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High-resolution, spatial thermal energy demand analysis and workflow for a city district

Hermann Edtmayer[a*], Lisa-Marie Fochler[a], Thomas Mach[a], Jennifer Fauster[b], Eva Schwab[b], Christoph Hochenauer[a]

[a]*Institute of Thermal Engineering, Graz University of Technology, Inffeldgasse 25b, 8010 Graz, Austria*
[b]*Institute of Urbanism, Graz University of Technology, Rechbauerstraße 12/II, 8010 Graz, Austria*

ABSTRACT

Knowledge about the demand of renewable thermal energy is essential for the integrated planning of sustainable cities. Planners and decision-makers need high-quality and comprehensive data for rapid and decisive action. However, little to no corresponding information is available for the status quo or possible development scenarios. Thus, new methods for urban building energy modelling and simulation with high resolution and accuracy are needed. In this paper, we present the research we conducted on the thermal energy demand of a city district in Graz, Austria. We developed a novel bottom-up, white box, multi-tool workflow for performing large-scale and high-resolution modelling, simulation and analysis of urban buildings in different development scenarios. We calculated the demand for heating, cooling and hot water in full-year dynamic building simulations and assessed the results quantitatively and spatially. Our results in the Scenario 2050 show that despite massive densification of the building stock by 88%, the calculated heat energy demand rises only by 4%; while the cooling demand soars by 432%. All results are available as hourly mean values and annual totals and in easy-to-understand spatial map representations, thus supporting stakeholders to meet the net-zero CO_2-equivalent emission targets of Graz.

Keywords

Large-scale and high-resolution urban building energy modelling;
Thermal energy demand;
Spatial energy analysis;
Integrated city district development

Abbreviations

UBEM – Urban building energy modelling
IDA ICE – IDA Indoor Climate and Energy
AGWR – Austrian address, buildings and dwellings register (in German: *Adress-, Gebäude- und Wohnraumregister*)
3D CAD – Three-dimensional computer-aided design
PostgreSQL – Object-relational database management system
BIM – Building information modelling
UIM – Urban information model
LoD 2 – Level of Detail 2
IfcSpace – Specific building information modelling tool
KPI – Key performance indicator
GFA – Gross floor area
GIS – Geographic information system
IPCC – Intergovernmental Panel on Climate Change
RCP – Representative Concentration Pathway

*Corresponding author – e-mail: hermann.edtmayer@tugraz.at

1. Introduction

Cities have to cope with complex and interdependent challenges such as the climate catastrophe, population growth, environmental problems, increasing resource consumption, etc. The establishment of integral spatial energy planning is therefore becoming increasingly urgent. Also, for securing sustainable development using renewable energy systems [1] as well as ensuring a high quality of life in the city [2]. Integral spatial energy planning can be seen as a favoured method in contemporary city development for addressing climate adaptation and achieving sustainable resource efficiency [3].

For more than 40 years the inherent link between spatial- and settlement structures and energy consumption has been discussed. However, it is only in recent years that spatial energy planning has experienced an upswing in practice due to the necessity of climate protection and energy transition measures, as Giffinger et al. describe in their publication for Austria [4]. Facing these issues through an integral and transdisciplinary approach has become more immanent in contemporary planning practices of cities. Sassen [5] describes his view on the trend how city space becomes increasingly privatised through the lack of public planning. Senett [6] as well as Bauriedl and Stüver [7] state out the need for a better use of new (digital) technologies in smart city planning. However a complete integral approach including the consequences of different spatial (and not just building oriented) scenarios is still a novelty. Where, among other aspects, spatial development is carried out in close coordination with energy infrastructure development [8].

A key element of the current and future energy infrastructure of cities and urban districts is the renewable thermal energy supply of buildings for space heating and cooling as well as domestic hot water [9]. To be able to optimally plan this infrastructure, knowledge about the spatial distribution of the thermal energy demand in the considered area is of great importance [10]. Another aspect to take into account is the spatial and temporal location of energy resources. Csontos et al. describe their research work on how to spatially investigate the potential for renewable-based district heating in peripheral rural areas of Hungary [11]. Approaches using GIS-tools to spatially locate and analyse potential heat sources [12] or to assess the solar potential for photovoltaic and solar thermal energy in urban environments [13] are also described in the literature. Ideally, this planning would include also the creation of a comprehensive data set on the status quo and possible development scenarios, as described in various recent publications. For example by Nageler et al. [14] for the two Austrian cities Gleisdorf and Salzburg, by Mohajeri et al [15] for a Swiss village, by Muñoz et al. [16] for the city of Valencia or by Alexander et al. [17] for the greater Dublin region. Planners, energy supply companies and municipal decision-makers need reliable and comprehensive data upon which to base their decisions to transform current structures and implement sustainable energy systems, which different topical studies describe. For example by Bjelic et al. [18] for the energy planning in Serbia, by Duygan et al. [19] for the spatial and socio-economic analysis of smart city projects in Switzerland and by Yigitcanlar et al. [20] to describe the link between smart city concepts and carbon dioxide emissions in the UK. All too often, however, little to no information is available about the thermal energy demand of city districts on the building level [21]. The local energy supplier, funding agencies, or databases with energy performance certificates can serve as sources of information about the status quo, but data protection laws or corporate interests can hinder the disclosure of these data or block access to them altogether [22].

Planners working in the field of spatial energy planning may face an even bigger problem, because they often do not have any meaningful information about possible future spatial developments of the thermal energy demand on the building level. And, if they do, these are in most cases generally estimates obtained using relatively coarse resolution models that calculate statically rather than dynamically. For example to develop an open source data set for EU28+ described by Müller et al. [10], to develop integrated spatial and energy planning for the region of Styria in Austria described by Stoeglehner and Abart-Heriszt [23], both based on a top-down approach. To use energy performance certificate databases for urban energy modelling, like Mutani and Todeschi [24] or for building stock characterisation as described by Heidenthaler et al. [25]. This is very suitable for general energy analyses as well as for the analysis of energy systems and the integration of renewable energy sources. And it is also very useful for studying larger areas such as entire regions or countries. However, for energy planning of city districts on the building level, it is mandatory to model and simulate in higher resolution.

State-of-the-art methods are already used to model energy systems, thermal energy infrastructure or building energy demand. Prina et al. [26] present in their comprehensive literature review the classification and challenges of bottom-up energy system models. 13 short-term and 9 long-term models are analysed in terms of resolution in time, space, techno-economic detail and sector-coupling. Gholami et al. [3] describe in a comprehensive review methods applied in urban and regional integrated energy planning. Langevin et al. show in their review paper [27] how different common modeling approaches for building stock energy models can be classified. In the class of bottom-up white box urban building energy models various publications ca be found. For example the review of Oraiopoulos and Howard [28] examined studies that present validated models in terms of the accuracy in UBEM. Todeschi et al. evaluate in their publication on urban building energy modelling [29] urban-scale building energy-use models and tools. Or Neuman et al. [30] describe the use of a bottom-up district energy modelling approach in their case study on positive energy districts in Vienna. However, these methods need to be further developed to improve the ability to model and simulate entire city districts, their buildings, and energy infrastructure at higher levels of resolution and accuracy. Therefore, the approach in this study focuses on increasing the temporal, spatial and physical resolution of the model beyond the current state of the art. By using a geographical information platform in combination with a 3D CAD tool, a geo-referenced and detailed model of the considered urban district is built, which represents each usage category in each building floor in a single thermal zone. In conjunction with a building physics simulation environment, we have implemented a detailed dynamic building simulation model of the entire district under study.

Another problem is that the results of such analyses carried out by scientists and experts are often highly complex and difficult to understand for stakeholders which are not experts in the field such as political decision-makers, investors or citizens [31]. To successfully implement sustainable and integrated smart city projects with a high share of renewables in the energy supply, it is necessary to involve all stakeholders to the same extent and at eye level. Therefore these results need to be translated into information that can be easily understood by all stakeholders involved in such development projects [32]. Hans Rosling and his famous TED talks [33] are a great example of how dry and complex statistical data can be presented in an interesting way that everyone can understand. To present the data in the desired form, new digital workflows for spatial energy analysis of urban districts are needed and therefore must be developed.

In this paper we present the results of an analysis of the thermal energy demand for a city district in Graz, Austria. The research project was carried out in the course of a long-term smart city initiative of the city of Graz and was therefore part of a sustainable and integral urban development [34]. The research questions addressed in this paper and worked on in the course of the research project are: Is it possible to create a large-scale analysis model for the thermal energy demand of the urban area under consideration, which has a significantly higher spatial and temporal resolution and thus more detailed results than the models available so far? And is it possible to automate the processing of the input data for the model, which is available from a variety of sources, to a higher degree than before, in order to enable the modelling and evaluation with the available resources? Can the status quo and different urban development scenarios be represented in this model and analysed in terms of thermal energy demand? Is it possible to analyse and process the research results in a way that enables research-to-public communication in order to inform and involve all important stakeholders in a higher quality than is currently possible? And finally, can a workflow be developed that combines all these questions and can thus be used as a model for future projects?

To address these questions, we developed a novel multi-tool workflow for high-resolution urban building energy modelling (UBEM). The aim was to thermally analyse the urban area under consideration both in its current state and in various sustainable urban development scenarios. The scenarios consider various factors of change such as population growth, demographic change, changes in mobility and resource consumption, as well as the provision of climate-adapted green spaces. In the analysis we simulated the energy demand of all buildings in the district for heating, cooling and hot water in bottom-up, whole-year detailed and dynamic multi-zone building simulation in the tool IDA ICE [35] and assessed the energy demand quantitatively and spatially. To present the results in a comprehensible and meaningful way, we post-processed them both in total figures and in geo-referenced, spatial map representations.

2. Multi-tool workflow and design of the scenarios

In this study we have developed a novel bottom-up, white box, multi-tool workflow for performing large-scale and high-resolution modelling, simulation and analysis of the energy demand of urban buildings. Applying this workflow provided a reliable and comprehensive dataset on thermal energy demand and its spatial distribution in different development scenarios for an urban district in Graz, Austria. We analysed the thermal energy demand of the buildings in a city district in terms of heating, domestic hot water and cooling. We post-processed the simulation results in the form of overall numbers and geo-referenced map representations in order to produce results that could be easily understood by all stakeholders involved.

To perform this analysis, we developed the novel workflow for urban building energy simulation based on a previously developed tool for automated urban building energy simulation described in several publications of Nageler et al. Publication [36] describes the prototype in whole, [37] the method to simulate large-scale thermal city models and [38] shows the validation of the method with consumption data available from buildings of the town Gleisdorf in Austria. In this workflow we process all available data of the buildings and ambient conditions into a newly developed 3D CAD urban information model (UIM). We designed UIM models for different simulation scenarios such as the status quo and two future sustainable urban transition perspectives. Subsequently, we stored all available and generated data in a central PostgreSQL [39] database. The automated urban building modeller uses the information from the database to generate simulation models for the simulation platform IDA ICE for each scenario. We then simulated each developed model in a dynamic building energy simulation for the timespan of one year. The simulation results consisting of hourly mean values of the targeted quantities were fed back into the database and post-processed to obtain the final results.

2.1. Multi-tool workflow

The developed, specific multi-tool workflow consists of five processing steps (Figure 1): 1) Obtain the data input from the stakeholders, 2) process the data into a geo-referenced 3D CAD city model (urban information model), 3) import the city model into a central database, 4) create building simulation models automated and simulate them dynamically, 5) analyse and process the results and feed them back to the stakeholders.

2.1.1. Input data from stakeholders

First, the input data were collected from several different stakeholder sources. The geometric 2D basis of the city model was created from the available cadastral data. This basis includes information on georeferencing, address data, year of construction as well as the building height and number of floors. The usage category (e.g. residential or office building) was assigned using data from the Austrian Address, Buildings and Dwellings Register (AGWR) [40]. The floor and room height were calculated specifically for each usage category from the building height and the number of floors. The renovation status for part of the buildings could be determined by examining a building renovation funding database [41]. In addition, high-resolution aerial photographs (oblique, orthophoto, and thermal scan) were available that supported the evaluation of the building data.

2.1.2. Urban Information Model

The previously described geometries and data were further processed with a geo-referenced 3D urban information model using the 3D CAD tool Vectorworks [42] (Figure 2). In this model, each building is represented with a resolution of one floor (Level of Detail - LoD 2 [43]) using the building information modeling

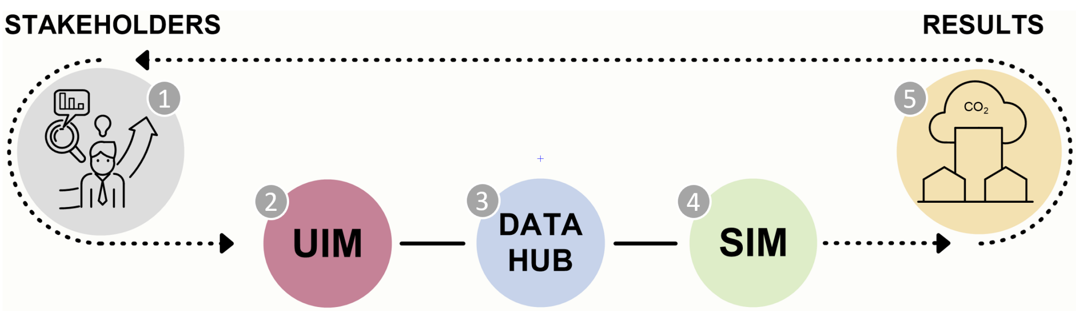

Figure 1: Process steps and order of the newly developed multi-tool workflow

Figure 2: Input data from stakeholders assigned to the geo-referenced 3D CAD city model (urban information model).

(BIM) method and the BIM tool IfcSpace [44]. BIM is a digital process structure that involves the creation, management and sharing of 3D CAD models in combination with other relevant data on the planning, design, construction and operation of buildings and infrastructure. The BIM element that represents the floor or thermal zone in 3D serves as a data container. The use of these geometric units in the UIM model enable automatic processing, numerical evaluation and graphical analysis. This method was used to design and analyse development scenarios and to carry out the status quo investigations.

2.1.3. Data hub

In the next sIn the next step, the data pre-processed in the UIM were imported into the data hub in the form of shape files. This data hub contains different georeferenced PostgreSQL databases for the individual development scenarios (project databases), as well as a typology database with general data from the literature on, e.g. building archetypes, materials or user profiles. A detailed description of the database design can be found in the publication of Nageler et al. [38]. The results of the building simulation, which is described in the next step, were also fed back into the databases of the scenarios. All of the information required for modelling, simulation, and evaluation was thus collected in this data hub and could be extracted using various tools in the following process steps.

2.1.4. High-resolution urban building modeling and simulation

Subsequently, a high-resolution building simulation model for the entire district was automatically generated for each scenario. To perform this step, we used a previously developed automated urban building modeler [36,38,45]both researchers and enterprises require ever more complex modelling and simulation methods. This has resulted in the need for new approaches that can be taken to create large-scale simulations as well as new methods to clearly visualize their dynamic simulation results. This study presents a prototype of a

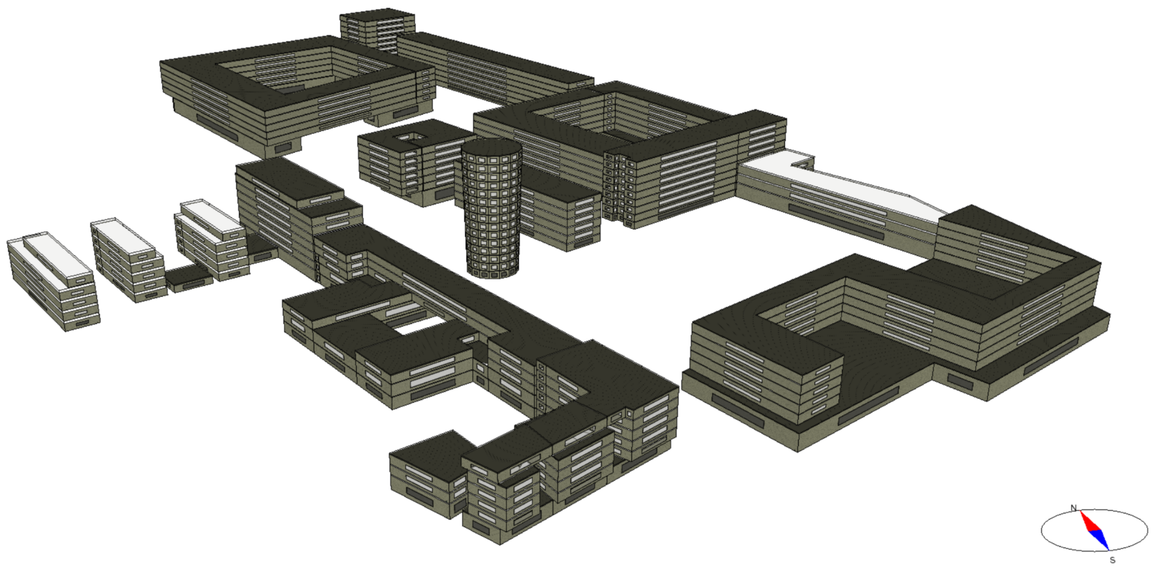

Figure 3: High-resolution urban building simulation model in IDA ICE for the “My Smart City Graz” city district segment of the 2030 Scenario.

simulation framework for large-scale simulations of district energy systems that offers three main advantages compared to the state of the art: (i to generate the models for the building simulation tool IDA ICE. Figure 3 shows a segment of the “My Smart City Graz” district under consideration in the 2030 Scenario. More information about this scenario and model is presented in section 2.2. The modeler processes the building data stored in the database together with information extracted from the typology database. In this step, each usage category in each building floor was modelled separately as one thermal zone. The result is a georeferenced building simulation model of all buildings in the district. A dynamic building simulation to analyse the buildings thermal performance over time under various environmental factors was then carried out with the district model of each scenario for the period of one year. Thereby the heat energy demand (required for heating and providing domestic hot water) and the cooling energy demand of each thermal zone was calculated in hourly mean values.

2.1.5. Post processing

Finally, in the post-processing step, the geo-referenced simulation results for each building in each scenario were fed back into the data hub and stored in the database. The results were spatially processed and analysed with the geo-information tool QGIS [46]. Whereby different spatial map representations showing various important key performance indicators (KPIs) were produced. Further analyses of the energy performance were carried out and core statements made about the thermal energy demand using SQL code to query the database or data processing software such as Microsoft Excel or Python. This allowed us to present highly complex energy systems and their behaviour in ways that could be understood by all stakeholders involved. Finally, the analyses were fed back to the stakeholders as part of the project, giving them the opportunity to ask questions and answers to be provided. These feedback loops were carried out several times with the stakeholders involved in the work presented here.

2.2. Design of the scenarios

The simulation models developed for the city district under consideration include the building development and use in three scenarios. The first scenario comprises the status quo of the current building stock based on the data status which was available for the year 2018 (Scenario 2018). The second scenario adds the Smart City district “My Smart City Graz” in the final development stage in 2030 (Scenario 2030) to the first scenario.

The third scenario (Scenario 2050) consists of a sustainable planning scenario that emerged from socio-ecological and spatial analysis and urban scenario developments which focus on circular, resource efficient and socio-ecological quality of urban space. Several different previously investigated development approaches were synthesised in this scenario. Each focusing on one specific topic, namely through resource efficiency, sharing and communal infrastructure, as well as a combination of situations of work/life. In Figure 4, the 3D CAD models of the three different scenarios are shown with the changes in the scenarios depicted in colours. Red indicates the added "My Smart City Graz" district, and yellow indicates the sustainable urbanism development study.

2.2.1. Scenario 2018 – status quo of the city district

In Scenario 2018, all available data from the year 2018 were included in the model. The general structural data for the buildings in this scenario are shown in Table 1.

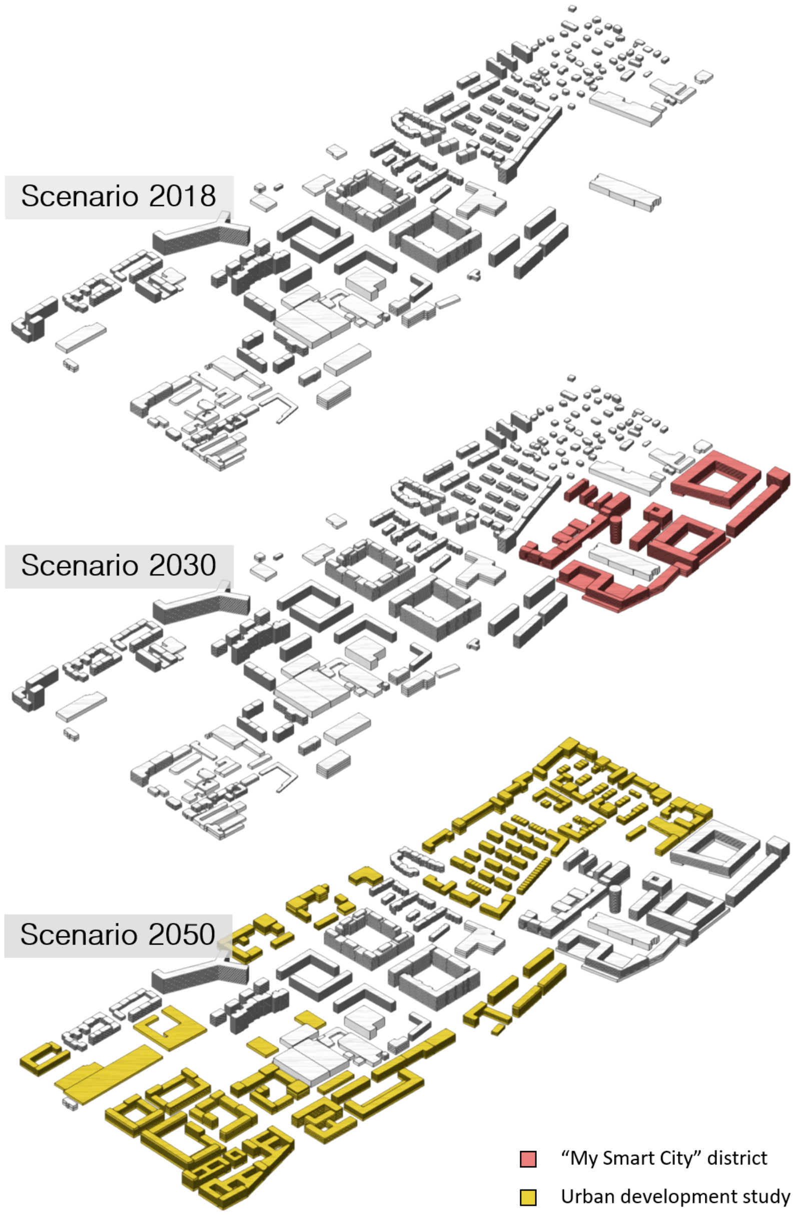

Figure 4: Comparison of the three scenarios used in this study. (Top) Scenario 2018 with data status quo for the year 2018; (middle) Scenario 2030 with the "My Smart City Graz" district currently under construction depicted in red; (bottom) Scenario 2050 with the synthesised urban development study for a possible development of the district. Differences from Scenario 2030 are depicted in yellow.

The model was designed by applying the following boundary conditions:

- Climatic boundary conditions: climate for the city of Graz in 2018 according to measurement

Table 1: Structural data for the buildings in Scenario 2018

Number of buildings	261
Number of thermal zones	904
Total building footprint	120 630 m²
Total conditioned building gross floor area	413 111 m²
Total conditioned building gross volume	1 625 284 m³

Scenario 2030 – status quo plus "My Smart City Graz" district

Table 2: Structural data for the buildings in Scenario 2030

Number of buildings	283
Number of thermal zones	1 037
Total building footprint	152 424 m²
Total conditioned building gross floor area	591 186 m²
Total conditioned building gross volume	2 247 660 m³

data from the Austrian Central Institute for Meteorology and Geodynamics ZAMG [47]

- Building geometry design: one volume element and thermal zone per floor according to cadastral and dwellings register data
- Construction of the building envelope: minimum thermal insulation according to the Austrian building standard OIB-RL6 [48]; when information was available from the building renovations funding database, the standard refurbishment type according to TABULA [49,50] was applied
- Building supply system: ideal heating and ideal cooling according to the IDA ICE user manual [51]
- Assumptions of usage: definitions of building usage categories as in the Austrian building standard OIB-RL6 [48], with usage according to the available AGWR (data per floor and usage profiles according to SIA2024:2015 [52])

2.2.2. Scenario 2030 – status quo plus "My Smart City Graz" district

In the design of the 2030 scenario the "My Smart City Graz" district was added to Scenario 2018. Figure 5

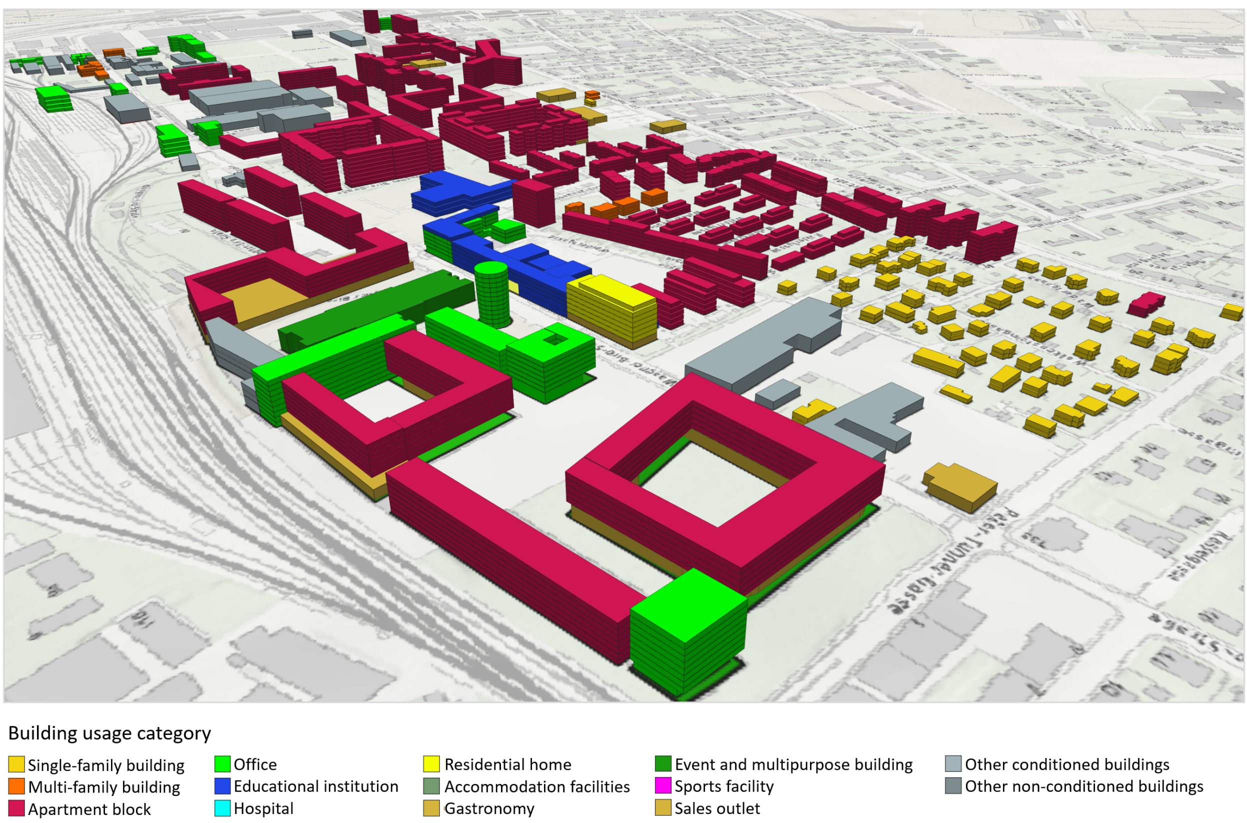

Figure 5: 3D CAD design of Scenario 2030 with the usage categories of building floors depicted in different colours.

shows the 3D CAD design of Scenario 2030 with the usage categories of the building floors depicted in different colours. This district is currently under construction and is expected to be finished by the year 2030. The general structural data for the buildings in Scenario 2030 are shown in Table 2. The model was designed by applying the boundary conditions from Scenario 2018 as well as:

- "My Smart City Graz" building design, construction data and usage categories according to the architectural design of the district.

2.2.3. Scenario 2050 – synthesised sustainable urban development study

This scientific approach to creating future-oriented designs for the urban district was developed in the context of sustainability, resource efficiency (land, water, etc.) and high quality of socio-ecological dimensions of urban space and life. The approach involved considering a sustainable life cycle (robustness and adaptability of the building structures) and development concepts that support sustainable mobility, provide public green and open spaces and encourage sustainable resource consumption through establishing "mixed use" e.g. linking functions of living and working. Through the entanglement of existential needs for living, an increase in the proportion of collectively and publicly used infrastructure was established. The remodelling and renovation of existing buildings, as well as targeted redensification, unsealing of infrastructure areas and the creation of biodiverse and climate-friendly green spaces, a resource-conserving and resource-efficient urban district was designed.

In the Scenario 2050 simulation model, we varied parameters such as the building design, building hull quality and usage class, and the predicted outdoor temperature. In Table 4 the settings for the varied boundary conditions in each scenario are compared. General structural data for the buildings in Scenario 2050 are shown in Table 3. The model was designed by applying the following boundary conditions:

- Climatic boundary conditions: outdoor temperatures for the city of Graz based on the climate prediction model IPCC RCP 8.5 [53,54] for the year 2050; temperature time series in hourly mean values created with Meteonorm [55]
- Building geometry design: one volume element and thermal zone per usage category (more than one zone per floor possible); this corresponds to Scenario 2018 for the unmodified building stock and according to the urban development study for the modified buildings
- Construction of the building envelope: the standard refurbishment type according to TABULA [49,50] was applied to all buildings regarding the thermal insulation
- Building supply system: ideal heating and ideal cooling according to IDA ICE user manual [51]
- Assumptions of usage: definitions of building usage categories as in the Austrian building standard OIB-RL6 [48], data similar to Scenario 2018 for the unmodified building stock and according to the urban development study for the modified buildings; usage profiles according to SIA2024:2015 [52];

Table 3: Structural data of the buildings in Scenario 2050

Number of buildings	310
Number of thermal zones	1 199
Total building footprint	196 169 m²
Total conditioned building gross floor area	775 291 m²
Total conditioned building gross volume	2 857 876 m³

Table 4: Settings of the boundary conditions in each scenario

Boundary conditions	Scenario 2018	Scenario 2030	Scenario 2050
Climate	Measurement data 2018	Measurement data 2018	IPCC RPC 8.5 prediction
Volume elements and thermal zones per floor	One	One	Multiple
Building envelope per usage category	OIB-RL6 standard or TABULA standard	OIB-RL6 standard or TABULA standard	TABULA standard
Usage category source	AGWR	AGWR 'My Smart City Graz' design	AGWR 'My Smart City Graz' design Urban development study

3. Results and discussion of the simulation and workflow

To provide the involved stakeholders with the desired information about the current and future thermal energy demand of the buildings in the investigated urban area, we first modelled the buildings of the different development scenarios in single storey resolution. A dynamic building simulation was then carried out with the district model of each scenario for the period of one year to calculate the heat energy (required for heating and providing domestic hot water) and the cooling energy demand. The result is the georeferenced thermal energy demand in the form of hourly mean values for each thermal zone in the buildings of all district scenarios. We then analysed the results to extract the most important findings and subsequently translated them into representative map depictions to make them easier to understand.

3.1 Sensitivity analysis of the thermal energy demand in the three scenarios

Table 5 shows the gross floor area (GFA) of the buildings in the studied city district for each scenario. A distinction is made between total GFA and the individual usage categories *housing, office* and *miscellaneous*. In addition, the relative percentage change in GFA between the scenarios in these categories is shown. The total GFA increased from initially around 413 000 m^2 in Scenario 2018 to around 775 000 m^2 in Scenario 2050, which represents an increase of 88%. The usage category *office* thereby recorded the highest growth of around 170 000 m^2 or 593%.

The output of the urban building energy simulation consists of the heat (heating + domestic hot water) and cooling energy demand in hourly mean values over a whole year for each building in each scenario. Table 6 shows the annual sum of the heat energy demand for the individual scenarios. Again, a

Table 5: Gross floor area of the buildings in the investigated city district; in total, for different usage categories and relative change between the scenarios.

	Gross floor area in m^2			
	Total	Housing	Office	Miscellaneous
scenario 2018	413 111	324 760	28 615	59 736
Scenario 2030	591 180	413 008	73 793	104 379
Scenario 2050	775 291	430 512	198 287	146 492
	Relative change			
2018 to 2030	43%	27%	158%	75%
2030 to 2050	31%	4%	169%	40%
2018 to 2050	88%	33%	593%	145%

Table 6: Heat energy demand of the simulated buildings for one year in each scenario and relative change between the scenarios.

	Heat energy demand in MWh/a			
	Total	Housing	Office	Miscellaneous
scenario 2018	41 239	23 041	1 730	16 468
Scenario 2030	48 336	26 222	3 343	18 770
Scenario 2050	42 792	20 925	6 505	15 363
	Relative change			
2018 to 2030	17%	14%	93%	14%
2030 to 2050	-11%	-20%	95%	-18%
2018 to 2050	4%	-9%	276%	-7%

Table 7: Cooling energy demand of the simulated buildings for one year in each scenario and relative change between the scenarios.

	Cooling energy demand in MWh/a			
	Total	Housing	Office	Miscellaneous
Scenario 2018	2 230	1 733	168	329
Scenario 2030	3 439	2 300	492	648
Scenario 2050	11 867	5 242	2 764	3 861
	Relative change			
2018 to 2030	54%	33%	193%	97%
2030 to 2050	245%	128%	462%	496%
2018 to 2050	432%	203%	1546%	1072%

Table 8: Heat energy demand related to the supplied GFA, comparison of the three scenarios.

	Heat energy demand in kWh/(m^{2}a)			
	Total	Housing	Office	Miscellaneous
scenario 2018	100	71	60	276
Scenario 2030	82	63	45	180
Scenario 2050	55	49	33	105

Table 9: Cooling energy demand related to the supplied GFA, comparison of the three scenarios.

	Cooling energy demand in kWh/(m^{2}a)			
	Total	Housing	Office	Miscellaneous
scenario 2018	5	5	6	6
Scenario 2030	6	6	7	6
Scenario 2050	15	12	14	26

distinction is made between the total sum of all thermal zones in the buildings and the distribution to the individual usage categories, and the relative change is listed. In total, the heat energy demand increases by 17% from Scenario 2018 to 2030 and decreases again by -11% until Scenario 2050, which results in a total change of plus 4%.

Table 7 shows the cooling energy demand in the same way as Table 6 shows the heat energy demand. For the cooling energy demand, there is a total increase of 432% from Scenario 2018 to 2050. The *office* sector shows the largest percentage increase with 1546%. The absolute increases are the same for *housing* and *miscellaneous* with around 3500 MWh/a and lower for *office* with around 2600 MWh/a.

If the sum of the thermal energy demand per year is related to the gross floor area supplied, the results in Table 8 clearly show that the total heating demand per supplied square metre drops continuously across the three scenarios to almost half of the initial value. Thereby the usage category miscellaneous shows the most significant drop by around -62%. The total cooling demand shown in Table 9, on the other hand, triples over this time. Especially for the usage category miscellaneous, the increase in specific cooling energy demand from 6 kWh/(m^{2}a) to 26 kWh/(m^{2}a) is particularly significant.

3.2. Map depictions and distribution of the thermal energy demand in the three scenarios

Figure 6 shows the post-processed and edited data in the form of geo-referenced map representations and of overall values. The top of this figure shows the distribution maps for the cooling demand in the district; the heat demand appears at the bottom of the figure. In the middle, a breakdown can be seen of the absolute numbers in terms of heat and cooling demand and gross floor area in the form of bar charts. The map depictions show the absolute cooling demand distribution in shades of blue, and the heat demand distribution is shown in yellow to red shades (heating + domestic hot water) in the form of heat maps as total energy demand per year (MWh/a). The colour intensity matches the local energy demand intensity, meaning that darker colours symbolise higher demand, and lighter colours, a lower demand. The solid lines show the contour plots of levels with a constant demand at equal intervals. The bar charts show the absolute values of the energy demand and the gross floor areas for each scenario.

What first catches the eye when we examine these results is that the cooling demand increases massively as we move from the status quo to Scenario 2030 and then on to Scenario 2050. An increase of about 54% can be observed in Scenario 2030 with the completion of the "My Smart City Graz" district. This is clearly visible in the upper right-hand corner of the cooling demand distribution map (#1). The bar charts also clearly reflect this change. At the same time, the total heat demand increases by only around 17% (#2). The conditioned GFA thereby increases by 43% from around 413 000 m^2 to 591 000 m^2.

If we examine Scenario 2050 more closely, we see a massive rise in cooling demand of around 432% (#3). In the map representations, we can see this both in areas where the building construction has remained the same, e.g. (#4), and where the building structure has been modified, e.g. (#5). In Scenario 2050, the GFA has increased by a total of 88% to 775 000 m^2 (#6), which leads to an additional cooling energy demand. In contrast, the heat energy demand decreases again between Scenario 2030 and Scenario 2050, resulting in an overall increase of only 4% (#7) although the conditioned GFA has increased significantly. The effect of lowering the heat energy demand by applying the good insulation standard of the newly built buildings is illustrated, for example, in (#8) in Scenario 2050. In addition, the effects of the expected influence of global warming by that year are seen in (#9), where the building structure remains the same between Scenarios 2030 and 2050.

3.3 Discussion of the results and the workflow

The results of this analysis indicate that a massive increase in the cooling energy demand (i.e. around 432%) will occur in the district under study by the year 2050 (Scenario 2050) due to the influence of climate change and the associated increase in the outdoor temperatures. The densification of the built environment through urban development reinforces this effect. The distribution of this demand and its magnitude will be spatially heterogeneous. Although the building structure in this scenario was designed in a scientific development study and may not correspond to the real building structure that will be present in 2050, we expect a similar development of the conditioned GFA and, thus, a similar increase in the cooling energy demand in terms of absolute numbers.

These results show how strongly the variance of cooling and heat energy demand is formed over the different scenarios and that external factors such as global warming or the urban development strategy of the city area have a significant influence on this. The neighbourhood developments planned today, including buildings and energy infrastructure, still need to work well in 2050. By this year, however, boundary conditions such as the effects of global warming can change or will have changed significantly. For this reason, planners need to have tools that enable them to predict future effects and take these into account in their current planning. To meet the increasing demand for cooling, more electrical energy is either needed to drive the chillers or alternative sources such as district cooling or cooling with groundwater must be used. In any case, the current infrastructure must be adapted to this or new, ideally more efficient infrastructure must be built. This challenge should be addressed at an early stage by taking appropriate, multi-layered measures in urban development. Furthermore, we can clearly see how renovation measures influence the energy efficiency of buildings and taking such measures can reduce CO2-equivalent emissions. As time is short, and the technological transition presents many challenges, decision-makers urgently need to take rapid and decisive action.

Compared to the previous work conducted by Gholami et al. described in their review paper on spatial energy planning [3] and also work we previously published on the topic of automated urban energy modelling and simulation, see Nageler et al. on the method in [36], on the Co-simulation workflow in [56] and in the report [57] on the application in two cities as well as Edtmayer et al. on the modelling and analysis of a low temperature heating network in [58], we were able to increase the degree of automation and thus the model resolution and at the same time the model size by developing this novel extended workflow. Furthermore, we were able to

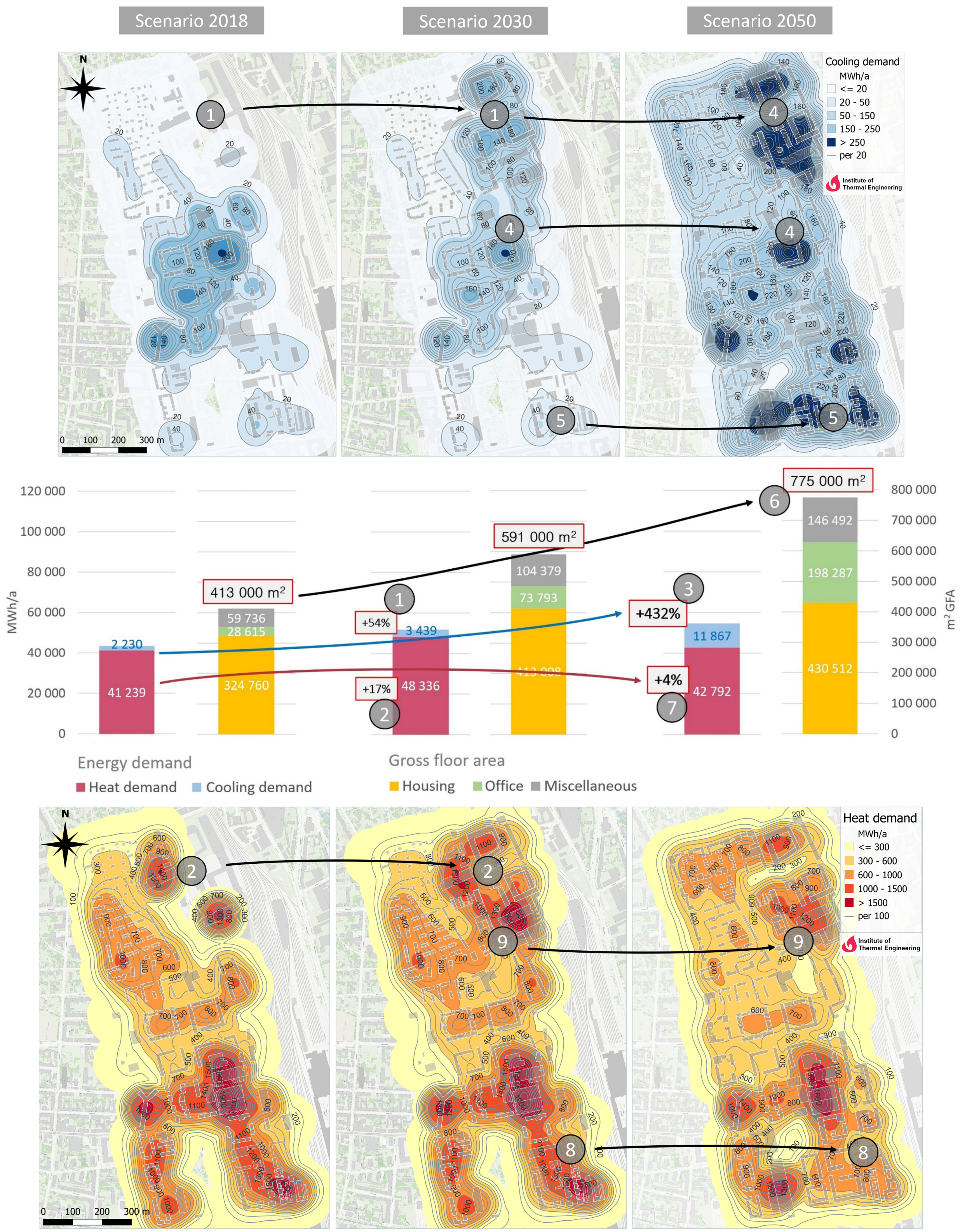

Figure 6: Comparison of the different scenarios of the district under consideration: heat map, contour plot, and absolute numbers for the calculated energy demand. (Top) cooling demand. (Middle) energy demand and gross floor area breakdown. (Bottom) heat demand (heating + domestic hot water).

improve the preparation of the input data and make them available for many different processing options via the UIM. With the preparation of the simulation results in the form of heat maps and contour plots, we were able to take a further step towards making the research results accessible to a wider range of stakeholders.

At the same time, our methodology and workflow still have a number of limitations. In our case, everything related to the topic of "data availability" still presents a big problem. The quality of the status quo data, such as those for building dimensions, structure, usage, type of heating system, refurbishment status, and so on, is often low. Sometimes the data are difficult or even impossible to access. In many cases, no data are available at all. The reasons for this include the still-low standard in digitalisation as well as legal obstacles related to data security and a lack of knowledge about it.

These limitations lead to a reduction in model precision. In some cases, the building models can only be created by making relatively rough assumptions. One example is the TABULA database on building typologies. These only represent a general average of the building structure in Austria. For some buildings, such as residential buildings, these assumptions fit relatively well, but for, e.g. event and multipurpose buildings, these can deviate strongly from reality. Furthermore, no standards are defined for industrial buildings in the TABULA project or the Austrian building standard OIB-RL6, and comparable data from other sources are still missing. The district investigated here, however, contains some industrial and factory buildings, and we could only provide coarse estimates for these in our study.

Furthermore, our results indicate that it is important to know how the status quo is in terms of energy efficiency and climate protection measures. But the various current climate assessment reports, see the IPCC 2014 [53] and 2016 [59] synthesis report, the climate protection reports for Austria [60] and Germany [61] already tell us that we are far from meeting our 2050 net-zero CO2 emission targets. For exactly this reason, our simulation models for development scenarios – purely because they allow us to make clear statements about the effects of structural measures – represent an important and effective tool for planners and decision-makers, enabling them to design a sustainable and integrated urban environment.

Another problem we faced is the lack of measurement data to validate the simulation models. Stakeholders such as energy suppliers who have access to such data do not normally share it in order to protect company interests. Data security is also often cited as an argument for restricting access. Our intensive efforts to overcome these restrictions in this regard have so far been unsuccessful. The results of several previous studies we conducted, especially the model validation presented by Nageler et al. in [38,62] and Schweiger et al. in [63] as well as the comparison of the IDA ICE model with other simulation tools presented by Nageler et al. in [37,64] and Schweiger et al. in [65], however, lead us to conclude that the simulation models used provide reliable results for this study.

Our vision for the future is to investigate development scenarios for entire cities in terms of their thermal energy demand and its spatial distribution. We see a research potential to further develop our workflow to model a larger number of buildings or thermal zones at higher levels of resolution. Therefore, we plan to further increase the degree of automation and improve the potential to create (even) more accurate models. As a subsequent development step, we are currently working on integrating the infrastructure of the thermal energy supply system into our simulation models. Furthermore, the area of data post-processing is one that requires significant advances in order to obtain more understandable and meaningful results. We have launched a new research project [66] on this topic, and specifically on energy modelling and analysis of urban buildings in combination with virtual reality, to create interactive and immersive virtual communication environments.

Changing microclimates through urban heating and heat island effects [67,68], an increase in CO2-equivalent emissions and ground sealing of areas due to demographic pressure [69], as well as its topographical location in a basin has led and will continue to lead to drastic temperature and wind speed increases over the course of the next decades. Therefore, more consideration should also be given to investigate the relationship of heating/cooling demands and the design of outdoor space, with the ratio of sealed soils, shade through vegetation etc, as well as the location of buildings with regards to existing wind directions.

The entire multi-tool workflow has been designed such that it can be further developed for application to topics like these. These could include a systematic microclimate analysis of city districts to investigate urban heat islands and their influence on the building climate. Or the application of quality assessment tools such as the Austrian klimaaktiv standard [70] for individual buildings [71] could be automated and applied to the modelling and simulation of entire city districts.

4. Conclusion

In summary, we have developed a novel bottom-up, white box, multi-tool workflow for performing large-scale and high-resolution modelling, simulation and analysis of the energy demand of urban buildings. Applying this workflow provided a reliable and comprehensive dataset on thermal energy demand, its magnitude and spatial distribution in different development scenarios for an urban district in Graz, Austria. This workflow can now be used by planners, energy supply companies and municipal decision-makers involved in the development of urban districts and their energy infrastructure.

In developing the workflow, we were able to increase the degree of automation and thus the model resolution and at the same time the model size. We were also able to improve the preparation of the input data and make them available for many different processing options through the UIM. With the preparation of the simulation results in the form of heat maps and contour plots, we were able to take a further step towards making the research results accessible to a wider range of stakeholders.

The results of the analysis of the district's thermal energy demand also show that a massive increase in cooling demand of about 432% is to be expected by 2050 (see Scenario 2050), and that the spatial distribution of this demand and its magnitude in the district will be heterogeneous, no matter which scenario we consider. At the same time, we expect the demand for heat energy to increase only slightly, i.e. by around 4%, despite the massive growth by 88% in terms of thermally conditioned gross floor area in this scenario.

These findings demonstrate how important it is for planners and decision-makers to have access to spatially mapped energy demand data. This is particularly important for their evaluation of different planning scenarios, as it enables them to assess the effects of different measures taken. By using the developed workflow, the results of studies on the thermal energy demand of urban districts have become easily accessible to all stakeholders involved. They can now further develop urban structures systematically in an energy-efficient manner and adapt these in response to climate change. In addition, energy planners can specifically adapt the energy supply infrastructure to fit the level and spatial distribution of the demand, creating more efficient and resilient designs; thus, it actively contributes to the efforts of stakeholders to provide a CO_2-neutral energy supply by 2050 for the city of Graz.

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Declaration of author contributions

H. Edtmayer: Writing - Original draft, Writing - Review & Editing, Conceptualization, Methodology, Investigation, Validation, Formal analysis, Visualisation, Software

L-M. Fochler: Conceptualization, Methodology, Software, Visualisation, Investigation

T. Mach: Conceptualization, Writing - Review & Editing, Supervision, Project administration, Funding acquisition, Resources

J. Fauster: Writing - Original draft, Conceptualization, Methodology, Investigation, Formal analysis, Visualisation

E. Schwab: Conceptualization, Writing - Review & Editing, Supervision, Project administration, Funding acquisition, Resources

C. Hochenauer: Writing - Review & Editing, Supervision, Resources

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