination of LCOH and LCON leads to an overall higher level of LCODH, even in B3 versions of ambitious refurbishments (Minimal value: 88.14€/MWh). A1 and A3 versions reach 84.41, respectively 84.80€/MWh, as their LCON are comparatively lower than for A2. The exact values for the total of 288 combinations of demand sensitivities and supply options are presented in table 56.

Table 56: Overview of LCODH. *Own approach based on applications of Fallahnejad, 2019b; Hasani, 2020.*

A/C Sensitivities	N Sensitivities	DH Sensitivities	Refurbishment levels				A/C Sensitivities	N Sensitivities	DH Sensitivities	Refurbishment levels			
			B0	B1	B2	B3				B0	B1	B2	B3
A1-C1	N1	DH1	98.59 €	91.87 €	89.14 €	84.96 €	A2-C2	N1	DH1	105.46 €	98.38 €	90.37 €	88.37 €
		DH2	98.20 €	91.60 €	88.92 €	84.81 €			DH2	105.97 €	98.04 €	90.06 €	88.14 €
		DH3	102.55 €	94.42 €	90.84 €	85.67 €			DH3	111.67 €	100.60 €	91.40 €	90.32 €
		DH4	106.31 €	96.95 €	92.68 €	86.58 €			DH4	116.66 €	105.00 €	93.69 €	91.26 €
	N2	DH1	99.69 €	93.11 €	90.42 €	86.31 €		N2	DH1	106.30 €	99.57 €	91.73 €	89.89 €
		DH2	99.30 €	92.83 €	90.20 €	86.16 €			DH2	106.81 €	99.23 €	91.42 €	89.66 €
		DH3	103.65 €	95.65 €	92.12 €	87.02 €			DH3	112.51 €	101.79 €	92.77 €	91.83 €
		DH4	107.41 €	98.18 €	93.96 €	87.93 €			DH4	117.50 €	106.19 €	95.05 €	92.77 €
	N3	DH1	101.68 €	95.66 €	93.21 €	89.46 €		N3	DH1	108.08 €	102.18 €	94.92 €	93.58 €
		DH2	101.29 €	95.38 €	92.99 €	89.32 €			DH2	108.59 €	101.84 €	94.61 €	93.35 €
		DH3	105.64 €	98.20 €	94.90 €	90.17 €			DH3	114.29 €	104.40 €	95.95 €	95.53 €
		DH4	109.40 €	100.74 €	96.75 €	91.08 €			DH4	119.28 €	108.80 €	98.24 €	96.47 €
A1-C2	N1	DH1	98.18 €	91.48 €	88.75 €	84.56 €	A3-C1	N1	DH1	98.01 €	91.65 €	87.85 €	85.30 €
		DH2	97.95 €	91.20 €	88.52 €	84.41 €			DH2	97.64 €	91.38 €	87.63 €	85.16 €
		DH3	102.08 €	94.03 €	90.44 €	85.20 €			DH3	100.51 €	93.28 €	88.98 €	85.69 €
		DH4	106.07 €	96.57 €	92.29 €	86.08 €			DH4	105.46 €	96.54 €	91.27 €	86.74 €
	N2	DH1	99.25 €	92.70 €	90.02 €	85.91 €		N2	DH1	99.12 €	92.88 €	89.12 €	86.67 €
		DH2	99.02 €	92.42 €	89.79 €	85.76 €			DH2	98.75 €	92.61 €	88.90 €	86.53 €
		DH3	103.15 €	95.25 €	91.71 €	86.55 €			DH3	101.62 €	94.51 €	90.25 €	87.06 €
		DH4	107.14 €	97.79 €	93.56 €	87.43 €			DH4	106.57 €	97.77 €	92.54 €	88.11 €
	N3	DH1	101.19 €	95.21 €	92.76 €	89.01 €		N3	DH1	101.14 €	95.46 €	91.95 €	89.85 €
		DH2	100.96 €	94.93 €	92.53 €	88.86 €			DH2	100.77 €	95.19 €	91.73 €	89.71 €
		DH3	105.09 €	97.76 €	94.45 €	89.65 €			DH3	103.64 €	97.09 €	93.08 €	90.24 €
		DH4	109.08 €	100.30 €	96.30 €	90.53 €			DH4	108.59 €	100.35 €	95.37 €	91.28 €
A2-C1	N1	DH1	105.63 €	98.63 €	90.70 €	88.68 €	A3-C2	N1	DH1	97.62 €	91.27 €	87.71 €	85.04 €
		DH2	105.86 €	98.30 €	90.39 €	88.58 €			DH2	97.25 €	91.00 €	87.49 €	84.80 €
		DH3	111.51 €	101.97 €	91.72 €	90.76 €			DH3	100.13 €	92.91 €	88.84 €	85.43 €
		DH4	116.66 €	105.23 €	94.00 €	91.54 €			DH4	105.09 €	96.17 €	91.14 €	86.48 €
	N2	DH1	106.51 €	99.83 €	92.05 €	90.19 €		N2	DH1	98.70 €	92.49 €	88.98 €	86.37 €
		DH2	106.74 €	99.49 €	91.74 €	90.09 €			DH2	98.33 €	92.22 €	88.76 €	86.13 €
		DH3	112.39 €	103.16 €	93.08 €	92.27 €			DH3	101.21 €	94.13 €	90.11 €	86.76 €
		DH4	117.54 €	106.42 €	95.36 €	93.04 €			DH4	106.17 €	97.39 €	92.41 €	87.81 €
	N3	DH1	108.34 €	102.50 €	95.30 €	93.95 €		N3	DH1	100.67 €	95.02 €	91.75 €	89.50 €
		DH2	108.57 €	102.16 €	94.99 €	93.85 €			DH2	100.30 €	94.75 €	91.54 €	89.26 €
		DH3	114.22 €	105.84 €	96.33 €	96.03 €			DH3	103.18 €	96.65 €	92.88 €	89.89 €
		DH4	119.37 €	109.10 €	98.61 €	96.81 €			DH4	108.14 €	99.92 €	95.18 €	90.94 €

In addition to district heating, also decentral heating is considered as a supply option for the case study district, as described in chapter 4. Figure 56 on the next page provides an overview of LCOH for decentral supply options, calculated with the “CM – Decentral heating supply”:

In contrast to the district heating options, here differences between initial refurbishments are marginal. Especially, for the non-refurbished initial status quo B0, differences in LCOH are minimal, ranging in cents/MWh. The further energetic

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refurbishment options are applied to the case study district, the more the LCOH levels diverge. While for B1 version LCOH still ranges of below 1€/MWh, B2 versions increase the range of more than 1.5€/MWh and reaches almost 3€/MWh LCOH for B3-versions. Overall, the level of LCOH for the decentral heating options are significantly higher than the LCODH for district heating options, ranging between 132.87 and 140.63 €/MWh. This is due to the relatively limited local potential for low- or no carbon heat generation. This, as for the district heating options, includes electric heat pumps and hydrogen fed-heat boilers. There are no differences in LCOH between C-sensitivities.

A Sensitivities	C Sensitivities	Refurbishment levels			
		B0	B1	B2	B3
A1	C1	140.61	139.12	138.22	135.77
	C2	140.61	139.12	138.22	135.77
A2	C1	140.51	138.70	136.59	132.87
	C2	140.51	138.70	136.59	132.87
A3	C1	140.63	139.13	138.24	135.78
	C2	140.63	139.13	138.24	135.78

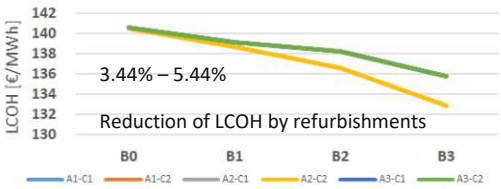

Figure 56: Levelized costs of heating for decentral heating options. *Own application of Hasani, 2019c.*

It is of interest to compare LCODH of district heating, and LCOH of decentral heating with LCOR to evaluate, whether energetic refurbishments are feasible from an economic perspective. This will be done via a comparison of total costs of heating over 50 years technical lifetime of energetic refurbishment measures in figure 57 on the next page (equation 57 in section 4.5.4).

As described in section 4.5.4, total costs of heating include eventual levelized refurbishment costs (LCOR), levelized costs of district heating (LCODH) for district heating options, including LCON and LCOH, or decentral supply (LCOH).

The results in figure 57 on the next page indicate total heating costs depending on supply set-up and demand sensitivity ranging between 225.5 and 316.5 million € over 50 years for the initial refurbishment status quo without any further refurbishments, considering district heating supply. The decentral equivalent leads to costs between 326 and 369.5 million € over 50 years.

Here the impact of initial refurbishment status on total costs can be clearly identified, as the A2 version is most costly due to its highest heat demand in B0. As there are no additional costs from refurbishment measures included, the higher LCODH of A2 leads to the overall higher total costs of A2 versions. These differences between the versions of initial refurbishment across the measure of total costs of heating over the lifetime of refurbishment measures are unique for the B0 versions. In all refurbished versions (B1, B2, B3) the total cost levels do not show these significant differences

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between A1-, A2-, and A3-versions. This is because for B0 versions, there is no refurbishment cost applicable for the calculation of total cost of heating over the lifetime of measures, which could balance the differences in heating supply costs for the refurbished version. As identified in section 5.1, higher refurbishment costs decrease demand for heating. Lower heating demand reduces LCODH (figure 55) and (figure 56). These effects are offset by the differences in refurbishment costs in B1, B2, and B3, as the different shares of initially unmodernized buildings in the case study district (A1, A2, A3) allow for different improvements of energetic performance, incurring different levels of refurbishment costs (figure 50).

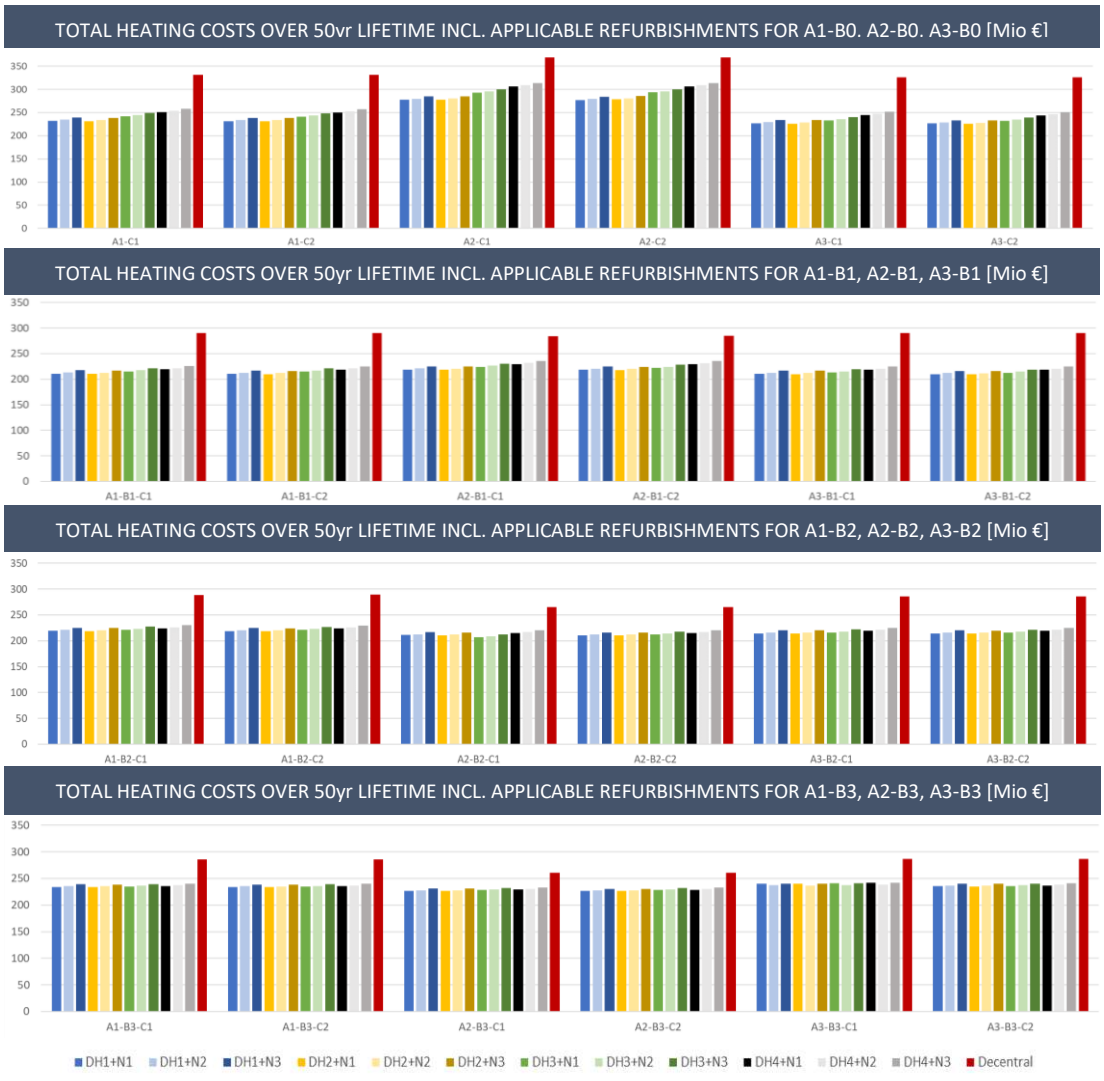

Figure 57: Total heating cost over lifetime for all refurbishment options and heat supply options. *Own approach.*

Total costs of heating over the lifetime of refurbishment measures can be reduced by application of basic refurbishment measures (B1): Assuming district heating supply of these sensitivity cases, total heating costs of between 209.5 and 236 million € occur. If decentral supply is assumed, costs between 284.5 and 290.5 million € result.

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Hence, basic refurbishment options are not only saving carbon emissions but costs for the owners of the buildings, which are therefore considered economically feasible. Average refurbishment options (B2) result in a total heating cost of between 207 and 230 million € for the complete district over 50 years considering district heating supply scenarios. For a decentral supply scenario, these costs are ranging between 265 and 290.5 million €. The values are even lower than for the basic refurbishment options, thereby also lower than for the no-refurbishment version of the initial refurbishment status (B0). Hence, they are considered economically feasible too.

For ambitious refurbishment options (B3), results are diverse: For district heating supply scenarios, costs range between 226.5 and 241.5 million € over 50 years. Here, a more detailed differentiation is required to identify economically feasible refurbishment options: For A1 and A3, whether total heating costs for no-refurbishment scenarios B0 are slightly less or more expensive than the ambitious refurbishment alternative over 50 years depends on the specific combination of the supply set-up options. For example, the combination of DH1 and N1 leads to total costs of 232 million € in the no-refurbishment scenario B0 for A1, while the ambitious refurbishment B3 implicates costs of 233 million € over 50 years. The opposite applies to DH3 N2 for A1: Here, the same no-refurbishment option B0 leads to cost of 244 million € for the no-refurbishment scenario B0 and 236 million € for the ambitious refurbishment scenario. In summary DH1 and DH2 scenarios are not considered economically feasible for A1, while for A3 this includes DH3 scenarios too. Provided higher energy costs for DH3 and DH4 scenarios, these are considered feasible for A1, as well as partly feasible for A3. However, for A2 the economics of all supply scenarios are considered feasible as they incur lower total costs of heating over the lifetime of refurbishment measures than the initial refurbishment variant. For decentral heating supply, all ambitious refurbishment measures are considered economically feasible.

In summary, most refurbishment options are considered economically feasible. Only for ambitious refurbishment options, some A1- and A3-combinations are not considered feasible.

However, if societies stay committed to reaching a net-zero emissions future energy system, feasibility should not be evaluated on economic terms only, as described in section 4.5.4 before. Carbon abatement costs emphasize a weight-parity between the decision parameters of economic and environmental feasibility (Ibrahim and Kennedy,

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2016: p. 2). The lower the costs and the higher the reductions of carbon emission, the lower the carbon abatement costs. The lower the carbon abatement cost, the more favorable a refurbishment measure is.

Results of carbon abatement costs for the case study scenarios are shown in figure 59. They mirror the results from the economic feasibility: All basic refurbishment options are considered feasible because their carbon abatement costs are negative: Owners save money and emissions simultaneously. The same applies to average refurbishment options. For ambitious refurbishment options, the only options not considered feasible are DH1 and DH2 set-ups for A1, as well as DH3 set-ups for A3. However, especially A1 options, this is marginally only. All options for A2 and decentral supply set-ups are considered feasible.

Furthermore, an interesting perspective is the comparison between A1-, A2-, and A3-versions of the initial refurbishment status (B0) and the respective refurbished versions (B1, B2, B3). In figure 59, there is a clear difference between the carbon abatement costs of A2-versions, compared with A1- and A3-versions. For these A2 versions, the carbon abatement costs are significantly more negative, and thereby more attractive, than for the other versions. Although, as shown in figure 57, there are no significant differences in the purely economic assessment of feasibility of refurbishments between A1, A2, and A3 for the options B1, B2, and B3, figure 58 suggests there is for the carbon-abatement-cost-based feasibility of options. This is due to significantly higher reductions of heat demand in A2, as shown in section 5.1 - especially by figure 50. Also, the logic derived from refurbishment templates by ARGE, 2012 (see chapter 4), why reductions are more significant for A2 was provided: Initially less modernized buildings allow for more costly refurbishment measures. This is because, on a cost-benefit level, refurbishment measures lead to greater benefits if being applied to a building with a low status quo of energetic performance. This building´s low energetic status quo is more significantly improved by the measure than an alternative building with a higher initial status of energetic performance would. Hence, as the A2-versions include more initially unmodernized buildings, their reductions of heat demand – and thereby carbon emissions – is more significant than for the A1- and A3-versions. This leads to a higher quotient in the equation for carbon-abatement-costs for A2, than for A1 and A3 – and thereby to more attractive carbon-abatement-costs. Accordingly, even if it did not influence choices for this case study, decision- making on carbon-abatement-costs is significantly impacted by the calibration of initial refurbishment status.

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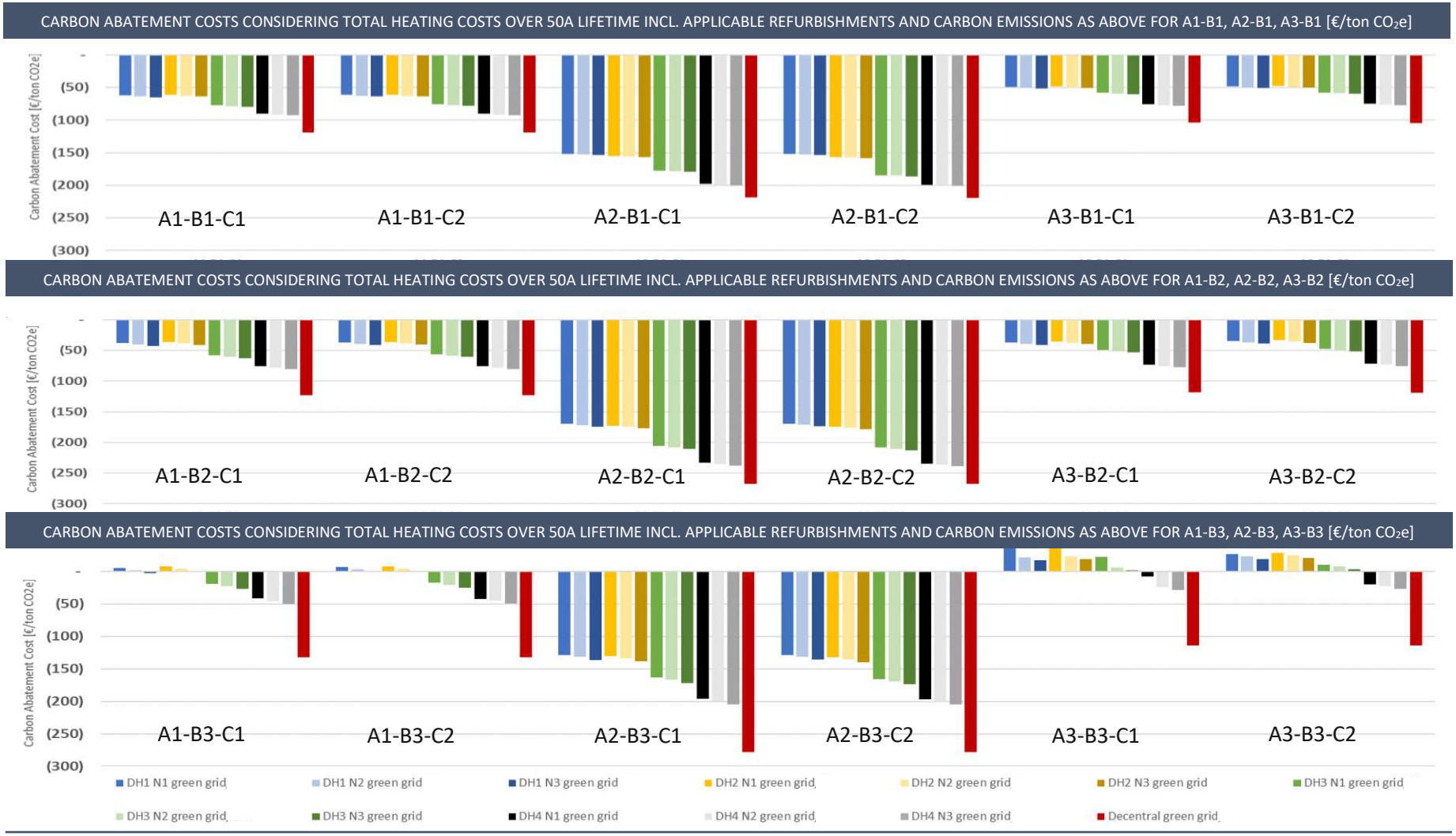

Figure 58: Carbon abatement costs for all refurbishment options considering various options for heat supply. *Own approach.*

6 CONCLUSIONS

This chapter will summarize and interpret the results from the previous chapter and thereby answer the research question. Furthermore, it will provide a recommendation of when and how to integrate heat planning and simulation tools, critically review the application of the new integrated toolchain of UBEMs and the Hotmaps toolbox, as well as provide an outlook on potential further research on the topic of integrated heat planning and simulation.

6.1 Interpretation of results

In chapter 5, results from sensitivity blocks A-D alongside the integrated toolchain of UBEM and the Hotmaps toolbox were presented. These will be summarized and interpreted to answer the research question from section 1.3:

"*What impacts do sensitivities on the demand side in UBEM and further alongside an integrated toolchain with the Hotmaps toolbox on the supply side have on indicators of heat demand, reduction of carbon emissions, total costs of heating over the lifetime of energetic refurbishments, and carbon abatement costs?*"

In summary and regarding the research question, the central results from the case study application of the integrated toolchain with sensitivities alongside are:

1. **Different approaches to calibrate the initial refurbishment status of buildings lead to different results on the demand side in UBEM**: In section 3.2.1 three approaches to assess the initial refurbishment status of buildings were introduced: Based on typical values for buildings´ ages, visual impression, or actual data from the use case area. All approaches were conducted for the case study district in section 4.1. The results showed different total heat demands for all sensitivity cases. They ranged from 46.3 to 52.6 GWh/yr – a spread of 13.61% from the lower bound of the range.

   This is an impact on heat demand.

2. **Variations in the approach to calibrate initial refurbishment status of buildings in UBEM create direct knock-on-effects in subsequent steps alongside the integrated toolchain with the Hotmaps toolbox**: Knock-on-effects from sensitivity block A need to be differentiated between direct and indirect effects: As a direct effect, different heat demands of initial status A1,

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A2, and A3 result in knock-on-effects for the design of the district- and decentral heating systems, as well as for their carbon emissions (range of 11.72% from the lower bound) and for total costs of heating over the lifetime of refurbishments (range of 39% from the lower bound) of exactly these three initial calibrations of the UBEM.

This is an impact on reductions of carbon emissions and total costs of heating over the lifetime of energetic refurbishments.

3. **Alternative approaches to calibrate initial refurbishment status of buildings in UBEM cause indirect knock-on-effects in subsequent steps alongside the integrated toolchain with the Hotmaps toolbox**: Furthermore, differences between initial refurbishment status of sensitivities A1, A2, and A3 influence the set of refurbishment options being available to buildings in block B, while maintaining cost-benefit principals, as described in section 4.2. This leads to indirect consequences alongside the integrated toolchain:
The heat demands for applied refurbishment options in block B differ between the respective initial variants A1, A2, and A3: While for the basic refurbishment options of A1, A2, and A3, the difference amounts to 0.5 GWh/yr (1.48% from the lower bound), for the average refurbishment options this difference is greater – amounts to 4.9 GWh/yr (20.85% from the lower bound). The heat demands for ambitious refurbishment of A1, A2, and A3 vary most significantly by 5 GWh/yr (32.68% from the lower bound).

This is an impact on heat demand.

These differences are reflected by the decision parameters of carbon emissions, total costs of heating and carbon abatement costs of the case study: For the basic refurbishment options (B1) between the different initial versions A1, A2, and A3, carbon emission reductions range 3.04% from the lower bound, total costs over a lifetime range 12.67% from the lower bound, while carbon abatement costs range 80.36% from their lower bound. For average options (B2) between the different initial versions A1, A2, and A3 reductions in carbon emissions range 17.08% from its lower bound, total costs

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over a lifetime ranges 11.02%, while carbon abatement costs range 87.15% from the lower bound. For ambitious options (B3) between A1, A2, and A3, carbon emission reductions range 24.64% from their lower bound, the total cost of heating over the lifetime of refurbishments ranges 6.72%, while carbon abatement costs range 119.87% from their lower bound. Hence, especially for the central decision-making variable of carbon abatement costs, the knock-on-effects from the assessment of the initial refurbishment status of the building stock (Sensitivity block A) have a significant impact.

This is an impact on reductions of carbon emissions, total costs of heating over the lifetime of energetic refurbishments, and carbon abatement costs.

4. **Divergence in the approach to assigning refurbishment options to initial refurbishment status leads to significant differences in heat demand in UBEM**: Based on the initial refurbishment status being assigned to buildings in sensitivity block A, different refurbishment options (Basic, average, and ambitious) were applied to the buildings in block B. On average, basic refurbishment options (B1) reduced the heat demand of the case study district by 30.58%, average refurbishment options (B2) reduced the heat demand by 44.8% on average, while the ambitious refurbishment measures (B3) reduced the heat demand by 61.44% on average. For ranges of diversity between the reductions of the different initial calibrations of models see conclusion 3 above.

This is an impact on heat demand.

5. **Reductions of heat demand between different levels of energetic refurbishment in UBEM show no linear development. They do not develop in parallel with other model calibrations of initial refurbishment status**: The degree of energetic improvement by refurbishment differs between the individual building types: Less modernized buildings allow for more measures to be realized economically, while better, though not ideal status prevents more effective measures from being implemented. Therefore, the reductions of heat demand between different levels of refurbishment are not linear. Different calibrations of the base model include different shares of non-modernized, slightly modernized, and modernized buildings. Therefore, on a district level, improvements of energetic performance develop not in

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parallel for all initial status models A1, A2, and A3. For example, in the case study of this thesis, variant A2 of the initial refurbishment status included many non-modernized buildings. As these allowed for more effective measures while keeping within the required limits of efficiency, the improvement of energetic status was more significant than for the variants of A1 and A3, which were indicated to have more modernized buildings initially.

This is an impact on heat demand.

6. **Variations in the approach to assigning refurbishment options to initial refurbishment status lead to knock-on-effects for the design of supply options and decision parameters**: The different levels of heat demand resulting from the assignment of different refurbishment options in sensitivity block B have an impact on the design of heat supply systems. Depending on demand and its density, more - or less - hectares are considered feasible for district heating, or in demand for decentral solutions. Also, capacities vary depending on the peak loads estimated for the hectares. Furthermore, decision parameters of reduction of carbon emissions, total cost of heating over the lifetime of the refurbishment, and carbon abatement costs are affected: The case study showed: While for basic refurbishments (B1) and average refurbishment options (B2), all renewable supply options indicated feasibility in terms of carbon emission reductions and total costs of heating over lifetime, for the ambitious refurbishment options (B3) combinations of low-cost of energy supply scenarios for A1 and A3 - marginally - did not indicate feasibility of refurbishment. This was mirrored by the carbon abatement costs, where the same refurbishment options were considered feasible or not.

This is an impact on reductions of carbon emissions, total costs of heating over the lifetime of energetic refurbishments, and carbon abatement costs.

7. **Alternatives in the approach to allocating heat demand from an individual building level to hectares do not affect total heat demand, but heat density measures**: As shown in figure 50, different methods of allocation of heat demand from the building- to hectare-level do not lead to differences in total heat demand on a district level. However, on an individual hectare

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level, differences occur (s. figure 51). Accordingly, values for heat densities are influenced by the alternative approaches on both, the individual hectare, as well as on the district level. For the approach to allocate heat demand to hectares according to their actual gross floor area on the hectare, there is a tendency of allocating more demand to the periphery of the district, as hectares on the edge of the area receive their small but actual shares of heat demand.

This is an impact on heat demand.

8. **The differences in heat density caused by the allocation of heat demand from building- to hectare level have knock-on-effects for the design of supply options**: There are minimal differences between values of reductions of carbon emissions, total costs of heating over the lifetime of energetic refurbishments, and carbon abatement costs, between the models created by the two options for allocating heat demand from a building- to a hectare-level: Tendentially more hectares, especially on the edges of demand centres and the overall use case area receive higher heat demand if the C2 option of allocation according to actual gross floor area is applied. If C1 (allocation according to the individual building´s centre) is applied, heat demand centralizes. Hence, the feasibility of district heating applications is affected as the central network and supply infrastructure is dependent on the existence of certain heat demand and heat densities. However, it is important to note that these are minimal variations.

This is an impact on the reductions of carbon emissions, total costs of heating over the lifetime of energetic refurbishments, and carbon abatement costs.

9. **The spatial constitution of bottom-up heat demand estimations from UBEM differs from the top-down demand estimations provided by the Hotmaps toolbox**: As UBEMs are based on bottom-up heat demand estimations for individual buildings, its indication of heat demand differs from the top-down approach adopted by the Hotmaps toolbox: There was a more differentiated distribution map of heat demand in the case study district from UBEM, while Hotmaps´ estimation of heat demand indicated a less diverse

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distribution of heat demand across the district. Furthermore, for the case study district heat demand estimations from the Hotmaps toolbox were slightly higher than the UBEM results for all sensitivities of initial refurbishment status. The results from UBEM seem to almost match with reality, considering the location and use of the local building stock on the district map, as well as a study on the local energy consumption in the district. However, as will be emphasized in the section of the critical discussion below, this can only be considered an indication, as there is no actual dataset of metered data available for verification.

This is an impact on heat demand.

10. **Varying calibrations of supply-side options have an impact on carbon emissions, supply costs, and carbon abatement costs**: Different scenarios for the future development of the energy system, as well as respective calibration values for the calculation modules provided by the Hotmaps toolbox influence the results for reductions in carbon emissions, total costs of heating over the lifetime of energetic refurbishments, and carbon abatement costs, which are found to be optimal by the toolbox. For example, in a scenario with higher prices for hydrogen, less hydrogen will be considered for the cost-benefit-optimal supply option. In another scenario, higher investment costs for large-scale heat pumps limit their consideration for the supply side, potentially favoring the application of other technologies instead.

This is an impact on the reductions of carbon emissions, total costs of heating over the lifetime of energetic refurbishments, as well as carbon abatement costs.

In conclusion, the research question can be answered by:

Sensitivities on the demand side in UBEM and further alongside an integrated toolchain with the Hotmaps toolbox on the supply side do have impacts on the indicators of heat demand, reductions of carbon emissions, total costs of heating over the lifetime of energetic refurbishments, and carbon abatement costs. Furthermore, knock-on effects are created. The earlier alongside the integrated toolchain these knock-on-effects are created, the more significant their impact on the indicators of

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heat demand, reductions of carbon emissions, total costs of heating over the lifetime of energetic refurbishments, and carbon abatement costs.

6.2 Critical discussion

While results from the integrated toolchain approach seem to be realistic in terms of dimension of total heat demand, its distribution on hectare-level, and in terms of heat density, they should be regarded as estimated representations only. The real demand for buildings is not known. Without measurements results cannot be verified. Further limitations of the integrated toolchain approach to heat planning and simulation will be discussed during the following paragraphs:

As described in chapter 3.1, the likelihood of non-precise interpretations of heat demand on the building level in UBEM is high. This is because the simplification of assigning generalized templates for building types and age classes, including certain energetic performance status and usage patterns to buildings, neglects the differences of individual user behavior, their individual temperature preferences, and the individuality of refurbishment measures being applied to buildings. Nevertheless, the estimation on building-level might come close to reality (see section 5.1) and for some users be the best alternative to start heat planning for a less carbon-intensive heat supply of the future. Especially, if the high granularity of results is required but no actual data has been made available by local energy providers. However, users should never consider the simulation results as an actual representation of demand but rather try to verify and enrich their database with actual metered or surveyed data.

Considering users would not always have access to metered or surveyed data for their use case areas, in chapter 4.1, an evaluation of the building stock´s energetic performance was conducted based on optical impression. As shown, this approach conveys a high risk for misinterpretation: Even though it might improve the accuracy of results in the best case, the relatively limited visual impression of the building´s refurbishment status (thickness of walls, ceilings, and insulation of roofs, and mostly even windows cannot be evaluated precisely) is likely to mislead the assessment, as has happened in the case study. Here, the initial status assessed based on visual impression appeared to show the highest difference from the official report on district-level heat demand and led to knock-on-effects. In addition, if users conduct the interpretation of initial refurbishment status based on visual impression, bias might occur, if users know about typical values of energetic performance for the building´s age class in the use case area in advance. In this case, users might – even unintentionally – assign the initial refurbishment status of buildings to fit the official

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distribution of energetic performance levels. They, therefore, create an alternative version of the approach A3, which is based on actual building information for their use case area. Thereby they undermine their opportunity to create an additional, unique perspective on the heat demand of their use case area. It would be based on visual impressions, instead of data from the district. The bias was avoided during the application of the case study for this thesis.

For the data-based approaches A1 (according to typical values for age classes) and A3 (according to actual data from the district) to calibrate the initial refurbishment status of the use case areas there might be impacts on data quality from the referenced datasets. These might be based on estimations and extrapolation of data too. Hence, even if – as it was true for the case study – these data-based approaches seem to perform well, users should be careful with assuming these databases for absolute proof. However, if the referenced data is officially used by authorities and created by experts on the built environment the likelihood of internal bias of input data should be minor.

Furthermore, the manual process to allocate heat demand from building- to hectare-level according to their actual gross floor area within the respective hectare (C2) might be complex and error-prone for users. Especially, if considering the relatively low differences in results compared with C1 options (allocation by centre location of buildings), the additional effort and higher likelihood of mistakes might not be compensated by a minimal improvement of the spatial accuracy of heat demand. However, if users want or need to gain this more granular perspective on heat demand, they should be very careful while applying the manual allocation process, as described in chapter 4. Accordingly, an approach to automate – and thereby simplify – the process as a stand-alone calculation module of the Hotmaps toolbox was described in section 4.3.3. This will be part of the outlook section below.

The above limitations to verification of results compared to actuals prohibit a general statement on whether top-down or bottom-up approaches are more precise. However, the new integrated approach provides the opportunity to assess refurbishment measures on a building level. Thereby, it allows addressing specific building classes with optimal cost-benefit conditions first, which can be useful to formulate decarbonization strategies for municipal districts.

However, users should be very clear on their expectation to spend more efforts and/or resources on the detailed assessment of heat demand via a bottom-up approach via

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UBEM in comparison to the top-down approach by the Hotmaps toolbox. Depending on the quality of data being available, the assessment approach chosen, and their level of expertise on the local building stock, users should expect between 1 and 7 full-workday equivalents of time to produce results for both, the demand, and the supply side of an integrated toolchain approach. The most important variables to influence the total amount of time required are two decisions: Whether to conduct an assessment based on visual impression of the building stock, which comes with demanding efforts of documentation (see appendix), as well as the number of sensitivities to be considered alongside an integrated toolchain. In the scope of this case study, many sensitivities were included to create a comprehension of the consequences for future users´ awareness. This should not be required for every application. However, the amount of different sensitivities on the supply side has been deliberately limited within the scope of this thesis. If users want to evaluate the impact of more - or more complex - scenarios of the supply side via the Hotmaps toolbox, the required time to derive results increases again.

According to the previous paragraphs, limitations of the new integrated toolchain approach to heat planning and simulation should be acknowledged before every application. However, for some user types, it might be the best approach to respond to their planning requirements. This will be described by a recommendation within the following section.

6.3 Recommendation for integration between heat planning and simulation tools

Despite the limitations of the new integrated toolchain approach, as described in section 6.2, via the case study application, its feasibility was proven. Demand-side results from UBEM were successfully integrated into the Hotmaps toolbox to simulate supply-side indicators.

As described above, its results were plausible, but need to be considered as estimates, as no actual, metered data for final verification was available for the case study district. However, given the results align with other publications on the heat demand from the district, which claim to be based on metered data, there is a likelihood that results of the new integrated toolchain of the Hotmaps toolbox and UBEM are reliable, even if this cannot be verified directly.

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Therefore, users wanting to conduct heat planning and simulation exercises with UBEM and the Hotmaps toolbox, which were identified as preferred tools in section 3.1, do have three options available:

1. Using an UBEM for bottom-up demand-side calibration, as well as a set of supply-side indications
2. Using the top-down approach to heat demand by the Hotmaps toolbox and leverage its extensive calculation modules for indications on the supply side of heating.
3. Combining both tools for an integrated toolchain, as described, and assessed by this thesis

For their decision-making on which option to choose the following decision matrix in figure 59 shall be recommended to future users of UBEM and Hotmaps:

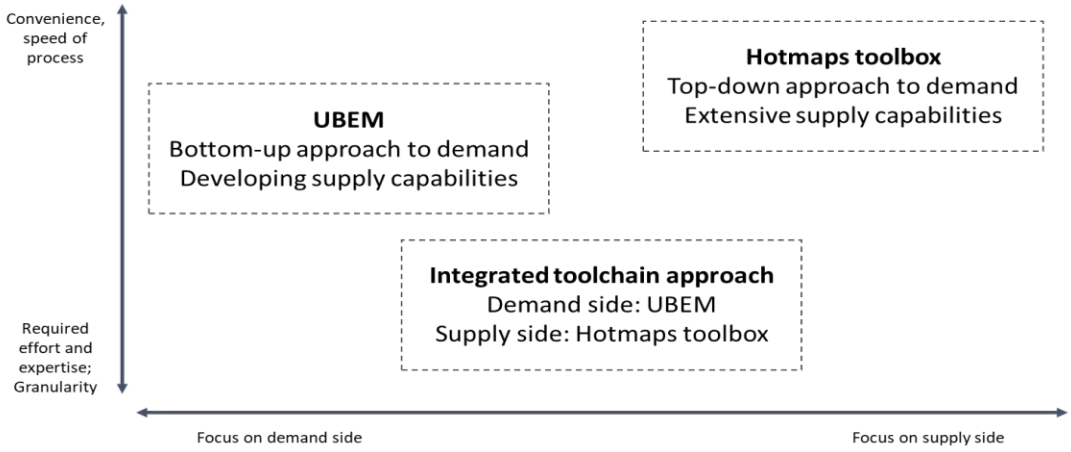

Figure 59: Decision matrix for options to apply heat planning and simulations tools. *Own approach.*

Decision parameters should be: Requirement of granularity, availability of data, time, and expertise, as well as of the user´s focus of interest. Users should decide for UBEM applications if they are focusing on the demand side and have resources available to conduct its more demanding model calibration. If users focus on the supply side or require a convenient and fast demand perspective to begin their heat planning and simulation process, they should apply the Hotmaps toolbox in isolation, instead of an integrated toolchain. If users require granular models on both, the demand and supply sides they should apply the new integrated toolchain, always minding consequences and limitations of model calibrations as described before.

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6.4 Outlook

Building upon the impacts of sensitivities alongside an integrated toolchain of UBEM with the Hotmaps toolbox on heat demands, reductions of carbon emissions, total costs of heating over the lifetime of energetic refurbishments, and carbon abatement costs, as described in this thesis, the following potentials for ongoing research have been identified:

In section 4.3.3, the potential for an automated stand-alone calculation module of the Hotmaps toolbox was described. The methodology to allocate heat demand according to the actual position of gross floor areas on a hectare scale was outlined. It should be automated via python code and integrated into the Hotmaps environment. This would allow for simpler and less error-prone applications by future users of integrated toolchain approaches to UBEM and the Hotmaps toolbox. Thereby, future users would be more likely to calculate supply-side scenarios based on the actual position of heat demand on the EPSG-hectare-raster, leading to slightly more precise results.

Cities are increasingly eager and required to assess the heat demand of their built environment to design their decarbonization roadmaps and policies accordingly. Both tools assessed for this thesis have been applied to cities. An integrated approach to UBEM and the Hotmaps toolbox might be an interesting option for these cities to gain a comprehensive understanding of the spatial distribution of their heat demand on building level and respective supply options. Also, future applied research should focus on verifying the results of this thesis by applying the methodology to further districts and cities. Ideally, with lots of additional cities to accelerate the decarbonization of the building sector by application of heat planning and simulation.

The quality of results is significantly dependent on the quality of input data. While on the national and federal state level there are building typologies available in Europe and the United States, for more specific areas, such as cities and districts typologies are mostly not available. Defining and explaining replicable standard approaches to design local building typologies by locals is another field for subsequent research, which the quality of results would benefit from.

To allow for the required mass-application of heat planning and simulation tool, sound business models for applying the models as part of wider scope collaboration between planers, cities, owners of buildings, energy companies, and craftsmen will be required. Research in the field of energy economics and business innovation could be beneficial to accelerate the application.

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To evaluate the further potential for synergies from integrated toolchain approaches, or potential collaboration, the Hotmaps development team, consisting of the TUW, e-think, Fraunhofer ISI, HES SO, University of Aalborg, EURAC Research, CREM, and Planergie should become connected to the UMI-development team around the Sustainable Design Lab at MIT and various universities worldwide.

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EXECUTIVE SUMMARY

This thesis focused on the assessment of an integrated toolchain consisting of the Hotmaps toolbox and Urban Building Energy Models for heat planning and simulation. Therefore, a case study was conducted on a district of the city of Kiel in Germany.

The research question was:

"*What impacts do sensitivities on the demand side in UBEM and further alongside an integrated toolchain with the Hotmaps toolbox on the supply side have on indicators of heat demand, reduction of carbon emissions, total costs of heating over the lifetime of energetic refurbishments, and carbon abatement costs?*"

Accordingly, alongside the toolchain sensitivities were applied to create a better understanding of the consequences of potential model calibrations by users. This included:

1. Variations in the calibration of the initial refurbishment status of buildings in the case study district in UBEM.
2. Variations in the assignment of refurbishment options to the different refurbishment status quo of the buildings in the case study district in UBEM.
3. Variations to the approach of allocating heat demand from the individual building-level in UBEM to the hectare-level in the Hotmaps toolbox.
4. Variations in the calibration of supply-side parameters of calculation modules in the Hotmaps toolbox.

Furthermore, a comparison block identified differences between the bottom-up heat demand assessment via UBEM compared to the top-down heat demand assessment provided by the Hotmaps toolbox.

Results of the assessment on both, the demand and the supply side were presented. Based on these, ten central impacts of variations to model calibration on heat demand, reductions of carbon emissions, total costs of heating over the lifetime of energetic refurbishment options, and carbon abatement costs were identified and interpreted: The calibration of initial refurbishment status of the models was found to have significant influence on further indicators of demand and supply, while alternatives in the approach to allocate heat demand from a building- to a hectare-level had marginal influence on assessed indicators only. Additionally, the results of

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the case study support the argument of building refurbishments to be economically and environmentally feasible.

Finally, limitations of the integrated toolchain approach were highlighted via a critical discussion to conclude with a recommendation for future users on when and how to apply an integrated toolchain of UBEM and the Hotmaps toolbox to their individual use case, as well as suggesting ideas for ongoing research on the topic of integrated heat planning and simulation tools.

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
3D	three-dimensional
A1	Sensitivity A1
A2	Sensitivity A2
A3	Sensitivity A3
ADD	Aldus Developers Desk
AGC	Association of German Cities
API	Application Programming Interface
ARGE	Arbeitsgemeinschaft Zeitgemäßes Bauen e.V.
Avg	Average
B1	Sensitivity B1
B2	Sensitivity B2
B3	Sensitivity B3
BEE	Bundesverband Erneuerbare Energie e.V.
C1	Sensitivity C1
C2	Sensitivity C2
CAD	Computer-aided design and drafting
CAU	Christian-Albrechts-Universität
CHP	Combined heat and power
C_{HS}	Cost of heat supply
CM	Calculation Module
C_N	Cost of network infrastructure
C_{NL}	Cost of eventual district heating networks over lifetime
CO_2	Carbon dioxide
Complan	Complan Kommunalberatung GmbH
COP	Coefficient of performance
COP21	21st Conference of the Parties
C_R	Cost of the refurbishments
CREM	Centre for energy and municipal research
C_{SL}	Cost of heat supply over lifetime
CSV	Comma-Separated-Value
C_{THL}	Total heating costs over lifetime
DENA	Deutsche Energie Agentur
DH1	District heating supply 1
DH2	District heating supply 2
DH3	District heating supply 3
DH4	District heating supply 4
DSM	Deutsches Schifffahrtsmuseum
DWD	Deutscher Wetterdienst
E	Energy supplied by the heating system set-up
EC	Energy Cities
EEA	European Environmental Agency
EEG	Energy Economics Group
ENEV	Energie-Einspar-Verordnung
EPSG	European Petroleum Survey Group
E_S	Energy savings achieved by the refurbishments
ESRI	Environmental Systems Research Institute
Etc.	Et cetera
EU	European Union

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EU ETS	European Union Emission Trading System
EUC	European Commission
EUIB	European Investment Bank
EUJ	Official Journal of the European Union
Eurostat	Statistical Office of the European Communities
FCH JU	Fuel Cells and Hydrogen Joint Technology Initiative
FFE	Forschungsgesellschaft für Energiewirtschaft mbH
GCC	German Constitutional Court
GFA	Gross floor area
GFC	German Federal Council
GFEA	German Federal Environmental Agency
GFLG	German Federal Law Gazette
GFME	German Federal Ministry for the Environment
GFMEC	German Federal Ministry for Economic Affairs and Climate Action
GFMI	German Federal Ministry for Interior
GFMJ	German Federal Ministry for Justice and Consumer Protection
GFOS	German Federal Office of Statistics
GFP	German Federal Parliament
GFRG	Government of the Federal Republic of Germany
GIS	Geographic information system
HCI	HIC Hamburg Institut Consulting GmbH
HES SO	Haute Ecole Spécialisée de Suisse occidentale
HPG	Heat protection glass
IBSH	Investitionsbank Schleswig-Holstein
ID	Unique Identifier
IDE	Individual development environment
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISI	Institut für System- und Innovationsforschung
IWU	Institut für Wohnen und Umwelt e.V.
JRC	Joint Research Centre
L	Lifetime of the refurbishments
LCODH	Levelized cost of district heating
LCOH	Levelized cost of heating
LCON	Levelized cost of network infrastructure
LCOR	Levelized cost of refurbishment
M18	Multifamily houses built before 1918
M48	Multifamily houses built before 1948
M57	Multifamily houses built before 1957
M68	Multifamily houses built before 1968
M78	Multifamily houses built before 1978
M87	Multifamily houses built before 1987
M87_SVP	Special type multifamily houses built before 1987 at Vineta Square
MAX	Maximal
MIN	Minimum
MIT	Massachusetts Institute of Technology
N1	Network sensitivity 1
N2	Network sensitivity 2
N3	Network sensitivity 3
NB	New buildings
NDC	Nationally Determined Contribution

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NOAA	National Oceanic and Atmospheric Administration
NRB	Non-residential buildings
NT_RB	Non-typologized residential buildings
NUTS	Nomenclature of units for territorial statistics
OPEX	Operational expenses
OSM	OpenStreetMap
OSMF	OpenStreetMap Foundation
PHI	Passivhaus Institut
PKGG	Projektgesellschaft Kiel-Gaarden GmbH
RES	Renewable Energy Systems
SDL	Sustainable Design Lab
SHG	Schleswig-Holstein Federal State Government
SHME	Schleswig-Holstein Ministry for the Energy Transition, Agriculture, Environmental Affairs, Nature, and Digitalization
SHMI	Schleswig-Holstein Federal State Ministry for the Interior
SHP	Schleswig-Holstein Federal State Parliament
SHSC	Schleswig-Holstein State Chancellery
STC	Single storey commercial buildings
TI	Thermal insulation
TUW	Technical University of Vienna
UBEM	Urban Building Energy Model
UMI	Urban Modelling Interface
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USDOE	United States Department of Energy
VDA	Verband der Automobilindustrie e.V.
YH	Youth hostels
ZEBAU	Zentrum für Energie, Bauen, Architektur und Umwelt GmbH

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LIST OF SYMBOLS

Symbol	Meaning
%	Percent = 1/100
€	Euro
Δ	Delta = Difference
∑	Sum
∀	Allquantor = Mathematical expression for “Applies to all x” = Universal quantifier
∈	Mathematical expression for “Element of “

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LIST OF UNITS

Unit	Meaning
%	Percent = 1/100
€	Euro
cm	Centimeter = 0.1 meter
CO_2e	Carbon dioxide emission equivalent
GWh	Gigawatt hour = 1,000,000,000 kWh
h	Hour
ha	Hectare = 10,000 m^2
K	Kelvin
km	Kilometer = 1,000 meter
kWh	Kilowatt hour
m	Meter
M	Mega = Million = 1,000,000
m^2	Square meter
MT	Megatons = 1,000,000 Tons
MWh	Megawatt hour = 1,000,000 kWh
t	Ton
TJ	Terajoule = 1,000,000,000,000 Joule = 277,778 kWh
W	Watt
yr	Year

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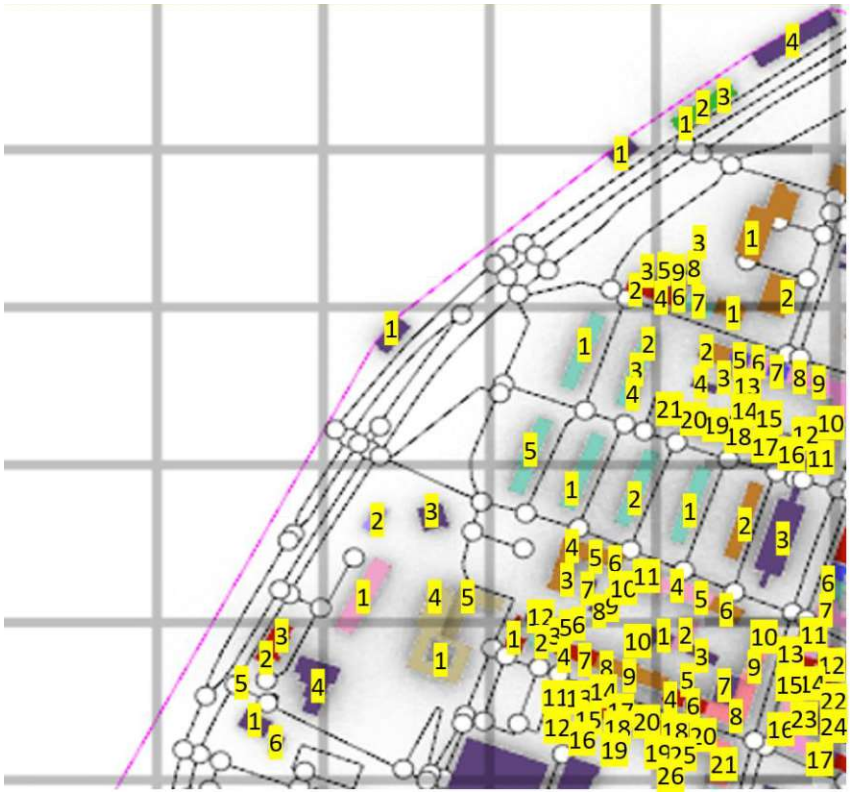
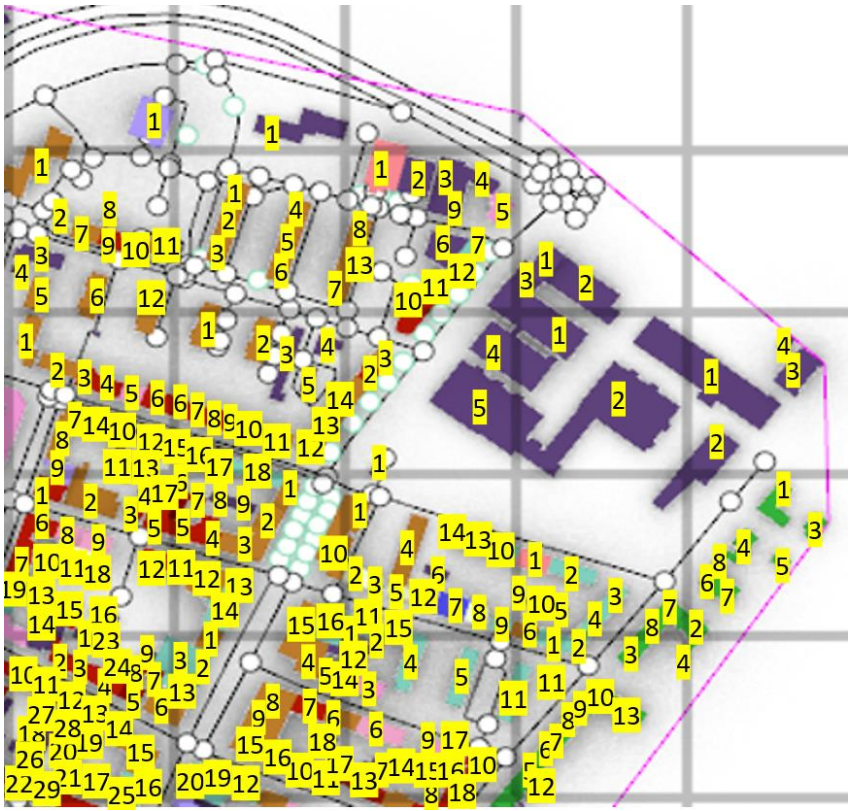
APPENDIX 1: Detailed navigation and control maps for the case study area

North-western corner of the case study district



Own approach based on a visualization of Kiel, 2020f in Mc Neel, 2021a.

North-eastern corner of the case study district



Own approach based on a visualization of Kiel, 2020f in Mc Neel, 2021a.

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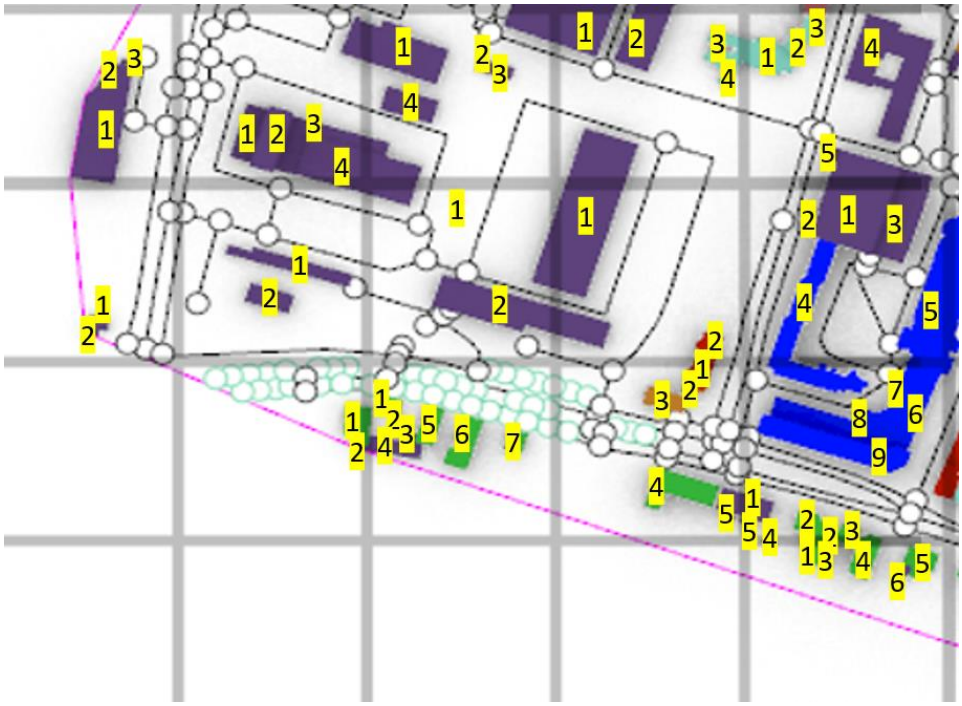
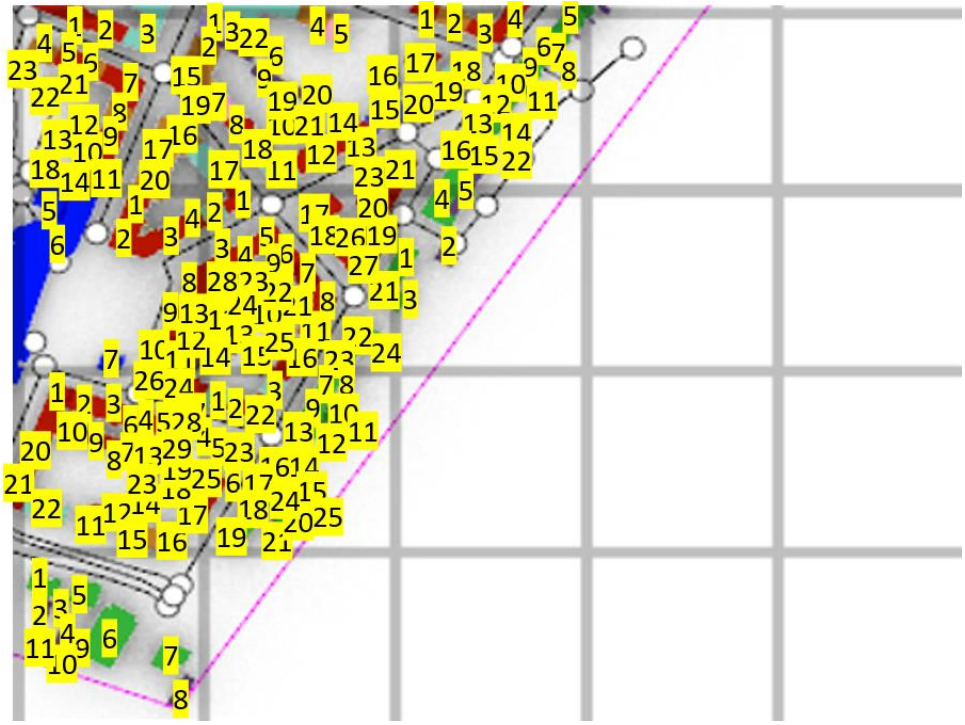
South-western corner of the case study district



Own approach based on a visualization of Kiel, 2020f in Mc Neel, 2021a.

South-eastern corner of the case study district



Own approach based on a visualization of Kiel, 2020f in Mc Neel, 2021a.

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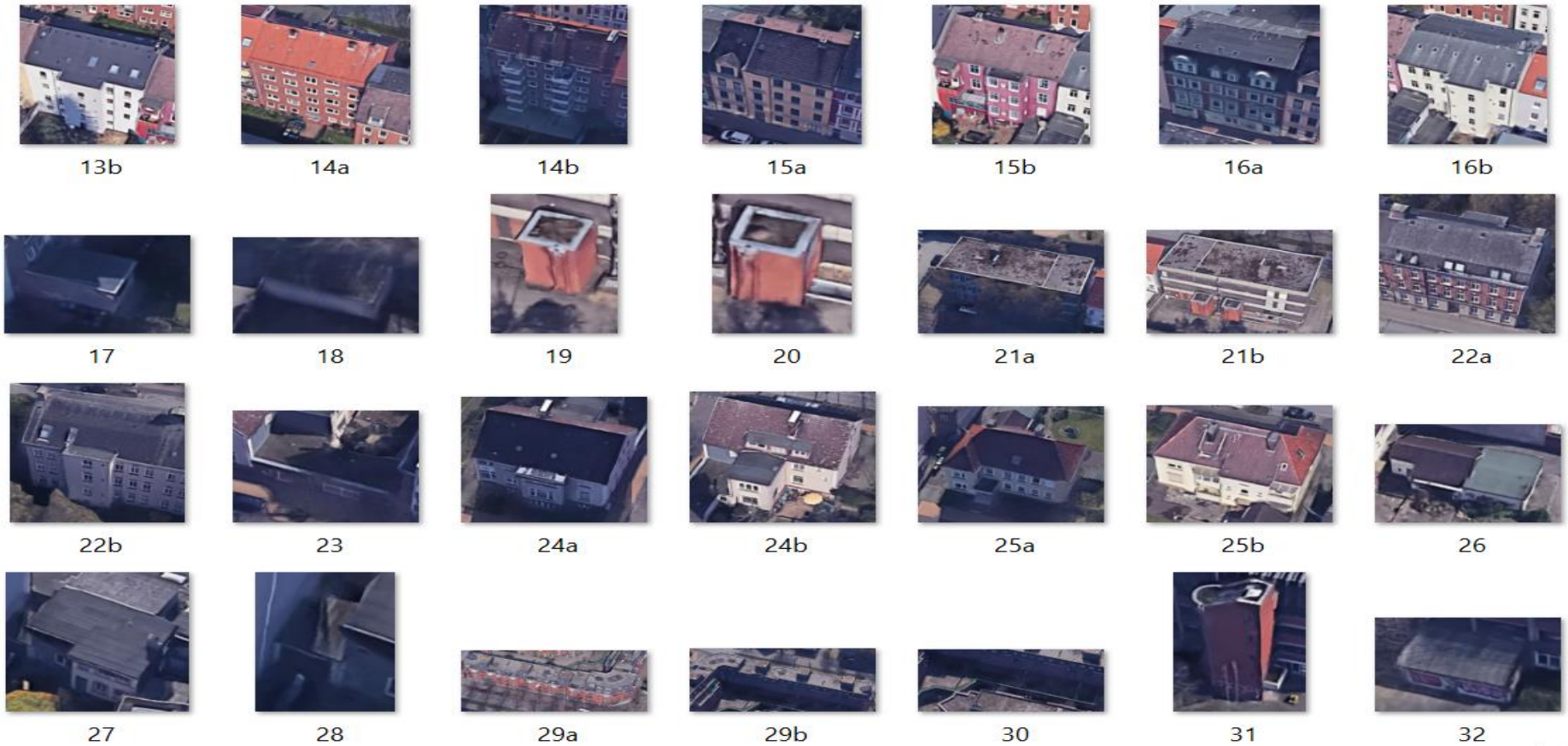
APPENDIX 2: Visual impression of the building stock in the case study area

The following screenshots are based on Google, 2021. As described in chapter 4, the screenshots are numbered according to their shp_ID, which will be connected to the Hotmaps_ID, the hectare, and further information in the Masterfile of buildings in the subsequent appendix 3.



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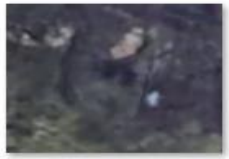
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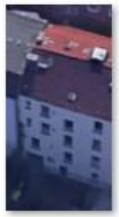
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APPENDIX 3: Masterfile of the building stock in the case study area

The following table provides the overview of building types, gross floor areas, and assumed initial refurbishment status. Important note: These assumptions of refurbishment status were not included in the geo-dataset provided by the city of Kiel, but solely based on statistical data, and interpretation of above visual impressions of the building stock. It is therefore no exact, metered, or real representation of data from the building stock. It should not be mis-interpretated as such.

The table includes abbreviations: N_HR = not heating relevant; n_m = initial refurbishment status “not modernized”; m_m = initial refurbishment status “slightly modernized”; g_m = initial refurbishment status “modernized”; Hm_ID = Hotmaps ID; GFA = Gross floor area.

shp	ID	Hm_ID	Building Type	GFA	3035: X	3025: Y	A1	A2	Description of visual impression for A2	A3
237	1	1_1	NRB	2728.40	4330056.13	3467331.21	n_m	n_m	commercial use	n_m
238	2	1_2	N_HR	20.48	4330063.22	3467365.06	n_m	n_m	commercial use	n_m
239	3	1_3	N_HR	0.00	4330071.99	3467373.18	n_m	n_m	commercial use	n_m
236	4	2_1	NRB	79.97	4330062.52	3467262.34	n_m	n_m	commercial use	n_m
235	5	2_2	N_HR	27.07	4330051.68	3467221.88	n_m	n_m	commercial use	n_m
241	6	4_1	NRB	221.57	4330156.9	3467438.98	m_m	n_m	commercial use	m_m
253	7	4_2	Before 1918	815.74	4330165.36	3467484.56	n_m	n_m	old roof; no insulation visible	n_m
254	8	4_3	Before 1918	1160.38	4330173.37	3467498.28	n_m	n_m	old roof; no insulation visible	n_m
264	9	4_4	NRB	2955.71	4330195.37	3467469.59	m_m	m_m	Glass building extensions, new ventilation	m_m
242	10	4_5	N_HR	0.00	4330150.44	3467465.15	n_m	n_m	commercial use	n_m
247	11	4_6	NRB	76.30	4330165	3467433.31	m_m	n_m	commercial use	m_m
614	12	5_1	NRB	356.93	4330132.66	3467333.01	m_m	n_m	commercial use	m_m
612	13	5_2	NRB	5792.95	4330141.34	3467331.4	m_m	n_m	commercial use	m_m
615	14	5_3	NRB	705.73	4330157.79	3467338.23	m_m	n_m	commercial use	m_m
613	15	5_4	NRB	2944.67	4330182.28	3467315.93	m_m	n_m	commercial use	m_m
240	16	6_1	NRB	498.47	4330152.54	3467259.05	m_m	n_m	commercial use	m_m
260	17	6_2	NRB	542.15	4330144.43	3467239.64	n_m	n_m	old roof; no insulation visible	n_m

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535	18	7_1	NRB	277.88	4330189.73	3467171.13	m_m	n_m	commercial use	m_m
530	19	7_2	N_HR	20.23	4330191.74	3467155.4	n_m	n_m	commercial use	n_m
259	20	8_1	N_HR	477.55	4330237.26	3467679.95	n_m	n_m	commercial use	n_m
268	21	9_1	Before 1978	1196.84	4330222.5	3467522.05	n_m	n_m	commercial use	n_m
255	22	9_2	NT_RB	150.80	4330230.38	3467570.82	m_m	n_m	commercial use	m_m
258	23	9_3	NRB	496.67	4330265.18	3467572.28	m_m	n_m	public building	m_m
256	24	9_4	YH	2278.89	4330264.78	3467510.99	m_m	m_m	modernized roof	m_m
400	25	9_5	YH	1023.69	4330281.42	3467511.55	m_m	m_m	modernized roof	m_m
257	26	10_1	YH	2941.02	4330267.51	3467481.63	g_m	m_m	modernized roof	g_m
246	27	11_1	NRB	2395.42	4330209.22	3467380.76	m_m	n_m	commercial use	m_m
262	28	11_2	N_HR	77.05	4330258.49	3467366.63	n_m	n_m	commercial use	n_m
243	29	11_3	N_HR	62.32	4330268.56	3467363.69	n_m	n_m	commercial use	n_m
263	30	11_4	NRB	400.05	4330219.7	3467348.45	m_m	n_m	commercial use	m_m
261	31	12_1	NRB	13.11	4330243.8	3467292.37	m_m	n_m	commercial use	m_m
396	32	12_2	NRB	3184.28	4330271.34	3467229.33	m_m	n_m	commercial use	m_m
245	33	13_1	NRB	166.01	4330208.29	3467177.43	m_m	n_m	old roof; no insulation visible	m_m
312	34	13_2	N_HR	0.00	4330210.64	3467164.9	n_m	n_m	garage	n_m
534	35	13_3	N_HR	78.29	4330215.95	3467160.15	n_m	n_m	commercial use	n_m
532	36	13_4	N_HR	254.67	4330208.98	3467152.94	n_m	n_m	commercial use	n_m
533	37	13_5	NRB	435.53	4330227.69	3467166.32	m_m	m_m	insulation visible	m_m
531	38	13_6	NRB	971.75	4330245.81	3467157.13	m_m	n_m	commercial use	m_m
397	39	13_7	NRB	244.18	4330271.49	3467152.54	m_m	n_m	commercial use	m_m
592	40	15_1	N_HR	176.48	4330392.04	3467810.63	n_m	n_m	commercial use	n_m
578	41	15_2	Before 1918	771.62	4330388.44	3467718.17	n_m	n_m	old roof; no insulation visible	n_m
579	42	15_3	N_HR	21.73	4330393.96	3467724.83	n_m	n_m	garden shed	n_m
252	43	16_1	Before 1957	1924.48	4330355.99	3467676.29	n_m	m_m	modernized roof	n_m
556	44	16_2	Before 1957	484.69	4330393.52	3467680.72	n_m	m_m	modernized roof	n_m

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554	45	16_3	Before 1957	477.97	4330387.62	3467664.69	n_m	m_m	modernized roof	m_m
553	46	16_4	Before 1957	651.02	4330381.65	3467649.99	m_m	m_m	modernized roof	m_m
154	47	16_5	Before 1957	1942.18	4330321.96	3467611.22	m_m	n_m	old roof; no insulation visible	m_m
156	48	17_1	Before 1957	1938.00	4330353.59	3467599.27	m_m	n_m	old roof; no insulation visible	m_m
166	49	17_2	Before 1957	1911.11	4330387.25	3467590.34	m_m	n_m	old roof; no insulation visible	m_m
153	50	17_3	Before 1968	1184.32	4330340.34	3467533.08	n_m	n_m	old roof; no insulation visible	n_m
155	51	17_4	Before 1968	1239.68	4330346.47	3467551.32	n_m	n_m	old roof; no insulation visible	n_m
160	52	17_5	Before 1968	910.93	4330361.09	3467546.18	n_m	n_m	old roof; no insulation visible	n_m
165	53	17_6	Before 1968	1067.26	4330373.14	3467541.85	n_m	n_m	old roof; no insulation visible	n_m
293	54	17_7	N_HR	0.00	4330358.69	3467523.37	n_m	n_m	garage	n_m
294	55	17_8	N_HR	0.00	4330361.74	3467511.07	n_m	n_m	garage	n_m
295	56	17_9	N_HR	0.00	4330370.4	3467516.6	n_m	n_m	garage	n_m
157	57	17_10	N_HR	27.32	4330375.45	3467525.84	n_m	n_m	storage shed	n_m
158	58	17_11	Before 1978	1254.69	4330394.53	3467527.38	n_m	n_m	old roof; no insulation visible	n_m
265	59	17_12	N_HR	46.73	4330321.83	3467504.84	n_m	n_m	storage shed	n_m
500	60	18_1	Before 1918	647.87	4330312.66	3467489.67	n_m	n_m	old roof; no insulation visible	n_m
250	61	18_2	Before 1957	908.93	4330329.72	3467489.18	m_m	n_m	old roof; no insulation visible	m_m
266	62	18_3	N_HR	69.62	4330337.21	3467497.55	n_m	n_m	storage shed	n_m
251	63	18_4	Before 1918	675.21	4330343.17	3467484.16	n_m	n_m	old roof; no insulation visible	n_m
501	64	18_5	Before 1918	52.83	4330342.22	3467496.11	n_m	n_m	storage shed	n_m
267	65	18_6	N_HR	11.22	4330345.87	3467501.34	n_m	n_m	storage shed	n_m
149	66	18_7	Before 1918	692.60	4330355.29	3467479.65	m_m	g_m	new roof, insulation visible	m_m
150	67	18_8	Before 1968	971.69	4330369.09	3467474.11	m_m	n_m	old roof; no insulation visible	m_m
12	68	18_9	Before 1968	833.31	4330381.96	3467469.43	m_m	m_m	modernized roof	m_m
495	69	18_10	N_HR	76.54	4330384.48	3467491.2	n_m	n_m	storage shed	n_m
398	70	18_11	Before 1968	102.52	4330340.91	3467427.2	m_m	n_m	old roof; no insulation visible	m_m
499	71	18_12	N_HR	57.17	4330342.13	3467438.76	n_m	n_m	garden shed	n_m

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399	72	18_13	Before 1918	173.98	4330352.97	3467450.36	m_m	m_m	insulation visible	m_m
9	73	18_14	Before 1918	1024.10	4330365.58	3467445.06	m_m	m_m	insulation visible	m_m
8	74	18_15	N_HR	0.00	4330356.37	3467435.66	n_m	n_m	storage shed	n_m
7	75	18_16	N_HR	0.00	4330354.89	3467431.17	n_m	n_m	storage shed	n_m
13	76	18_17	Before 1918	826.72	4330379.92	3467440.56	m_m	m_m	insulation visible	m_m
11	77	18_18	N_HR	15.33	4330370.63	3467427.84	n_m	n_m	storage shed	n_m
10	78	18_19	N_HR	25.65	4330368.67	3467423.91	n_m	n_m	storage shed	n_m
15	79	18_20	Before 1918	707.41	4330393.05	3467435.31	m_m	n_m	old roof; no insulation visible	m_m
606	80	19_1	N_HR	8409.93	4330300.64	3467401.38	n_m	n_m	public building	n_m
551	81	19_2	NRB	1854.08	4330344.34	3467390.47	m_m	n_m	public building	m_m
5	82	19_3	Before 1957	291.57	4330383.78	3467376.23	m_m	n_m	public building	m_m
6	83	19_4	Before 1957	73.55	4330386.77	3467363.84	m_m	n_m	public building	m_m
244	84	20_1	NRB	5513.86	4330313.24	3467289.95	m_m	n_m	commercial use	m_m
22	85	20_2	Before 1918	1112.96	4330374.98	3467208.93	m_m	n_m	old roof; no insulation visible	m_m
488	86	21_1	Before 1918	367.59	4330369.81	3467192.58	m_m	n_m	old roof; no insulation visible	m_m
249	87	21_2	Before 1968	67.50	4330364.06	3467183.72	m_m	n_m	commercial use	m_m
248	88	21_3	Before 1968	676.27	4330352.45	3467178.74	m_m	n_m	old roof; no insulation visible	m_m
272	89	21_4	NRB	2131.95	4330356.58	3467128.79	m_m	g_m	new roof, insulation visible	m_m
19	90	21_5	N_HR	10.04	4330382.92	3467120.27	n_m	n_m	commercial use	n_m
593	91	22_1	Before 1957	692.77	4330417.5	3467824	m_m	n_m	old roof; no insulation visible	m_m
585	92	22_2	Before 1957	678.58	4330430	3467833	m_m	n_m	old roof; no insulation visible	m_m
586	93	22_3	Before 1957	680.28	4330442	3467841	m_m	n_m	old roof; no insulation visible	m_m
182	94	22_4	N_HR	609.86	4330486	3467877	n_m	n_m	commercial use	n_m
584	95	23_1	Before 1968	2628.21	4330465.82	3467760.96	m_m	n_m	old roof; no insulation visible	m_m
583	96	23_2	Before 1968	2236.75	4330472.9	3467710.71	m_m	g_m	new roof, insulation visible	m_m
590	97	23_3	N_HR	76.75	4330422.46	3467730.34	n_m	n_m	old roof; no insulation visible	n_m
580	98	23_4	Before 1918	776.39	4330399.92	3467713.29	m_m	m_m	modernized roof	m_m

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587	99	23_5	N_HR	74.84	4330407.24	3467717.48	n_m	n_m	storage shed	n_m
589	100	23_6	Before 1918	777.38	4330411.1	3467709.54	m_m	n_m	old roof; no insulation visible	m_m
581	101	23_7	Before 1957	1097.11	4330425.63	3467705.65	m_m	m_m	insulation visible	m_m
591	102	23_8	N_HR	14.20	4330419.34	3467720.82	n_m	n_m	storage shed	n_m
588	103	23_9	N_HR	76.22	4330408.99	3467718.18	n_m	n_m	storage shed	n_m
582	104	24_1	Before 1968	778.92	4330444.46	3467702.24	m_m	n_m	old roof; no insulation visible	m_m
566	105	24_2	Before 1968	925.71	4330434.74	3467674.19	m_m	n_m	old roof; no insulation visible	m_m
564	106	24_3	N_HR	52.51	4330440.83	3467656.03	n_m	n_m	garden shed	n_m
563	107	24_4	N_HR	89.15	4330427.45	3467653.51	n_m	n_m	garage	n_m
567	108	24_5	Before 1948	448.83	4330448.48	3467670.85	m_m	n_m	old roof; no insulation visible	g_m
568	109	24_6	NB	834.27	4330458.86	3467663.67	n_m	n_m	old roof; no insulation visible	n_m
569	110	24_7	Before 1948	639.49	4330471.72	3467661.67	m_m	m_m	modernized roof	g_m
570	111	24_8	NB	742.52	4330484.65	3467657.86	n_m	n_m	old roof; no insulation visible	n_m
571	112	24_9	NB	743.43	4330497.24	3467652.14	n_m	n_m	old roof; no insulation visible	n_m
573	113	24_10	NB	1280.46	4330504.5	3467627.9	n_m	n_m	old roof; no insulation visible	n_m
572	114	24_11	NB	839.63	4330496.62	3467610	n_m	n_m	old roof; no insulation visible	n_m
565	115	24_12	N_HR	22.27	4330487.58	3467619.97	n_m	n_m	storage shed	n_m
560	116	24_13	N_HR	0.00	4330454.18	3467648.05	n_m	n_m	storage shed	n_m
575	117	24_14	N_HR	0.00	4330455.18	3467638.65	n_m	n_m	garage	n_m
552	118	24_15	N_HR	0.00	4330465.49	3467635.01	n_m	n_m	garage	n_m
562	119	24_16	Before 1957	408.60	4330475.73	3467611.12	m_m	m_m	modernized roof	m_m
561	120	24_17	Before 1957	404.47	4330461.58	3467615.91	m_m	m_m	modernized roof	m_m
559	121	24_18	Before 1957	403.78	4330448.3	3467620.12	m_m	m_m	modernized roof	m_m
558	122	24_19	Before 1957	408.23	4330434.32	3467625.32	m_m	m_m	modernized roof	m_m
557	123	24_20	Before 1957	405.55	4330420.34	3467629.58	m_m	m_m	modernized roof	m_m
555	124	24_21	Before 1957	408.97	4330406.42	3467634.2	m_m	m_m	modernized roof	m_m
167	125	25_1	Before 1957	1903.77	4330417.65	3467579.43	m_m	n_m	old roof; no insulation visible	m_m

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171	126	25_2	Before 1968	1914.44	4330448.99	3467566.55	m_m	n_m	old roof; no insulation visible	m_m
170	127	25_3	N_HR	4634.23	4330471.3	3467555.86	n_m	n_m	garage	n_m
159	128	25_4	Before 1978	669.09	4330407.46	3467524.04	m_m	n_m	old roof; no insulation visible	m_m
168	129	25_5	Before 1978	856.66	4330420.57	3467519.02	m_m	n_m	old roof; no insulation visible	m_m
169	130	25_6	Before 1968	1053.88	4330438.22	3467508.14	m_m	n_m	old roof; no insulation visible	m_m
322	131	25_7	Before 1957	171.77	4330500.39	3467505.31	m_m	n_m	old roof; no insulation visible	m_m
323	132	25_8	NB	853.86	4330502.74	3467522.26	n_m	n_m	old roof; no insulation visible	n_m
506	133	26_1	N_HR	150.55	4330399.2	3467492.28	n_m	n_m	garage	n_m
296	134	26_2	Before 1978	221.58	4330414.33	3467493.99	m_m	n_m	commercial use	m_m
297	135	26_3	N_HR	136.26	4330424.14	3467481.42	n_m	n_m	garage	n_m
401	136	26_4	Before 1918	897.93	4330407.08	3467453.7	m_m	n_m	old roof; no insulation visible	m_m
17	137	26_5	N_HR	172.05	4330414.63	3467460.27	n_m	n_m	storage shed	n_m
409	138	26_6	Before 1918	641.72	4330419.84	3467448.85	m_m	m_m	modernized roof	m_m
4	139	26_7	N_HR	1445.35	4330437.99	3467453.76	n_m	n_m	garden shed	n_m
404	140	26_8	Before 1987	2304.45	4330442.89	3467445.3	n_m	n_m	old roof; no insulation visible	n_m
405	141	26_9	Before 1987	739.80	4330455.93	3467472.78	n_m	n_m	old roof; no insulation visible	n_m
453	142	26_10	Before 1987	1233.21	4330459.91	3467489.03	n_m	n_m	old roof; no insulation visible	n_m
528	143	26_11	NB	500.26	4330490.07	3467485.84	m_m	m_m	modernized roof	n_m
519	144	26_12	Before 1918	125.25	4330502.48	3467479.95	m_m	n_m	storage shed	m_m
336	145	26_13	Before 1918	274.02	4330484.57	3467472.02	m_m	n_m	old roof; no insulation visible	m_m
338	146	26_14	Before 1918	33.24	4330489.12	3467464.25	m_m	n_m	old roof; no insulation visible	m_m
512	147	26_15	Before 1978	1452.38	4330477.45	3467450.07	m_m	n_m	old roof; no insulation visible	m_m
511	148	26_16	NB	1525.11	4330471.56	3467427.88	m_m	n_m	old roof; no insulation visible	n_m
513	149	26_17	Before 1948	823.64	4330490.21	3467417.24	m_m	n_m	old roof; no insulation visible	g_m
16	150	26_18	Before 1978	734.02	4330406.43	3467430.36	m_m	n_m	old roof; no insulation visible	m_m
270	151	26_19	Before 1918	73.85	4330409.14	3467412.67	m_m	n_m	storage shed	m_m
402	152	26_20	Before 1918	626.37	4330419.48	3467426.15	m_m	m_m	insulation visible	m_m

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403	153	26_21	Before 1987	1651.46	4330435.44	3467416.84	m_m	n_m	old roof; no insulation visible	n_m
318	154	26_22	N_HR	109.08	4330506.91	3467446.7	n_m	n_m	garage	n_m
517	155	26_23	N_HR	73.25	4330491.28	3467436.86	n_m	n_m	storage shed	n_m
518	156	26_24	N_HR	54.10	4330496.17	3467434.32	n_m	n_m	storage shed	n_m
271	157	26_25	N_HR	7.39	4330410.47	3467415.8	n_m	n_m	storage shed	n_m
269	158	26_26	Before 1918	70.32	4330403.85	3467411.9	m_m	n_m	storage shed	m_m
14	159	26_27	Before 1968	1010.49	4330394.66	3467464.79	m_m	n_m	old roof; no insulation visible	m_m
516	160	26_28	Before 1978	484.51	4330491.7	3467456.07	m_m	n_m	commercial use	m_m
520	161	26_29	N_HR	39.03	4330504.61	3467432.94	n_m	n_m	storage shed	n_m
33	162	27_1	Before 1957	427.56	4330410.39	3467371.75	m_m	n_m	public building	m_m
34	163	27_2	Before 1957	378.84	4330422.24	3467382.11	m_m	n_m	public building	m_m
408	164	27_3	Before 1957	431.75	4330429.92	3467386.88	m_m	n_m	old roof; no insulation visible	m_m
35	165	27_4	NRB	1639.05	4330472.56	3467369.09	m_m	n_m	old roof; no insulation visible	m_m
32	166	27_5	N_HR	32.22	4330438.09	3467316.67	n_m	n_m	commercial use	n_m
407	167	28_1	N_HR	12562.98	4330452.12	3467288.72	n_m	n_m	garage	n_m
31	168	28_2	N_HR	55.18	4330424.21	3467274.73	n_m	n_m	commercial use	n_m
406	169	28_3	N_HR	4594.75	4330477.98	3467280.64	n_m	n_m	garage	n_m
374	170	28_4	M87_SVP	9129.30	4330418.39	3467217.61	n_m	n_m	old roof; no insulation visible	n_m
410	171	28_5	M87_SVP	5121.40	4330489.63	3467216.24	n_m	n_m	old roof; no insulation visible	n_m
21	172	29_1	NRB	1114.97	4330394.67	3467116.33	m_m	n_m	commercial use	m_m
372	173	29_2	NRB	459.64	4330425.42	3467106.06	m_m	n_m	old roof; no insulation visible	g_m
373	174	29_3	Before 1968	527.35	4330443.94	3467101.22	m_m	n_m	old roof; no insulation visible	m_m
18	175	29_4	N_HR	31.46	4330405.35	3467101.61	n_m	n_m	commercial use	n_m
20	176	29_5	N_HR	10.05	4330398.88	3467105.31	n_m	n_m	commercial use	n_m
37	177	29_6	M87_SVP	321.42	4330473.42	3467176.56	n_m	n_m	commercial use	n_m
375	178	29_7	M87_SVP	1589.40	4330481.28	3467172.57	n_m	n_m	old roof; no insulation visible	n_m
30	179	29_8	M87_SVP	1701.84	4330445.22	3467162.29	m_m	n_m	commercial use	n_m

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29	180	29_9	M87_SVP	4824.13	4330440	3467151.13	m_m	n_m	old roof; no insulation visible	n_m
380	181	30_1	NRB	500.78	4330426.38	3467093.76	m_m	n_m	commercial use	g_m
377	182	30_2	N_HR	97.46	4330438.65	3467099.53	n_m	n_m	storage shed	n_m
379	183	30_3	N_HR	16.40	4330433.84	3467089.71	n_m	n_m	storage shed	n_m
378	184	30_4	Before 1918	1620.74	4330454.67	3467093.99	m_m	m_m	insulation visible	m_m
24	185	30_5	Before 1957	219.48	4330483.96	3467085.92	m_m	n_m	old roof; no insulation visible	m_m
23	186	30_6	N_HR	52.69	4330475.3	3467078.7	n_m	n_m	commercial use	n_m
178	187	31_1	NT_RB	8630.30	4330591.93	3467819.42	m_m	n_m	old roof; no insulation visible	m_m
602	188	32_1	Before 1968	2979.27	4330524.41	3467796.42	m_m	m_m	modernized roof	m_m
605	189	32_2	STC	144.94	4330524.65	3467735.77	m_m	n_m	commercial use	m_m
604	190	32_3	N_HR	1095.73	4330511.22	3467729.82	n_m	n_m	bunker	n_m
603	191	32_4	N_HR	21.23	4330523.65	3467714.24	n_m	n_m	storage shed	n_m
180	192	32_5	Before 1968	614.92	4330554.32	3467712.15	m_m	n_m	old roof; no insulation visible	m_m
595	193	32_6	Before 1968	983.57	4330551.86	3467750.63	m_m	n_m	old roof; no insulation visible	m_m
597	194	32_7	Before 1968	1110.41	4330567.56	3467756.58	m_m	n_m	old roof; no insulation visible	m_m
598	195	32_8	N_HR	252.70	4330568.8	3467746.48	n_m	n_m	storage shed	n_m
599	196	32_9	Before 1918	1048.99	4330570.56	3467742.54	m_m	m_m	modernized roof	m_m
600	197	32_10	Before 1968	649.73	4330582.02	3467742.5	m_m	n_m	old roof; no insulation visible	m_m
601	198	32_11	Before 1968	943.70	4330597.68	3467740.45	m_m	n_m	old roof; no insulation visible	m_m
596	199	32_12	Before 1968	1646.14	4330589.03	3467702.88	m_m	n_m	old roof; no insulation visible	m_m
179	200	33_1	Before 1968	864.20	4330521.96	3467686.78	m_m	n_m	old roof; no insulation visible	m_m
181	201	33_2	Before 1968	953.88	4330534.97	3467668.41	m_m	n_m	old roof; no insulation visible	m_m
455	202	33_3	Before 1918	533.57	4330551.05	3467661.48	m_m	n_m	old roof; no insulation visible	m_m
456	203	33_4	Before 1918	952.90	4330563.58	3467655.41	m_m	n_m	old roof; no insulation visible	m_m
458	204	33_5	NB	928.46	4330578.54	3467650.91	m_m	n_m	old roof; no insulation visible	n_m
459	205	33_6	Before 1918	943.63	4330590.13	3467646.93	m_m	n_m	old roof; no insulation visible	m_m
457	206	33_7	Before 1968	713.58	4330540.81	3467633.6	m_m	n_m	old roof; no insulation visible	m_m

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462	207	33_8	Before 1968	378.24	4330534.78	3467619.48	m_m	n_m	old roof; no insulation visible	m_m
461	208	33_9	NT_RB	289.45	4330533.65	3467605.38	g_m	n_m	commercial use	g_m
175	209	33_10	N_HR	1088.78	4330574.74	3467620.29	n_m	n_m	garage	n_m
302	210	33_11	N_HR	76.97	4330568.17	3467599.18	n_m	n_m	storage shed	n_m
176	211	33_12	N_HR	150.78	4330598.4	3467616.13	n_m	n_m	garage	n_m
574	212	33_13	NB	822.40	4330508.71	3467646.22	m_m	n_m	old roof; no insulation visible	n_m
594	213	33_14	N_HR	14.58	4330556.64	3467687.23	n_m	n_m	storage shed	n_m
454	214	33_15	Before 1968	1188.37	4330540.28	3467635.57	m_m	n_m	old roof; no insulation visible	m_m
172	215	34_1	Before 1918	443.54	4330528.97	3467590.05	m_m	n_m	old roof; no insulation visible	m_m
183	216	34_2	Before 1968	585.77	4330553.43	3467582.61	m_m	n_m	old roof; no insulation visible	m_m
184	217	34_3	Before 1918	463.29	4330577.36	3467576.74	m_m	n_m	old roof; no insulation visible	m_m
298	218	34_4	N_HR	100.47	4330584.25	3467591.9	n_m	n_m	storage shed	n_m
173	219	34_5	Before 1918	1089.30	4330590.18	3467567.71	m_m	n_m	old roof; no insulation visible	m_m
328	220	34_6	Before 1918	1046.37	4330522.67	3467568.27	m_m	n_m	old roof; no insulation visible	m_m
327	221	34_7	Before 1918	1190.56	4330512.51	3467556.99	m_m	n_m	old roof; no insulation visible	m_m
330	222	34_8	Before 1978	687.35	4330539.67	3467564.47	m_m	n_m	old roof; no insulation visible	m_m
331	223	34_9	Before 1978	1033.32	4330558.07	3467557.78	m_m	n_m	old roof; no insulation visible	m_m
349	224	34_10	N_HR	52.74	4330525.33	3467548.42	n_m	n_m	storage shed	n_m
350	225	34_11	STC	1056.67	4330540.16	3467550.2	n_m	n_m	commercial use	n_m
329	226	34_12	Before 1918	899.90	4330583.85	3467547.59	m_m	n_m	old roof; no insulation visible	m_m
346	227	34_13	Before 1918	82.42	4330520.62	3467529.41	m_m	n_m	storage shed	m_m
335	228	34_14	NRB	396.08	4330527.45	3467508.79	m_m	n_m	commercial use	g_m
348	229	34_15	Before 1918	236.42	4330539.78	3467513.28	m_m	n_m	storage shed	m_m
542	230	34_16	N_HR	0.00	4330560.27	3467509.9	n_m	n_m	garage	n_m
299	231	34_17	Before 1918	457.95	4330596.07	3467588.79	m_m	n_m	storage shed	m_m
351	232	34_18	STC	1070.87	4330550.76	3467546.79	n_m	n_m	commercial use	n_m
324	233	34_19	Before 1948	367.66	4330506.68	3467532.19	m_m	n_m	old roof; no insulation visible	g_m

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337	234	34_20	Before 1957	52.47	4330516.77	3467518.75	m_m	n_m	storage shed	m_m
316	235	35_1	N_HR	68.38	4330541.91	3467496.11	n_m	n_m	garage	n_m
326	236	35_2	Before 1918	624.35	4330542	3467479.97	m_m	m_m	insulation visible	m_m
548	237	35_3	Before 1918	642.67	4330552.6	3467473.84	m_m	n_m	old roof; no insulation visible	m_m
549	238	35_4	Before 1918	637.16	4330563.62	3467467.54	m_m	m_m	insulation visible	m_m
537	239	35_5	Before 1918	140.39	4330574.05	3467461.58	m_m	n_m	old roof; no insulation visible	m_m
540	240	35_6	Before 1968	1977.95	4330592.69	3467451.81	m_m	n_m	old roof; no insulation visible	m_m
539	241	35_7	Before 1918	94.58	4330592.65	3467474.15	m_m	n_m	storage shed	m_m
538	242	35_8	Before 1918	37.55	4330582.4	3467476.4	m_m	n_m	storage shed	m_m
543	243	35_9	N_HR	43.15	4330589.48	3467485.23	n_m	n_m	commercial use	n_m
521	244	35_10	Before 1968	904.43	4330516.64	3467469.71	m_m	n_m	old roof; no insulation visible	m_m
523	245	35_11	Before 1918	422.79	4330530.8	3467462.25	m_m	n_m	old roof; no insulation visible	m_m
525	246	35_12	Before 1968	1005.60	4330541.35	3467454.66	m_m	n_m	old roof; no insulation visible	m_m
321	247	35_13	Before 1918	855.00	4330551.96	3467447.55	m_m	n_m	old roof; no insulation visible	m_m
526	248	35_14	Before 1978	635.56	4330562.45	3467441.59	m_m	n_m	old roof; no insulation visible	m_m
527	249	35_15	Before 1968	2555.68	4330578.5	3467420.21	m_m	n_m	old roof; no insulation visible	m_m
524	250	35_16	Before 1957	1478.97	4330574.46	3467403.19	m_m	n_m	old roof; no insulation visible	m_m
343	251	35_17	N_HR	56.29	4330558.97	3467408.33	n_m	n_m	storage shed	n_m
522	252	35_18	N_HR	95.87	4330516.7	3467442.72	n_m	n_m	garage	n_m
345	253	35_19	N_HR	47.74	4330552.11	3467428.34	n_m	n_m	garage	n_m
342	254	35_20	Before 1968	261.60	4330542.29	3467420.6	m_m	n_m	commercial use	m_m
341	255	35_21	N_HR	41.80	4330543.71	3467409.57	n_m	n_m	storage shed	n_m
514	256	35_22	Before 1918	726.73	4330505.83	3467408.45	m_m	n_m	old roof; no insulation visible	m_m
550	257	35_23	N_HR	67.08	4330553.11	3467494.07	n_m	n_m	garage	n_m
536	258	35_24	N_HR	38.19	4330580.35	3467479.76	n_m	n_m	storage shed	n_m
344	259	35_25	Before 1957	119.16	4330566.62	3467406.4	m_m	n_m	storage shed	m_m
339	260	35_26	N_HR	14.22	4330518.55	3467418.4	n_m	n_m	storage shed	n_m

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340	261	35_27	N_HR	36.44	4330523.49	3467449.52	n_m	n_m	storage shed	n_m
608	262	35_28	N_HR	137.62	4330521.88	3467439.42	n_m	n_m	garage	n_m
515	263	35_29	Before 1918	818.40	4330518.12	3467402.26	m_m	n_m	old roof; no insulation visible	m_m
325	264	35_30	Before 1918	425.74	4330530.86	3467488.71	m_m	g_m	new roof, insulation visible	m_m
347	265	35_31	N_HR	74.27	4330534.04	3467501.78	n_m	n_m	storage shed	n_m
529	266	35_32	Before 1918	353.48	4330502.42	3467479.75	m_m	n_m	old roof; no insulation visible	m_m
317	267	36_1	Before 1918	1033.56	4330532.97	3467395.91	m_m	n_m	old roof; no insulation visible	m_m
319	268	36_2	Before 1918	1098.98	4330548.47	3467387.93	m_m	n_m	old roof; no insulation visible	m_m
320	269	36_3	Before 1957	1537.54	4330566.06	3467383.09	m_m	n_m	old roof; no insulation visible	m_m
42	270	36_4	Before 1968	0.00	4330515.73	3467376.55	m_m	n_m	old roof; no insulation visible	m_m
43	271	36_5	Before 1918	1068.45	4330530.52	3467372.63	m_m	n_m	old roof; no insulation visible	m_m
53	272	36_6	Before 1968	789.11	4330544.56	3467366.33	m_m	n_m	old roof; no insulation visible	m_m
54	273	36_7	Before 1918	2143.53	4330558.78	3467357.07	m_m	n_m	old roof; no insulation visible	m_m
68	274	36_8	Before 1968	823.45	4330554.8	3467341.11	m_m	n_m	old roof; no insulation visible	m_m
66	275	36_9	Before 1918	925.31	4330549.64	3467329.89	m_m	n_m	old roof; no insulation visible	m_m
65	276	36_10	Before 1918	1342.09	4330547.91	3467322.4	m_m	n_m	old roof; no insulation visible	m_m
412	277	36_11	Before 1918	151.87	4330542.87	3467312.47	m_m	n_m	old roof; no insulation visible	m_m
284	278	36_12	N_HR	497.77	4330535.84	3467333.7	n_m	n_m	garage	n_m
283	279	36_13	N_HR	302.85	4330534.1	3467331.02	n_m	n_m	garden shed	n_m
276	280	36_14	N_HR	29.48	4330529.78	3467308.2	n_m	n_m	storage shed	n_m
55	281	36_15	Before 1968	1242.03	4330570.11	3467348.54	m_m	n_m	old roof; no insulation visible	m_m
71	282	36_16	Before 1968	1866.93	4330579.72	3467336.8	m_m	n_m	old roof; no insulation visible	m_m
70	283	36_17	Before 1968	1484.37	4330574.04	3467324.43	m_m	n_m	old roof; no insulation visible	m_m
273	284	36_18	N_HR	43.42	4330525.47	3467309.53	n_m	n_m	storage shed	n_m
57	285	36_19	Before 1968	587.32	4330591.59	3467366.83	m_m	n_m	old roof; no insulation visible	m_m
69	286	36_20	Before 1968	1241.54	4330567.15	3467307.47	m_m	n_m	old roof; no insulation visible	m_m
278	287	36_21	N_HR	293.70	4330528.85	3467361.95	n_m	n_m	garage	n_m

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277	288	36_22	N_HR	94.35	4330521.76	3467356.88	n_m	n_m	garage	n_m
41	289	36_23	N_HR	0.00	4330506.08	3467370.55	n_m	n_m	garage	n_m
72	290	36_24	Before 1957	848.10	4330598.21	3467319.08	m_m	n_m	old roof; no insulation visible	m_m
67	291	37_1	Before 1918	814.19	4330560	3467289.55	m_m	n_m	old roof; no insulation visible	m_m
60	292	37_2	Before 1918	2802.61	4330553.54	3467273.37	m_m	n_m	old roof; no insulation visible	m_m
61	293	37_3	Before 1918	654.22	4330579.44	3467274.12	m_m	n_m	old roof; no insulation visible	m_m
63	294	37_4	Before 1918	680.31	4330590.26	3467279.42	m_m	n_m	old roof; no insulation visible	m_m
502	295	37_5	M87_SVP	337.10	4330521.19	3467298.38	m_m	n_m	commercial use	n_m
410	296	37_6	N_HR	5121.40	4330507.96	3467260.94	n_m	n_m	old roof; no insulation visible	n_m
46	297	37_7	M87_SVP	133.44	4330549.17	3467212.65	m_m	n_m	commercial use	n_m
62	298	37_8	Before 1918	2017.97	4330592.42	3467243.79	m_m	n_m	old roof; no insulation visible	m_m
58	299	37_9	Before 1918	1358.71	4330586.36	3467222.76	m_m	n_m	old roof; no insulation visible	m_m
51	300	37_10	Before 1918	361.11	4330578.82	3467208.82	m_m	g_m	new roof, insulation visible	m_m
280	301	37_11	N_HR	141.88	4330591.29	3467202.05	n_m	n_m	storage shed	n_m
281	302	37_12	N_HR	134.00	4330595.87	3467209.9	n_m	n_m	storage shed	n_m
64	303	37_13	N_HR	180.00	4330597.82	3467223.31	n_m	n_m	storage shed	n_m
282	304	37_14	STC	37.21	4330562.44	3467274.78	m_m	n_m	storage shed	m_m
382	305	38_1	Before 1918	937.58	4330516.18	3467183.61	m_m	n_m	old roof; no insulation visible	m_m
38	306	38_2	Before 1918	1470.29	4330531.96	3467180.22	m_m	m_m	modernized roof	m_m
47	307	38_3	Before 1918	1392.15	4330548.5	3467175.5	m_m	n_m	old roof; no insulation visible	m_m
49	308	38_4	Before 1918	808.16	4330564.81	3467172.57	m_m	n_m	old roof; no insulation visible	m_m
52	309	38_5	Before 1918	796.27	4330575.41	3467167.37	m_m	n_m	old roof; no insulation visible	m_m
48	310	38_6	N_HR	61.00	4330553.71	3467164.01	n_m	n_m	storage shed	n_m
275	311	38_7	N_HR	49.01	4330547.03	3467157.15	n_m	n_m	storage shed	n_m
274	312	38_8	Before 1918	254.38	4330540.52	3467152.84	m_m	m_m	modernized roof	m_m
40	313	38_9	N_HR	3.95	4330541.03	3467159.46	n_m	n_m	garden shed	n_m
392	314	38_10	Before 1918	567.69	4330529.55	3467163.21	m_m	n_m	old roof; no insulation visible	m_m

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389	315	38_11	Before 1918	601.64	4330538.84	3467119.87	m_m	n_m	old roof; no insulation visible	m_m
384	316	38_12	N_HR	50.51	4330550.83	3467121	n_m	n_m	storage shed	n_m
393	317	38_13	N_HR	67.73	4330562.72	3467139.83	n_m	n_m	storage shed	n_m
390	318	38_14	Before 1968	119.50	4330568.45	3467129.68	m_m	n_m	storage shed	m_m
383	319	38_15	Before 1968	1173.57	4330561.98	3467105.64	m_m	n_m	old roof; no insulation visible	m_m
386	320	38_16	Before 1978	1010.77	4330576.51	3467102.5	m_m	n_m	old roof; no insulation visible	m_m
95	321	38_17	Before 1918	296.26	4330594.48	3467122.36	m_m	n_m	old roof; no insulation visible	m_m
311	322	38_18	Before 1918	45.70	4330585.09	3467130.12	m_m	n_m	storage shed	m_m
44	323	38_19	N_HR	28.27	4330585.95	3467137.09	n_m	n_m	storage shed	n_m
381	324	38_20	Before 1918	821.26	4330504.26	3467150.04	m_m	m_m	insulation visible	m_m
376	325	38_21	Before 1918	804.27	4330496.04	3467130.23	m_m	n_m	old roof; no insulation visible	m_m
36	326	38_22	Before 1957	847.82	4330512.12	3467121.67	m_m	g_m	new roof, insulation visible	m_m
395	327	38_23	Before 1968	65.19	4330573.62	3467134.34	m_m	n_m	storage shed	m_m
59	328	38_24	Before 1918	669.35	4330591.21	3467185.51	m_m	n_m	old roof; no insulation visible	m_m
96	329	38_25	Before 1918	317.85	4330601.15	3467132.65	m_m	n_m	old roof; no insulation visible	m_m
50	330	38_26	Before 1918	1427.67	4330573.38	3467191.74	m_m	n_m	old roof; no insulation visible	m_m
368	331	38_27	STC	39.70	4330594.17	3467161.54	m_m	n_m	commercial use	m_m
385	332	38_28	M87_SVP	46.93	4330589.46	3467156.89	g_m	n_m	storage shed	n_m
394	333	38_29	N_HR	41.85	4330586.67	3467153.69	n_m	n_m	garage	n_m
45	334	38_30	N_HR	23.17	4330587.07	3467131.63	n_m	n_m	storage shed	n_m
25	335	39_1	Before 1957	466.63	4330511.6	3467077.82	m_m	n_m	old roof; no insulation visible	g_m
26	336	39_2	N_HR	63.52	4330512.7	3467066.59	n_m	n_m	storage shed	n_m
314	337	39_3	N_HR	90.10	4330520.22	3467061.55	n_m	n_m	storage shed	n_m
27	338	39_4	N_HR	130.93	4330521.58	3467051.86	n_m	n_m	storage shed	n_m
391	339	39_5	Before 1918	1006.47	4330531.14	3467070.4	m_m	n_m	old roof; no insulation visible	m_m
39	340	39_6	NRB	3196.05	4330544.86	3467049.76	m_m	n_m	public building	g_m
369	341	39_7	Before 1957	1095.80	4330575.39	3467039.55	m_m	n_m	old roof; no insulation visible	g_m

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370	342	39_8	N_HR	254.90	4330582.59	3467019.08	n_m	n_m	storage shed	n_m
28	343	39_9	N_HR	37.66	4330524.21	3467044.15	n_m	n_m	storage shed	n_m
315	344	39_10	N_HR	79.01	4330521.78	3467038.63	n_m	n_m	storage shed	n_m
313	345	39_11	N_HR	68.51	4330516.06	3467042.91	n_m	n_m	storage shed	n_m
208	346	40_1	NRB	0.00	4330682.74	3467814.22	m_m	n_m	public building	g_m
206	347	41_1	Before 1968	1066.37	4330641.75	3467773.76	m_m	n_m	old roof; no insulation visible	m_m
205	348	41_2	Before 1968	1057.40	4330636.87	3467757.59	m_m	n_m	old roof; no insulation visible	m_m
204	349	41_3	Before 1968	1052.32	4330630.1	3467740.16	m_m	n_m	old roof; no insulation visible	m_m
192	350	41_4	Before 1968	1067.99	4330676.03	3467761.27	m_m	n_m	old roof; no insulation visible	g_m
191	351	41_5	Before 1968	1044.10	4330670.83	3467745.53	m_m	n_m	old roof; no insulation visible	g_m
207	352	41_6	Before 1968	1282.04	4330664.81	3467727.18	m_m	n_m	old roof; no insulation visible	g_m
190	353	41_7	Before 1968	1061.15	4330700.22	3467716.45	m_m	n_m	old roof; no insulation visible	g_m
202	354	42_1	Before 1968	1630.71	4330620.33	3467694.03	m_m	n_m	old roof; no insulation visible	g_m
203	355	42_2	Before 1968	1626.68	4330652.97	3467684.2	m_m	n_m	garage	g_m
484	356	42_3	N_HR	307.88	4330668.01	3467671.7	n_m	n_m	garage	n_m
189	357	42_4	N_HR	132.87	4330689.14	3467682.39	n_m	n_m	garage	n_m
510	358	42_5	N_HR	104.83	4330679.68	3467658.95	n_m	n_m	garage	n_m
460	359	42_6	Before 1918	902.52	4330601.09	3467641.73	m_m	n_m	old roof; no insulation visible	m_m
469	360	42_7	Before 1918	1056.75	4330613.61	3467637.69	m_m	n_m	old roof; no insulation visible	m_m
470	361	42_8	Before 1918	1068.56	4330628.52	3467632.73	m_m	n_m	old roof; no insulation visible	m_m
471	362	42_9	Before 1948	1062.34	4330642.06	3467628.09	m_m	n_m	old roof; no insulation visible	g_m
472	363	42_10	Before 1968	1504.26	4330660.96	3467622.24	m_m	n_m	old roof; no insulation visible	g_m
467	364	42_11	Before 1968	1193.06	4330681.48	3467620.33	m_m	n_m	old roof; no insulation visible	g_m
481	365	42_12	Before 1968	980.30	4330694.05	3467633.74	m_m	n_m	old roof; no insulation visible	g_m
482	366	42_13	Before 1968	1661.74	4330705.19	3467648.91	m_m	m_m	modernized roof	g_m
177	367	42_14	Before 1968	145.34	4330598.23	3467616.3	m_m	n_m	old roof; no insulation visible	g_m
199	368	42_15	Before 1968	716.73	4330610.58	3467612.5	m_m	n_m	old roof; no insulation visible	g_m

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200	369	42_16	Before 1918	898.94	4330623.62	3467608.11	m_m	m_m	modernized roof	m_m
201	370	42_17	Before 1957	1634.08	4330647.91	3467600.1	m_m	n_m	old roof; no insulation visible	g_m
187	371	43_1	Before 1968	735.07	4330664.88	3467584.87	m_m	n_m	old roof; no insulation visible	g_m
198	372	43_2	Before 1968	965.50	4330658.5	3467571.16	m_m	n_m	old roof; no insulation visible	g_m
197	373	43_3	Before 1968	2664.35	4330646.14	3467554.07	m_m	n_m	old roof; no insulation visible	g_m
185	374	43_4	Before 1918	1601.45	4330618.6	3467560.11	m_m	m_m	modernized roof	m_m
174	375	43_5	Before 1918	997.29	4330602.58	3467565.01	m_m	n_m	old roof; no insulation visible	m_m
301	376	43_6	N_HR	52.79	4330601.97	3467594.23	n_m	n_m	storage shed	n_m
300	377	43_7	Before 1918	0.00	4330615.74	3467589.35	m_m	n_m	storage shed	m_m
304	378	43_8	N_HR	0.00	4330633.04	3467582.71	n_m	n_m	garage	n_m
305	379	43_9	N_HR	0.00	4330644.87	3467578.79	n_m	n_m	garage	n_m
465	380	43_10	Before 1968	1955.61	4330691.94	3467554.68	m_m	n_m	old roof; no insulation visible	g_m
333	381	43_11	Before 1918	914.68	4330602.69	3467542.49	m_m	n_m	old roof; no insulation visible	m_m
334	382	43_12	Before 1968	2522.10	4330618.54	3467531.43	m_m	n_m	commercial use	g_m
332	383	43_13	Before 1957	1433.15	4330634.15	3467525.84	m_m	m_m	insulation visible	g_m
547	384	43_14	Before 1957	1513.42	4330629.47	3467510.62	m_m	m_m	insulation visible	g_m
473	385	43_15	Before 1968	2004.37	4330675.1	3467509.38	m_m	n_m	old roof; no insulation visible	g_m
496	386	43_16	Before 1957	2018.51	4330688.55	3467509.76	m_m	n_m	old roof; no insulation visible	g_m
546	387	44_1	Before 1968	192.59	4330621.06	3467496.5	g_m	n_m	old roof; no insulation visible	g_m
545	388	44_2	Before 1957	228.56	4330612.36	3467479.71	m_m	n_m	old roof; no insulation visible	g_m
544	389	44_3	Before 1957	419.28	4330601.18	3467483.86	m_m	n_m	commercial use	g_m
151	390	44_4	Before 1968	1726.80	4330677.31	3467482.22	g_m	n_m	old roof; no insulation visible	g_m
152	391	44_5	Before 1918	755.94	4330689.15	3467473.02	m_m	n_m	old roof; no insulation visible	m_m
444	392	44_6	Before 1968	1120.47	4330695.75	3467444.68	g_m	n_m	old roof; no insulation visible	g_m
434	393	44_7	Before 1918	1156.99	4330677.09	3467450.53	m_m	m_m	insulation visible	m_m
492	394	44_8	Before 1968	1916.59	4330656.12	3467455.36	g_m	n_m	old roof; no insulation visible	g_m
491	395	44_9	Before 1968	1602.29	4330649.22	3467443.68	g_m	n_m	old roof; no insulation visible	g_m

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129	396	44_10	Before 1968	805.90	4330672.45	3467415.7	g_m	n_m	old roof; no insulation visible	g_m
430	397	44_11	Before 1918	653.24	4330684.33	3467408.58	m_m	m_m	insulation visible	m_m
423	398	44_12	Before 1957	1230.10	4330639.25	3467399.32	m_m	n_m	old roof; no insulation visible	g_m
541	399	44_13	Before 1957	2007.80	4330602.01	3467463.93	m_m	n_m	old roof; no insulation visible	g_m
450	400	44_14	Before 1918	319.30	4330698.47	3467467.46	m_m	n_m	old roof; no insulation visible	m_m
490	401	44_15	Before 1968	1686.94	4330644.07	3467431.19	g_m	n_m	old roof; no insulation visible	g_m
413	402	44_16	Before 1968	697.18	4330658.99	3467420.54	g_m	n_m	old roof; no insulation visible	g_m
137	403	44_17	N_HR	35.82	4330691.17	3467422.06	n_m	n_m	storage shed	n_m
607	404	44_18	N_HR	0.00	4330682.14	3467426.45	n_m	n_m	garage	n_m
290	405	44_19	Before 1957	1091.27	4330619.92	3467399.92	m_m	n_m	commercial use	g_m
420	406	44_20	Before 1957	2179.10	4330613.9	3467412.21	m_m	n_m	old roof; no insulation visible	g_m
411	407	45_1	Before 1968	1507.90	4330602.92	3467388.59	g_m	n_m	old roof; no insulation visible	g_m
56	408	45_2	Before 1968	175.82	4330596.57	3467377.52	g_m	m_m	modernized roof	g_m
503	409	45_3	NRB	265.68	4330612.47	3467386.64	m_m	n_m	commercial use	g_m
121	410	45_4	Before 1968	699.52	4330655.15	3467392.97	g_m	n_m	old roof; no insulation visible	g_m
429	411	45_5	Before 1978	580.31	4330668.03	3467385.74	m_m	n_m	old roof; no insulation visible	m_m
493	412	45_6	Before 1957	66.97	4330648.35	3467362.19	m_m	n_m	garage	g_m
414	413	45_7	NB	1030.47	4330607.81	3467344.81	m_m	n_m	old roof; no insulation visible	n_m
415	414	45_8	Before 1918	1112.06	4330617.39	3467331.42	m_m	m_m	insulation visible	m_m
422	415	45_9	N_HR	120.18	4330634.09	3467358.39	n_m	n_m	garage	n_m
288	416	45_10	N_HR	0.00	4330638.16	3467333.9	n_m	n_m	storage shed	n_m
417	417	45_11	Before 1957	1444.57	4330637.22	3467309.58	m_m	g_m	new roof, insulation visible	g_m
418	418	45_12	Before 1918	1110.68	4330652.64	3467313.97	m_m	n_m	old roof; no insulation visible	m_m
425	419	45_13	Before 1918	1114.45	4330667.35	3467321.6	n_m	n_m	old roof; no insulation visible	n_m
426	420	45_14	Before 1918	752.56	4330668.67	3467330.89	m_m	n_m	old roof; no insulation visible	m_m
125	421	45_15	N_HR	77.33	4330679.56	3467328.24	n_m	n_m	storage shed	n_m
427	422	45_16	Before 1948	1182.27	4330679.18	3467338.86	m_m	n_m	old roof; no insulation visible	m_m

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118	423	45_17	Before 1957	873.89	4330605.09	3467308.82	m_m	m_m	insulation visible	g_m
416	424	45_18	Before 1918	849.24	4330625.79	3467321.52	m_m	n_m	old roof; no insulation visible	m_m
287	425	45_19	N_HR	0.00	4330642.08	3467349.99	n_m	n_m	garage	n_m
419	426	45_20	N_HR	125.10	4330654.89	3467347.81	n_m	n_m	garage	n_m
289	427	45_21	N_HR	0.00	4330649.17	3467330.33	n_m	n_m	storage shed	n_m
421	428	45_22	N_HR	119.74	4330623.92	3467380.6	n_m	n_m	garage	n_m
126	429	45_23	Before 1918	286.44	4330685.48	3467304.28	g_m	n_m	old roof; no insulation visible	m_m
611	430	45_24	Before 1918	407.60	4330689.65	3467288.62	g_m	n_m	old roof; no insulation visible	m_m
609	431	45_25	Before 1918	49.53	4330684.35	3467291.22	g_m	n_m	storage shed	m_m
610	432	45_26	Before 1918	13.98	4330680.04	3467292.78	g_m	n_m	storage shed	m_m
504	433	45_27	N_HR	67.59	4330696.78	3467359.91	n_m	n_m	storage shed	n_m
119	434	46_1	Before 1918	1192.91	4330615.01	3467296.83	g_m	g_m	new roof, insulation visible	m_m
94	435	46_2	Before 1957	581.14	4330601.59	3467285.6	g_m	n_m	old roof; no insulation visible	g_m
93	436	46_3	Before 1918	800.85	4330602.34	3467259.48	g_m	m_m	insulation visible	m_m
105	437	46_4	Before 1918	810.15	4330614.5	3467263.91	g_m	n_m	old roof; no insulation visible	m_m
109	438	46_5	Before 1918	1310.86	4330628.46	3467270.39	g_m	n_m	old roof; no insulation visible	m_m
112	439	46_6	Before 1918	871.06	4330640.23	3467261.3	g_m	n_m	old roof; no insulation visible	g_m
114	440	46_7	Before 1918	166.04	4330648.87	3467250.92	g_m	n_m	old roof; no insulation visible	g_m
117	441	46_8	Before 1918	1253.17	4330658.27	3467236.2	g_m	m_m	insulation visible	g_m
110	442	46_9	N_HR	27.95	4330637.46	3467249.39	n_m	n_m	storage shed	n_m
108	443	46_10	N_HR	0.00	4330630.52	3467229.7	n_m	n_m	garage	n_m
88	444	46_11	Before 1918	787.79	4330651.38	3467220.81	g_m	n_m	old roof; no insulation visible	g_m
285	445	46_12	Before 1918	94.51	4330608.66	3467219.15	g_m	n_m	commercial use	g_m
78	446	46_13	N_HR	25.92	4330616.12	3467214.99	n_m	n_m	storage shed	n_m
279	447	46_14	N_HR	144.66	4330596.41	3467204.5	n_m	n_m	storage shed	n_m
77	448	46_15	N_HR	12.83	4330615.02	3467210.05	n_m	n_m	storage shed	n_m
85	449	46_16	Before 1918	1009.90	4330640.64	3467205.81	g_m	n_m	old roof; no insulation visible	g_m

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120	450	46_17	Before 1918	1451.49	4330657.82	3467285.25	g_m	m_m	modernized roof	g_m
115	451	46_18	Before 1918	53.31	4330661.39	3467273.06	g_m	n_m	commercial use	g_m
122	452	46_19	Before 1918	1437.96	4330671.14	3467260.72	g_m	n_m	old roof; no insulation visible	g_m
577	453	46_20	Before 1918	1017.32	4330681.35	3467276.07	g_m	m_m	modernized roof	g_m
124	454	46_21	Before 1978	1228.85	4330691.38	3467239.23	m_m	n_m	old roof; no insulation visible	m_m
132	455	46_22	Before 1918	774.66	4330676.7	3467220.34	g_m	n_m	old roof; no insulation visible	g_m
131	456	46_23	Before 1968	743.67	4330671.48	3467208.48	g_m	m_m	insulation visible	g_m
133	457	46_24	N_HR	84.50	4330685.32	3467214.26	n_m	n_m	storage shed	n_m
79	458	46_25	N_HR	20.05	4330625.35	3467197.88	n_m	n_m	garden shed	n_m
291	459	46_26	Before 1918	62.60	4330669.03	3467266	g_m	n_m	storage shed	g_m
116	460	46_27	N_HR	25.13	4330664.85	3467264.77	n_m	n_m	commercial use	n_m
106	461	46_28	N_HR	0.00	4330623.88	3467232.42	n_m	n_m	commercial use	n_m
104	462	46_29	N_HR	83.12	4330601.21	3467244.04	n_m	n_m	storage shed	n_m
107	463	46_30	N_HR	0.00	4330628.29	3467237.47	n_m	n_m	garage	n_m
111	464	46_31	N_HR	0.00	4330642.97	3467234.2	n_m	n_m	storage shed	n_m
113	465	46_32	N_HR	0.00	4330646.01	3467228.11	n_m	n_m	storage shed	n_m
123	466	46_33	N_HR	84.11	4330664.85	3467263.09	n_m	n_m	storage shed	n_m
83	467	46_34	Before 1918	515.57	4330634.95	3467196.63	g_m	n_m	old roof; no insulation visible	g_m
286	468	46_35	N_HR	0.00	4330631.02	3467240.03	n_m	n_m	storage shed	n_m
92	469	46_36	Before 1957	800.70	4330665.17	3467195.35	g_m	m_m	modernized roof	g_m
75	470	47_1	Before 1957	679.75	4330603.09	3467181.53	g_m	n_m	old roof; no insulation visible	g_m
76	471	47_2	Before 1918	311.43	4330611.01	3467177.89	g_m	n_m	old roof; no insulation visible	g_m
81	472	47_3	Before 1957	585.73	4330631.48	3467187.97	g_m	n_m	old roof; no insulation visible	g_m
367	473	47_4	N_HR	73.02	4330593.87	3467162.01	n_m	n_m	storage shed	n_m
387	474	47_5	N_HR	0.00	4330600.93	3467156.62	n_m	n_m	storage shed	n_m
102	475	47_6	N_HR	32.58	4330639.25	3467119.26	n_m	n_m	storage shed	n_m
87	476	47_7	Before 1968	799.28	4330658.29	3467184.17	g_m	n_m	old roof; no insulation visible	g_m

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130	477	47_8	N_HR	62.19	4330669.14	3467188.05	n_m	n_m	garden shed	n_m
86	478	47_9	Before 1968	364.96	4330645.72	3467171.11	g_m	n_m	old roof; no insulation visible	g_m
91	479	47_10	N_HR	117.59	4330657.31	3467167.71	n_m	n_m	storage shed	n_m
90	480	47_11	NRB	0.00	4330655.45	3467164.63	m_m	n_m	storage shed	g_m
84	481	47_12	Before 1918	749.85	4330644.28	3467162.57	g_m	n_m	old roof; no insulation visible	g_m
89	482	47_13	N_HR	98.47	4330653.19	3467159.57	n_m	n_m	storage shed	n_m
73	483	47_14	Before 1918	136.65	4330644.1	3467138.43	g_m	n_m	old roof; no insulation visible	g_m
74	484	47_15	N_HR	30.70	4330646.1	3467126.24	n_m	n_m	storage shed	n_m
100	485	47_16	Before 1918	1081.70	4330631.46	3467140.66	g_m	n_m	old roof; no insulation visible	g_m
99	486	47_17	Before 1918	1113.33	4330625.67	3467128	g_m	g_m	new roof, insulation visible	g_m
98	487	47_18	Before 1918	766.83	4330618.01	3467114.05	g_m	n_m	old roof; no insulation visible	g_m
97	488	47_19	Before 1968	870.27	4330610.93	3467103.01	g_m	n_m	old roof; no insulation visible	g_m
101	489	47_20	N_HR	18.43	4330628.97	3467108.27	n_m	n_m	storage shed	n_m
310	490	47_21	NRB	85.86	4330633.86	3467108.28	g_m	n_m	storage shed	g_m
80	491	47_22	Before 1918	946.90	4330624.52	3467175.48	g_m	n_m	old roof; no insulation visible	g_m
388	492	47_23	Before 1918	545.26	4330610.6	3467150.43	g_m	n_m	old roof; no insulation visible	g_m
103	493	47_24	N_HR	0.00	4330638.25	3467124.95	n_m	n_m	storage shed	n_m
222	494	48_1	N_HR	0.00	4330804.53	3467819.57	n_m	n_m	commercial use	n_m
195	495	49_1	Before 1987	4241.14	4330727.42	3467790.86	m_m	n_m	old roof; no insulation visible	n_m
306	496	49_2	N_HR	2973.84	4330744.71	3467785.32	n_m	n_m	garage	n_m
307	497	49_3	N_HR	1576.41	4330763.45	3467785.36	n_m	n_m	commercial use	n_m
309	498	49_4	NRB	590.23	4330781.5	3467780.7	g_m	n_m	commercial use	g_m
220	499	49_5	NB	795.75	4330792.54	3467763.19	m_m	m_m	insulation visible	n_m
576	500	49_6	NRB	1866.02	4330760.92	3467745.08	g_m	n_m	commercial use	g_m
214	501	49_7	Before 1957	640.77	4330775.95	3467737.85	g_m	n_m	old roof; no insulation visible	g_m
194	502	49_8	Before 1968	1055.28	4330711.03	3467750.37	g_m	n_m	old roof; no insulation visible	g_m
308	503	49_9	NRB	345.64	4330769.42	3467768.08	g_m	n_m	commercial use	g_m

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497	504	49_10	Before 1918	1125.11	4330740.94	3467697.62	g_m	n_m	old roof; no insulation visible	g_m
486	505	49_11	Before 1957	969.39	4330755.87	3467711.52	g_m	n_m	old roof; no insulation visible	g_m
213	506	49_12	Before 1957	371.16	4330760.45	3467720.18	g_m	n_m	old roof; no insulation visible	g_m
193	507	49_13	Before 1968	1059.62	4330706.58	3467733.7	g_m	n_m	old roof; no insulation visible	g_m
188	508	50_1	N_HR	31.13	4330712.53	3467602.96	n_m	n_m	storage shed	n_m
483	509	50_2	Before 1918	711.60	4330719.66	3467668.11	g_m	n_m	old roof; no insulation visible	g_m
485	510	50_3	Before 1968	604.07	4330721.68	3467670.1	g_m	n_m	old roof; no insulation visible	g_m
217	511	50_4	NRB	3261.36	4330797.74	3467669.94	g_m	n_m	commercial use	g_m
218	512	50_5	NRB	2234.35	4330782.91	3467639.67	g_m	n_m	commercial use	g_m
466	513	51_1	Before 1968	2772.73	4330700.35	3467570.26	g_m	n_m	old roof; no insulation visible	g_m
475	514	51_2	STC	1057.18	4330704.79	3467534.8	m_m	n_m	commercial use	g_m
463	515	51_3	STC	76.20	4330716.67	3467530.82	g_m	n_m	commercial use	g_m
211	516	51_4	Before 1968	491.98	4330736.18	3467551.35	g_m	n_m	old roof; no insulation visible	g_m
186	517	51_5	STC	100.69	4330728.21	3467524.87	g_m	n_m	commercial use	g_m
507	518	51_6	N_HR	88.98	4330752.1	3467539.02	n_m	n_m	garage	n_m
468	519	51_7	Before 1948	1898.30	4330759.95	3467514.08	g_m	n_m	old roof; no insulation visible	g_m
209	520	51_8	STC	1042.31	4330775.91	3467509.41	g_m	n_m	commercial use	g_m
210	521	51_9	Before 1957	617.69	4330789.4	3467501.81	g_m	n_m	old roof; no insulation visible	g_m
479	522	51_10	Before 1957	606.51	4330793.17	3467548.28	g_m	n_m	old roof; no insulation visible	g_m
476	523	51_11	Before 1957	608.79	4330704.79	3467504.91	g_m	n_m	old roof; no insulation visible	g_m
196	524	51_12	STC	82.01	4330740.73	3467519.96	g_m	n_m	garage	g_m
477	525	51_13	Before 1957	608.88	4330780.3	3467551.56	g_m	n_m	old roof; no insulation visible	g_m
212	526	51_14	Before 1957	606.00	4330765.56	3467558.15	g_m	n_m	old roof; no insulation visible	g_m
464	527	51_15	Before 1957	531.48	4330718.6	3467500.94	g_m	n_m	old roof; no insulation visible	g_m
508	528	52_1	N_HR	54.36	4330696.46	3467497.32	n_m	n_m	storage shed	n_m
303	529	52_2	N_HR	212.32	4330708.45	3467494.85	n_m	n_m	storage shed	n_m
445	530	52_3	NB	739.31	4330711.4	3467464.24	m_m	m_m	insulation visible	n_m

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449	531	52_4	Before 1957	1760.19	4330766.21	3467470.97	g_m	n_m	old roof; no insulation visible	g_m
148	532	52_5	Before 1957	1400.78	4330796.85	3467461.4	g_m	n_m	old roof; no insulation visible	g_m
446	533	52_6	Before 1978	1569.22	4330718.79	3467435.64	m_m	n_m	old roof; no insulation visible	m_m
494	534	52_7	N_HR	74.36	4330721.86	3467414.93	n_m	n_m	storage shed	n_m
437	535	52_8	N_HR	0.00	4330746.22	3467398.96	n_m	n_m	garden shed	n_m
498	536	52_9	N_HR	1220.46	4330750.19	3467424.62	n_m	n_m	old roof; no insulation visible	n_m
448	537	52_10	Before 1918	1117.46	4330773.67	3467413.24	g_m	n_m	old roof; no insulation visible	g_m
164	538	52_11	Before 1957	1393.72	4330796.59	3467460.09	g_m	n_m	old roof; no insulation visible	g_m
474	539	52_12	N_HR	597.89	4330705.59	3467487.15	n_m	n_m	storage shed	n_m
135	540	52_13	N_HR	71.03	4330717.33	3467411.44	n_m	n_m	storage shed	n_m
505	541	52_14	Before 1978	98.19	4330735.48	3467415.48	g_m	n_m	garage	m_m
3	542	52_15	N_HR	664.23	4330743.4	3467415.67	n_m	n_m	garage	n_m
2	543	52_16	N_HR	274.09	4330749.39	3467415.97	n_m	n_m	garage	n_m
447	544	52_17	NB	691.03	4330762.13	3467419.42	m_m	n_m	old roof; no insulation visible	n_m
441	545	52_18	Before 1918	562.36	4330766.3	3467402.83	g_m	m_m	insulation visible	g_m
134	546	52_19	Before 1918	127.04	4330700.69	3467406.41	g_m	n_m	old roof; no insulation visible	g_m
147	547	52_20	Before 1918	770.98	4330751.3	3467338.66	g_m	n_m	old roof; no insulation visible	g_m
431	548	53_1	Before 1918	854.22	4330713.11	3467397.27	g_m	n_m	old roof; no insulation visible	g_m
432	549	53_2	Before 1968	1086.37	4330727.79	3467390.68	g_m	n_m	old roof; no insulation visible	g_m
436	550	53_3	Before 1918	1525.47	4330745.9	3467385.2	g_m	n_m	old roof; no insulation visible	g_m
439	551	53_4	Before 1918	736.28	4330759.36	3467394.98	g_m	n_m	old roof; no insulation visible	g_m
145	552	53_5	Before 1957	0.00	4330782.23	3467381.27	g_m	n_m	old roof; no insulation visible	g_m
442	553	53_6	Before 1918	0.00	4330775.38	3467372.49	g_m	n_m	old roof; no insulation visible	g_m
146	554	53_7	N_HR	0.00	4330783.37	3467366.71	n_m	n_m	storage shed	n_m
440	555	53_8	Before 1987	1201.89	4330766.27	3467360.69	m_m	n_m	old roof; no insulation visible	n_m
443	556	53_9	N_HR	27.01	4330781.58	3467358.64	n_m	n_m	storage shed	n_m
438	557	53_10	Before 1918	132.18	4330757.21	3467349.12	g_m	n_m	old roof; no insulation visible	g_m

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144	558	53_11	N_HR	29.58	4330767.06	3467346.76	n_m	n_m	storage shed	n_m
141	559	53_12	Before 1918	131.95	4330751.36	3467338.32	g_m	n_m	old roof; no insulation visible	g_m
139	560	53_13	Before 1918	131.40	4330745.79	3467329.66	g_m	g_m	new roof, insulation visible	g_m
143	561	53_14	N_HR	22.62	4330756.03	3467331.19	n_m	n_m	storage shed	n_m
140	562	53_15	N_HR	53.36	4330746.06	3467313.64	n_m	n_m	storage shed	n_m
138	563	53_16	Before 1918	261.68	4330738.82	3467323.26	g_m	n_m	old roof; no insulation visible	g_m
136	564	53_17	Before 1918	364.79	4330710.9	3467369.92	g_m	m_m	insulation visible	g_m
435	565	53_18	Before 1957	1173.04	4330733.44	3467360.22	g_m	n_m	old roof; no insulation visible	g_m
433	566	53_19	Before 1968	884.59	4330724.5	3467351.9	g_m	n_m	old roof; no insulation visible	g_m
428	567	53_20	Before 1957	1129.83	4330709.09	3467344.56	g_m	n_m	old roof; no insulation visible	g_m
127	568	53_21	Before 1918	1592.00	4330700.03	3467307.91	g_m	n_m	old roof; no insulation visible	g_m
142	569	53_22	N_HR	31.20	4330754.58	3467329.33	n_m	n_m	storage shed	n_m
161	570	53_23	N_HR	66.68	4330754.18	3467327.06	n_m	n_m	storage shed	n_m
489	571	54_1	Before 1968	928.72	4330699.78	3467258.46	g_m	n_m	old roof; no insulation visible	g_m
424	572	54_2	N_HR	141.33	4330722.77	3467258.56	n_m	n_m	storage shed	n_m
128	573	54_4	Before 1987	3126.69	4330716.49	3467285.31	m_m	n_m	old roof; no insulation visible	n_m
1	574	54_5	N_HR	1104.75	4330723.23	3467288.86	n_m	n_m	garage	n_m
221	575	55_1	NRB	1169.10	4330819.06	3467729.76	g_m	n_m	commercial use	g_m
224	576	55_2	NRB	1748.11	4330838.68	3467714.54	g_m	m_m	modernized roof	g_m
219	577	55_3	NRB	514.82	4330814.75	3467718.37	g_m	n_m	commercial use	g_m
487	578	56_1	NRB	3765.75	4330819.94	3467688.15	g_m	n_m	commercial use	g_m
227	579	56_2	NRB	2203.10	4330866.95	3467639.2	g_m	n_m	commercial use	g_m
480	580	57_1	Before 1987	891.30	4330809.89	3467542.45	g_m	n_m	old roof; no insulation visible	n_m
358	581	57_2	Before 1957	1071.14	4330832.19	3467534.95	g_m	n_m	old roof; no insulation visible	g_m
223	582	57_3	Before 1957	762.24	4330856.85	3467518.17	g_m	n_m	old roof; no insulation visible	g_m
216	583	57_4	Before 1957	804.36	4330845.93	3467505.9	g_m	n_m	old roof; no insulation visible	g_m
366	584	57_5	N_HR	64.93	4330829.39	3467512.31	n_m	n_m	garage	n_m

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478	585	57_6	Before 1968	830.86	4330818.25	3467493.54	g_m	n_m	old roof; no insulation visible	g_m
362	586	57_7	Before 1968	1224.36	4330887.37	3467508.08	g_m	n_m	old roof; no insulation visible	g_m
361	587	57_8	Before 1978	679.79	4330878.37	3467498.83	g_m	n_m	old roof; no insulation visible	m_m
215	588	57_9	N_HR	20.49	4330810.28	3467519.7	n_m	n_m	storage shed	n_m
509	589	57_10	N_HR	45.83	4330817.74	3467516.64	n_m	n_m	garage	n_m
356	590	58_1	Before 1957	821.52	4330818.55	3467492.55	g_m	m_m	modernized roof	g_m
357	591	58_2	Before 1957	925.26	4330832.41	3467489.33	g_m	n_m	old roof; no insulation visible	g_m
360	592	58_3	Before 1978	888.21	4330865.65	3467484.18	g_m	m_m	modernized roof	g_m
363	593	58_4	NRB	309.91	4330880.27	3467480.55	g_m	n_m	storage shed	g_m
451	594	58_5	Before 1918	215.24	4330796.75	3467397.55	g_m	n_m	old roof; no insulation visible	g_m
452	595	58_6	Before 1968	298.33	4330804.58	3467408.6	g_m	n_m	old roof; no insulation visible	g_m
352	596	58_7	Before 1968	983.97	4330814.22	3467421.74	g_m	n_m	old roof; no insulation visible	g_m
353	597	58_8	Before 1968	898.03	4330823.73	3467434.23	g_m	n_m	old roof; no insulation visible	g_m
354	598	58_9	Before 1918	730.17	4330830.81	3467445.1	g_m	m_m	insulation visible	g_m
355	599	58_10	NB	1266.79	4330845.52	3467455	g_m	m_m	glass building extensions, new roof	n_m
292	600	58_11	STC	30.73	4330774.45	3467413.3	g_m	n_m	commercial use	g_m
163	601	58_12	N_HR	53.44	4330786.79	3467398.75	n_m	n_m	storage shed	n_m
359	602	58_13	Before 1968	1292.79	4330862.3	3467446.5	g_m	n_m	old roof; no insulation visible	g_m
162	603	59_1	N_HR	88.89	4330802.55	3467393.1	n_m	n_m	storage shed	n_m
232	604	60_1	NRB	2008.55	4330905.83	3467663.2	g_m	n_m	commercial use	g_m
365	605	60_2	NRB	1765.93	4330910.63	3467605.76	g_m	n_m	commercial use	g_m
233	606	60_3	NRB	2197.85	4330963.17	3467659.02	g_m	m_m	modernized roof	g_m
234	607	60_4	NRB	0.00	4330957.13	3467678.4	g_m	n_m	commercial use	g_m
229	608	61_1	Before 1968	570.04	4330954.97	3467594.62	g_m	n_m	old roof; no insulation visible	g_m
364	609	61_2	Before 1918	1165.72	4330902.35	3467497.78	g_m	n_m	old roof; no insulation visible	g_m
231	610	61_3	Before 1957	248.18	4330972.4	3467562.99	g_m	n_m	old roof; no insulation visible	g_m
371	611	61_4	Before 1978	574.07	4330932.43	3467553.15	g_m	n_m	old roof; no insulation visible	g_m

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230	612	61_5	Before 1968	170.83	4330951.9	3467538.86	g_m	n_m	old roof; no insulation visible	g_m
225	613	61_6	Before 1957	788.09	4330912.24	3467527.23	g_m	m_m	modernized roof	g_m
228	614	61_7	Before 1957	544.32	4330921.27	3467521.15	g_m	n_m	old roof; no insulation visible	g_m
226	615	61_8	N_HR	168.47	4330917.69	3467536.35	n_m	n_m	garage	n_m