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UserGRIDs - User-Centered Smart Control and Planning of Sustainable Microgrids

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UserGRIDs

User-Centered Smart Control and Planning of Sustainable Microgrids

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1 Introduction

Greenhouse gas emissions caused by energy consumption in the building sector must be massively reduced in the coming years. Improvements in the thermal insulation of buildings and the increased use of renewable energy sources in the energy supply are proven measures.

If we extend the consideration from individual buildings to entire urban neighbourhoods or districts, additional reduction potential can be tapped. The information and energy technology networking of individual buildings to form a micro grid opens up opportunities for more efficient operational management and targeted planning of sustainable transformation. However, the number of buildings in a micro grid and the interactions that need to be taken into account increase the complexity.

The UserGRIDs project is based on the assumption that this complexity can be overcome through the increased use of new digital technologies and that, as a result, significant improvements in the energy behaviour of urban units can be achieved. The overarching project goal is to use the continuously growing possibilities of digital methods and tools to minimise the greenhouse gas emissions induced by energy consumption of urban energy systems.

The digital methods and tools developed in the UserGRIDs project were organised into eight digital energy services in a modular structure. The development, implementation and evaluation of the services took place as realistically as possible. Graz University of Technology's largest campus, which will be developed into the Innovation District Inffeld by 2030, served as the development environment. The basis is formed by a data model to describe the energy-related infrastructure, which acts as a "single source of truth" and an IoT platform in which energy-related sensor data were bundled and stored.

The functionalities of the digital energy services are aimed at two approaches:

- An **Energy Management System** (EMS) utilises predictive control methods, weather forecasts and real-time user assessments to provide optimal control schedules for heating and cooling of buildings. The aim is to achieve high energy efficiency, minimise greenhouse gas emissions and maximise user comfort.

- The **Energy Structure Planning** focuses on the further development and expansion of the energy supply and consumption infrastructure. Transient simulation models are used to analyse transformation and expansion scenarios in terms of functionality and efficiency.

The project idea is also based on a broad interdisciplinary and inter-institutional approach. All key **stakeholders** of the case study Innovation District Inffeld are directly involved, resulting in a correspondingly broad and heterogeneous project consortium.

1.1 Reference to superordinate goals

The UserGRIDs project fits seamlessly into the objectives of the programme “Vorzeigeregion Energie” and is a cornerstone in the development of a sustainable TU Graz.

- The project develops digital energy services for city districts, which support energy efficiency, renewable energy sources, coupling between heating, cooling and electricity, aiming to reduce greenhouse gas emissions. UserGRIDs implements and evaluates these services at a district and makes corresponding model solutions available for reproduction. This matches with the designated target *“... development and model use of local energy and energy-related transport technologies for the large-scale field testing of intelligent system solutions in live operation* [[1]]”.

- In UserGRIDs an established and capable consortium of science, energy suppliers, control system developers, component manufacturers and property managers has set itself the goal of defining model solutions and bringing the findings to the national and international market in appropriate business models. This fits to *“…Strengthening and developing Austria as a lead market for innovative energy and energy-related transport technologies and services* [[1]]”.

- UserGRIDs implements and evaluates methods and tools for direct user participation for a whole district. The development process is guided by broad stakeholder management to ensure acceptance. This corresponds to the target *“… Involvement and active participation of users* [[1]]”.

Sustainability approach at TU Graz

The development of the UserGRIDs project and the definition of the associated objectives are directly linked to TU Graz's activities to promote sustainable development within the organisation. The "Sustainability Advisory Board", the "Climate-Neutral TU Graz 2030" project, the founding of the "Innovation District Inffeld" and the "Energy Policy 2020+" have created the environment to enable corresponding research and development projects.

The **Sustainability Advisory Board** [[2]], founded in 2020, is a point of contact for sustainability agendas at TU Graz. Its most important tasks include advising the Rectorate on sustainability issues, the further development of the sustainability strategy and the development of project proposals, as well as support of the publication of sustainability reports [[3]], The idea of a research project was developed in the course of a workshop of the Sustainability Advisory Board, which finally led to the UserGRIDs project.

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[1] Leitfaden Vorzeigeregion Energie (Ausschreibung 2019), 2.2 Programmziele, page 6

[2] https://www.tugraz.at/en/tu-graz/organisational-structure/committees/sustainability-advisory-board/

[3] https://www.tugraz-verlag.at/en/gesamtverzeichnis/interdiszipinaeres/tu-graz-nachhaltigkeitsbericht-2020-ebook/

In 2020, the project **Climate-Neutral TU Graz 2030** [[4]] was launched in order to prepare a greenhouse gas (GHG) balance for the entire Graz University of Technology for the first time. This related to the year 2017 and has since formed the basis of comparison for assessing the further development of greenhouse gas emissions caused by TU Graz. Based on this, the "**Roadmap - Climate Neutral TU Graz 2030**" was developed, which defines more than 40 measures for development towards climate neutrality and thus forms an important basis for setting the targets aimed for in the UserGRIDs project.

Another basis for UserGRIDs was created by the idea of an innovation zone. The aim was to provide a favourable environment for testing sustainable energy technologies. Founded in 2021, the **Innovation District Inffeld** comprises the entire Campus Inffeldgasse of TU Graz, the largest of the three TU Graz sites. The district has become a test and demonstration area for the digital energy services developed in UserGRIDs.

With the adoption of the **Energy Policy 2021+**, these and other components of sustainable development at TU Graz were created as a guideline for corporate management and a binding framework for all employees:

With the adoption of the "CO_2 Roadmap to a Climate-Neutral TU Graz 2030" by the rectorate, we are committed to consistent decarbonisation. At the suggestion of the Sustainability Advisory Board of TU Graz, packages of measures in the areas of energy, mobility, building construction, material procurement and compensation are being defined and implemented. The energy management system makes an important contribution to monitoring and steering this ambitious project. We uphold the requirements of DIN EN ISO 50001.

We are committed to continuous improvement, compliance with legal and other requirements and the provision of the necessary resources. The evaluation is published in regular sustainability reports. As an internationally recognised research institution, we go beyond the state of the art and bundle our interdisciplinary, sustainable solutions in the Field of Expertise "Sustainable Systems".

The "Innovation District Inffeld" serves as a "living lab" to think ahead and test the energy systems of the future in close cooperation with stakeholders. When constructing buildings, we are guided by the principles of the "Graz Declaration for Climate Protection in the Built Environment" Energy management requires responsible employees at all levels who actively collaborate and think along with us. They are supported in this through appropriate training and further education. The company management and employees are committed to this energy policy. [[5]]

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4 https://www.tugraz.at/en/tu-graz/university/climate-neutral-tu-graz/climate-neutral-tu-graz/
5 https://www.tugraz.at/TU_Graz/Universitaet/Klimaneutral/Energiepolitik2021plus-Klimaneutrale-TU-Graz.pdf

1.2 Innovation District Inffeld

The Innovation District Inffeld comprises the entire Campus Inffeldgasse of Graz University of Technology [6]. With the opening of the Electrotechnical Institute in 1970, a steady development into a comprehensive university location began, which developed into the largest campus of Graz University of Technology by 2022 (Figure 1). In addition to conventional office and teaching facilities, the district includes an extensive research infrastructure. Numerous laboratories, workshops and experimental facilities consume large amounts of energy, sometimes with very high peak loads, driven by research. The district's infrastructure, which reflects its more than fifty-years of history, is highly heterogeneous and complex. In the reference year 2022, the site area covers 146 230 m² and the gross floor area (GFA) of all rooms stands at 141 408 m², resulting in a building density of 0.9.

Figure 1: Innovation District Inffeld in reference year 2022 (background image google earth)

The majority of the buildings in the Innovation District Inffeld are supplied with **district heating** in the reference year 2022. The usual connection to the municipal district heating network in the district's development history was replaced by **brine-water heat pumps** in combination with **deep probes** from the construction of buildings IN13, IN19 and IN23 (opened in 2019). The subsequent buildings PE136 and IN33 were also equipped with heat pumps. The two temporary container buildings (BU.IN17 and BU.IN28) are heated (and cooled) using electrical energy.

[6] https://www.tugraz.at/en/tu-graz/university/buildings-of-tu-graz/

In the **scenario for the year 2042**, it can be assumed that both the site area and the building density will have changed significantly (Figure 2). The "Data House" (Building A) and "Silicon Austria Labs Building" (Building B) were put into operation in 2023. In addition, the Cybersecurity Campus (Building C) is already in an advanced development phase in 2022.

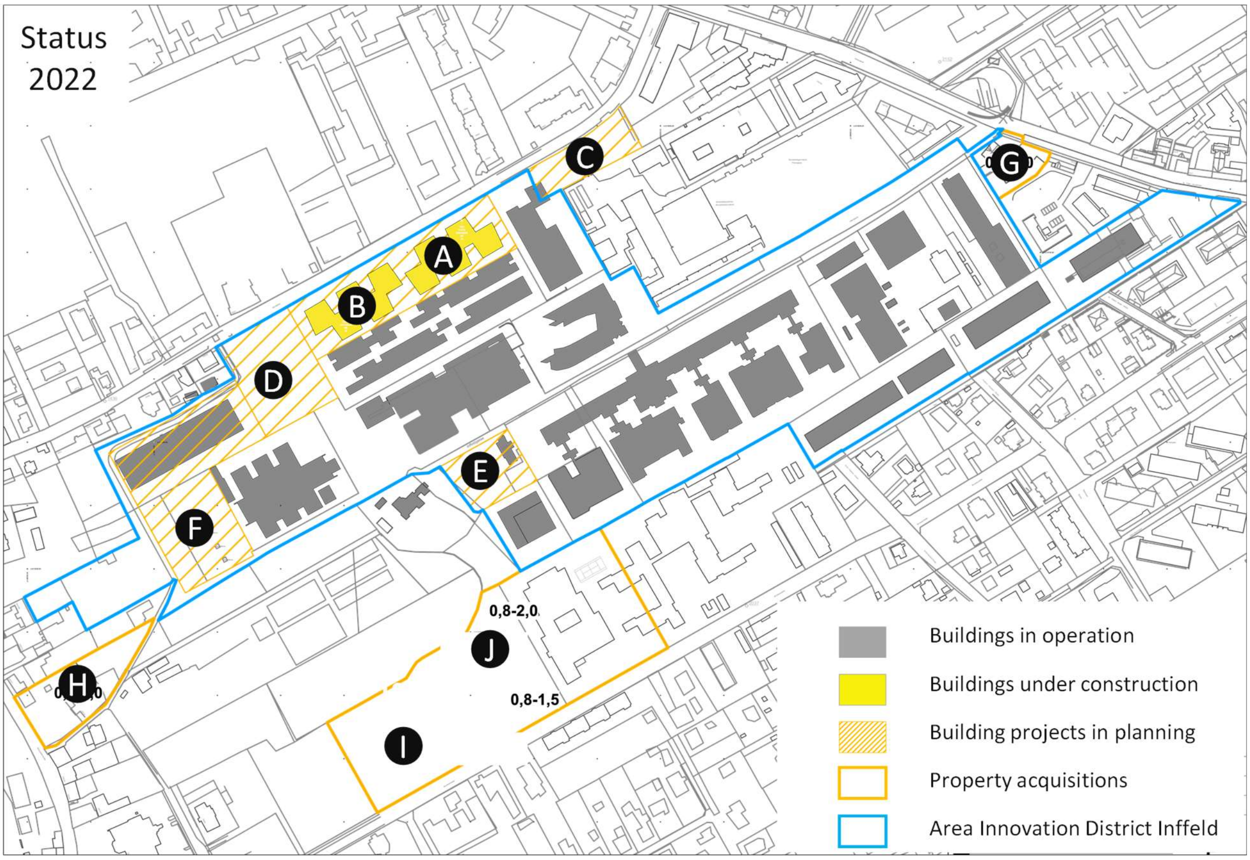

Figure 2: Planned buildings and realised area enlargement in 2022

The development plan of TU Graz [7] describes the construction of three further buildings.

<u>Auditorium and office building</u> (Building D)

... it is intended to provide the best possible conditions for teaching by expanding and modernising the infrastructure and also facilitate a wide range of events, symposia and congresses. With two large lecture theatres, seminar rooms, IT classrooms and student common areas, teaching will be the main use of the building. In addition, institute areas with associated laboratory areas and testing rooms will be created.

[7] Entwicklungsplan 2024plus der Technischen Universität Graz (Bearbeitungsstand: 14.04.2023)

Production Technology Centre 2nd construction phase (Building E)

... is to become a production technology centre that meets international standards and proves to be a leading pioneer in production and materials research. The centre will focus on sustainable production and digital transformation. The building will also be equipped with appropriate laboratory space for teaching and research.

NAWI Graz Geocentre (Building F)

... is planned as an inter-university centre (together with the University of Graz) and will house five institutes of Graz University of Technology and eight chairs of the University of Graz in the fields of geoscience, geotechnics and hydraulic engineering. This means that all the large laboratories of the Faculty of Civil Engineering will be located at the Innovation District Inffeld.

Together with additional properties (G, H, I, J), a site area of at least 180 101 m² will be created by 2042. Depending on the development of activity, a gross floor area (GFA) of 223 217 m² to 252 914 m² can be achieved, which would result in an urban density of 1.24 to 1.40.

Scenario for energy supply in the year 2042

In 2022, a number of different measures to increase sustainability have already been adopted and partially implemented at the Innovation District Inffeld. The continuation of these measures must be taken into account when assuming the 2042 scenario.

- In 2023, which is after the reference year 2022, two further buildings, the "Data House" and "Silicon Austria Labs Building", started operation. Both buildings are equipped with efficient **heat pumps and depth probes**. It can be assumed that all subsequent buildings will be equipped in the same way.

- At the end of the reference year 2022, seven **photovoltaic systems** for electricity production were installed and further systems were being planned (view chapter 2.1.6). The expansion plan aims to utilise all suitable roof surfaces to generate electrical energy and also to use suitable vertical surfaces for PV use.

- In 2022 and 2023, the range of **electric mobility services** was significantly expanded. Starting with just a few, the number of charging points was increased to over forty. It should be noted that up to two hundred charging points will be installed by 2042.

In addition, work is being carried out on a **masterplan** for the sustainable development of the district, the installation of an **electrolyser for hydrogen production** is being prepared and concepts for the thermal **refurbishment** of buildings IN12 and IN18 are being planned. The replacement of district heating with a large heat pump and a networked heating and cooling system is also being investigated for the period up to 2030.

1.3 Functionality and implementation concept

Achieving climate neutrality is a complex and demanding challenge. What is needed is information that helps to reduce energy consumption, increase the share of renewable energy sources and reduce greenhouse gas emissions. Based on this ambition, the UserGRIDs project is developing an IoT framework with the aim of providing information that supports the achievement of this goal at various levels.

A data-processing IoT framework is positioned as a “mirror” of the district buildings and its energy technology systems. The elements of the IoT framework are in constant data exchange with the real system respectively provide it with corresponding information. All data-generating units are categorised into eight basic functions, which are labelled as **digital energy services** (Figure 3).

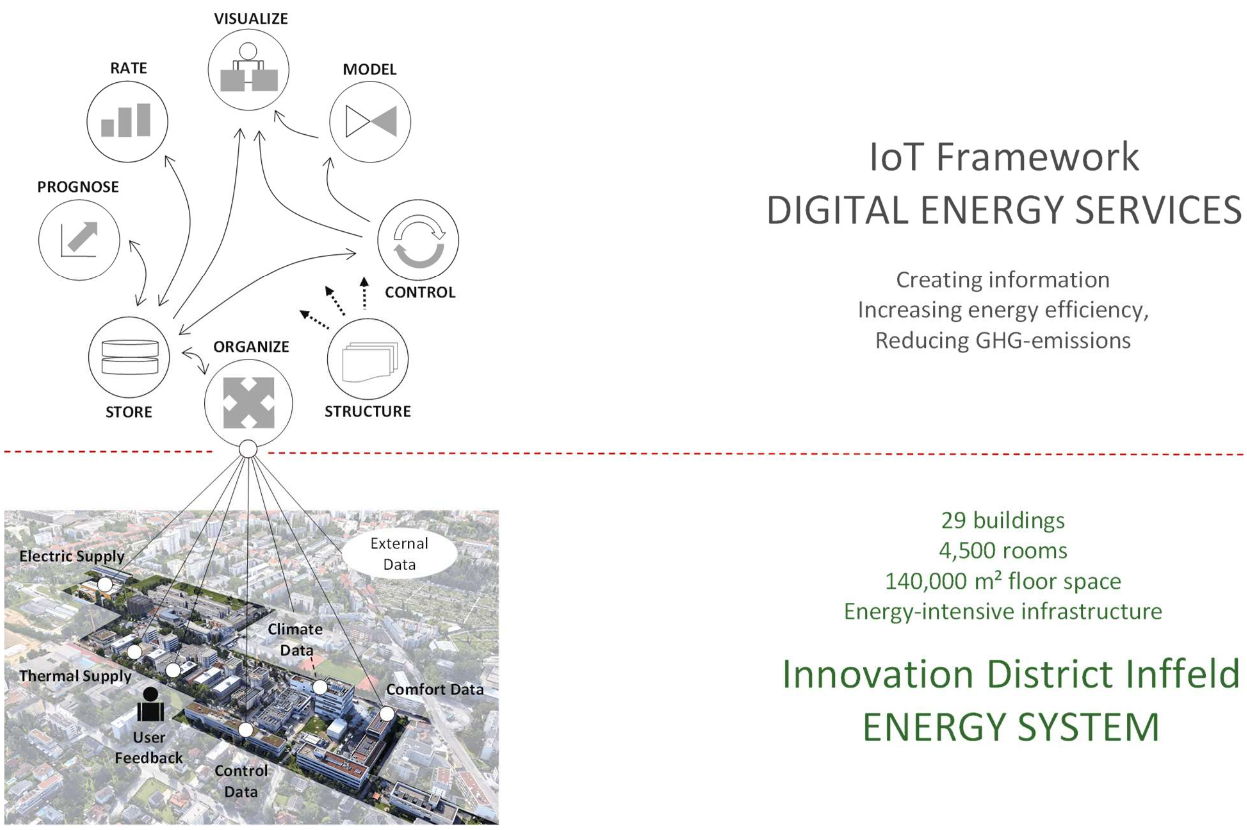

Figure 3: Functionality and dataflows of the digital energy services

The digital energy service STRUCTURE contains a model of the most important data relevant to energy performance for buildings, uses and electrical and thermal supply systems of the district. It forms a “single source of truth” data source for all other services. The status quo in the year 2022 as well as optional future development variants are implemented. The digital energy service ORGANIZE bundles real time data from different systems of the district. Sensor readings from the thermal and electrical supply systems, comfort data, user feedback, information on climatic conditions and control settings are transmitted to the IoT Framework.

Sensor data are stored in STORE and made available to all other digital energy services by an user Interface. The service PROGNOSE compares the results of prognostic data models with the current measurement data and thus helps to detect operational errors. The service RATE analyses the transmitted values from the energy systems and submits them to an energy and emission-related evaluation. The service MODEL performs "Scenario Modelling" in numerical simulation models to obtain recommendations for the transformation and expansion of the district. The service CONTROL, on the other hand, includes optimisation models for more efficient operation and calculates advantageous settings for the control system of district buildings and feeds these back into the buildings energy system. All services send data needed for analysis to the service VISUALIZE in order to make the important information accessible to different groups of stakeholders via dashboards.

At the end of the structure definition, the question of the technological implementation of the desired functionalities was asked. In the first step, this led to an investigation into the characteristics, strengths and weaknesses of IoT platforms used on the market and in research.

1.4 State of the Art of IoT Platforms

To assess the state-of-the-art as well as the requirements and challenges for IoT middleware in smart energy systems we devised a two-stage research plan, comprising a literature review and a quantitative expert survey. The literature review included reviewing the IoT platforms architectures, functional and non-functional requirements, and the most common technologies and protocols in order to form survey questions that represent the real market needs of the people who operate these services in the energy sector. Project partner IST summarized this in a scientific article:

► *Alfalouji, Q.; Schranz, T.; Kümpel, A.; Schraven, M.; Storek, T.; Gross, S.; Monti, A.; Müller, D.; Schweiger, G. IoT Middleware. Platforms for Smart Energy Systems: An Empirical Expert Survey. Buildings 2022, 12, 526 [8].*

The results of review and survey show that IoT platforms need to cover a wide range of functionalities, non-functional requirements and scales. To match the growing demand there exists a considerable number of commercial and non-commercial IoT solutions. However, only few commercial competitors include the energy sector into their portfolio. Possible reasons include the severity of security risks in what is considered to be critical infrastructure and a lack of universal standards. Furthermore, other requirements such as openness, availability, reliability, and avoiding vendor-locks need to be considered as well. The application layer protocols used by most of the middleware platforms are MQTT and HTTP, while on network communication level LoRAWAN, WiFi and 4G/LTE are the prevalent technologies.

[8] https://doi.org/10.3390/buildings12050526

1.5 Principles of development

The application phase was already based on principles and development regulations. These were discussed, further developed and revised several times during the course of the project. The principles outlined below should be seen as the basis for all project activities carried out. They should also be taken into account as a framework for future activities.

- **Cooperation with the sustainability activities of TU Graz**
  The project supports the endeavours to increase sustainability at TU Graz. In addition to the scientific objectives, the adopted Energy Policy 2020+ is seen as a basis for the project activities. The consortium works closely with institutions and projects in the field of increasing sustainability at TU Graz.

- **Continuous stakeholder integration**
  The development and use of the services have an impact on a wide variety of people and institutions, both inside and outside the Innovation District Inffeld. These stakeholders are proactively informed and involved in the development process in order to define objectives and procedures in mutual coordination.

- **Editability and extendability**
  The UserGRIDs project sees itself as the initial project of the Innovation District Inffeld, on the basis of which further internal and external projects will be built. The structure and implementation of the digital energy services must be modular in order to ensure that they can be edited and expanded as part of further projects.

- **Documentation and transparency**
  The aim is to document the structure and technological implementation of digital energy services in a way that is comprehensible and meaningful for third parties. This ensures transparency with regard to functionality and technical structure, and thus guarantees reproducibility as a basis for further activities.

- **Networking and cooperation**
  The application of the "single source of truth" principle requires the merging of information from different data sources into a consistent data basis. All services to be developed refer to the same data basis in order to avoid incoherent parallelism in data creation.

- **Compliance with ethical principles**
  The project processes large volumes of data, partly on the basis of machine learning and AI (artificial intelligence) methods. As a basis for all activities, the aim is to comply with the "legal", "ethical" and "robust" guidelines adopted by the European Commission (Ethics Guidelines for Trustworthy AI, 8 April 2019) [9].

[9] https://op.europa.eu/en/publication-detail/-/publication/d3988569-0434-11ea-8c1f-01aa75ed71a1

2 Digital energy services

The overall system of eight digital energy services (Figure 3) has a modular structure. This has several advantages. The development of the individual services can be carried out as independently as possible and, in some cases, in parallel. The modular structure also allows existing services to be improved or additional services to be added and linked to the existing services in subsequent development steps. The initial situation, motivation, development and implementation of the individual services at the Innovation District Inffeld are described as follows.

2.1 STRUCTURE

European urban districts are generally the result of at least decades of development, characterised by constant growth and change. This is accompanied by a continuous increase in demands on the technical infrastructure and an increase in system complexity. Accordingly, the building and energy infrastructure is also a reflection of the technical development history that has taken place. Old systems and their components have been partially preserved, partially modernised or completely replaced. This results in a system structure that, on the one hand, follows comprehensible criteria and, on the other, is based on historical contexts that can only be reconstructed to a limited extent. The information describing the energy system is also widely distributed across different data holders, sources, media and formats, and does not provide a standardised or consistent database. However, if different services access different source data, the processing results are also inconsistent, not comparable and the desired networking to form an overall system is not possible in a meaningful way. Therefore, the creation of a meaningful and consistent database for the respective status quo, but also for all optional development scenarios to be evaluated, is an indispensable basis. This results in the following objective for the digital energy service STRUCTURE.

The **target** of this service is to collect, structure and store all information required for modelling and assessing the energy behaviour of the current district energy systems and possible future development scenarios and to make it available to all other digital energy systems, defined as a “single source of truth”.

As part of the development and implementation of the STRUCTURE digital energy service, numerous data sources were identified, access to the data holders was established and the information contained was checked and analysed. Climate data, building volumes, construction structures and the central components of the heat and electricity supply were recorded (01). Room numbers, room sizes and assigned uses (02) were exported from TU Graz's internal information system, TU Graz_online [[10]], in order to create a consistent data model that describes the state of the building structure and energy supply systems for the selected reference year 2022 and for the 2042 scenario.

[10] https://www.campusonline.tugraz.at/home/

The resulting consistent database acts as a "single source of truth" and provides the other services with a consistent database for further processing (03), partly machine-readable in semi-automated form (04). The work described in chapters 2.1.1 to 2.1.6 was carried out in order to set up and test the structure for the Innovation District Inffeld shown in Figure 4.

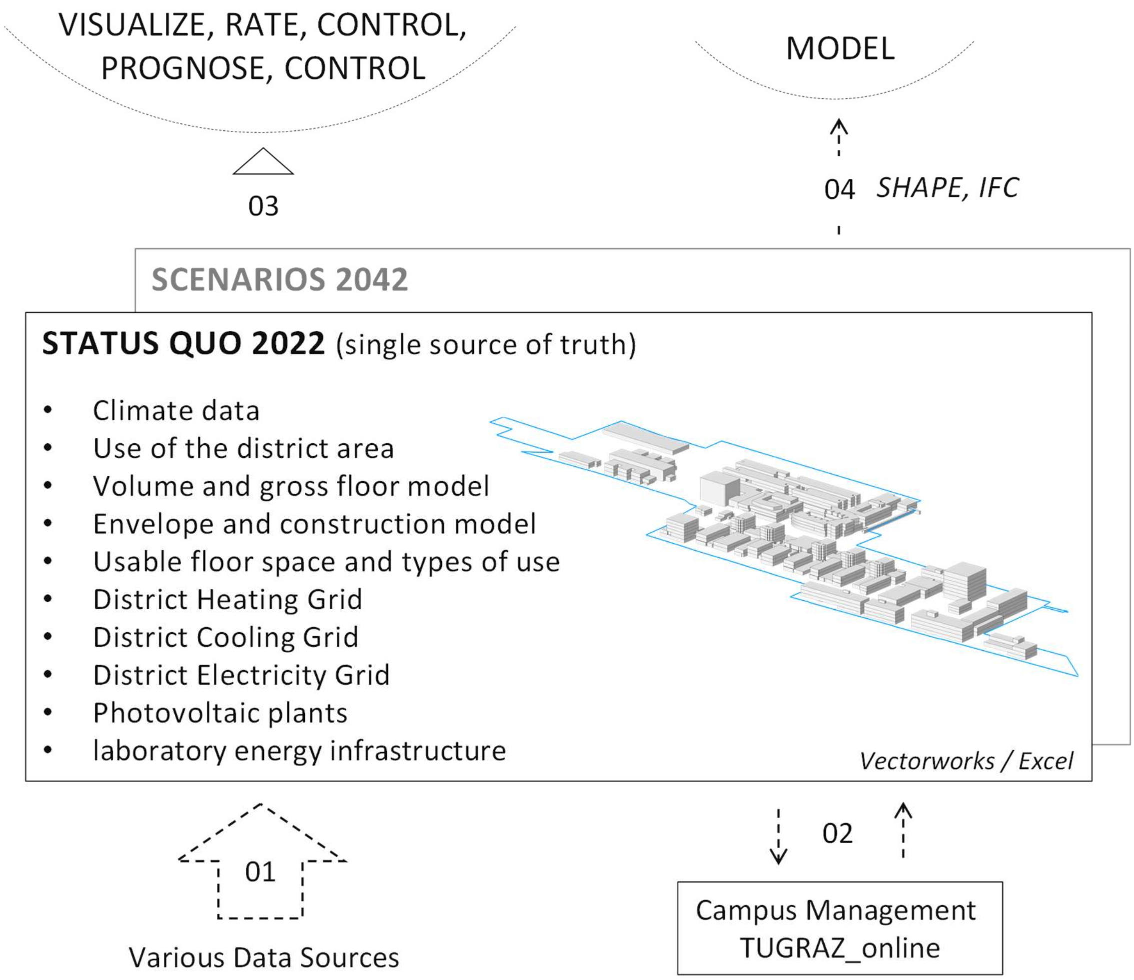

Figure 4: Functional scheme of digital energy service STRUCTURE

2.1.1 Setting up the climatic framework

Climatic conditions, such as the outside air temperature, humidity and solar radiation, have a major influence on the energy consumption of buildings and the production of electrical energy from PV systems. The analysis and evaluation of energy consumption, system behaviour and efficiency can only be carried out taking into account the respective climatic conditions. The type and form of the climate data must also always be harmonised with the purpose of the respective analysis. In the UserGRIDs project, climate data is used as measured data sets, as short-term forecasts and as scenarios far into the future.

Climate data measured locally and by meteorological institutions
For some applications, locally measured climate data is preferable, as it provides a location-specific picture of the climatic conditions. In this sense, the climate data measurement installed at the Innovation District Inffeld as part of the project (chapter 2.2.2) forms one basis for the energy analysis of the buildings (chapter 2.5.3) and the photovoltaic systems (chapter 2.5.4) as well as for the control system (chapter 2.6.3).

If no reliable local climate data is available for an analysis, measured values from meteorological institutions must be applied. In the reference year 2022, the local climate station was not yet fully operational, which is why values from GeoSphere Austria [[11]] were used. The measuring point is located on the grounds of the University of Graz and is therefore 2.4 km away. This results in a solar irradiation of 1328 kW/m² and an average outside air temperature of 11.8°C in the reference year 2022. These boundary conditions are used as the basis for validating the simulation model in the MODEL service (chapter 2.7.3).

Forecast of outdoor air temperature and radiation
The PROGNOSE and CONTROL services work with predictive methods and therefore require forecasts of the climatic parameters outdoor air temperature and solar radiation. Climate data from Meteoblue AG models [[12]] are used for this purpose (chapter 2.2.2). Climatic parameters are updated hourly for a forecast horizon of one week and stored in service STORE, from where they can be retrieved for further applications.

Predicted climatic conditions for the year 2042
Due to the dynamic nature of climate change, the greatest uncertainties arise when assuming climatic conditions far in the future. For the 2042 scenario, a climate data set with an hourly resolution for the reference year 2022 was created using the Meteonorm 8 [[13]] climate data generator, based on monthly values from the climate data set measured in 2022. Based on this, Meteonorm was used to create a forecast for the year 2042. This is based on the development path "Representative Concentration Pathways 8.5 (RPC8.5 for short), of the Intergovernmental Panel on Climate Change (IPCC) [[14]]. According to this, an annual average outside air temperature of 13.0 °C will be reached in 2042 and solar irradiation will amount to 1363 kWh/m²a. A more detailed presentation of the climate data generation carried out is documented in the COOL-QUARTER-PLUS project [[15]]. A comparison with the values published in "ÖKS15 Climate Scenarios for Austria" [[16]] shows that the outdoor air temperatures forecast in this way are close to the upper limit of the fluctuation range of the ÖKS15 models (for the year 2042: 12.96°C) [[17]].

[11] https://data.hub.zamg.ac.at/
[12] https://content.meteoblue.com
[13] https://meteonorm.com/meteonorm-version-8
[14] https://www.ipcc.ch/
[15] https://nachhaltigwirtschaften.at/de/sdz/projekte/cool-quarter-plus.php
[16] https://www.bmk.gv.at/themen/klima_umwelt/klimaschutz/anpassungsstrategie/publikationen/oeks15.html
[17] Leuprecht et al., „ÖKS15 Bias Corrected EURO-CORDEX Models, Version 2“, CCCA Data Cent

2.1.2 Creating volume, construction and open space models

Information on buildings and sites from a wide variety of sources was brought together in a data model. This is organised into coordinated sub-models, each of these contains information on different aspects and possible applications. The implementation was carried out in the CAD programme Vectorworks [18]. Figure 5 shows an overview of the graphical representations of the building-related submodels.

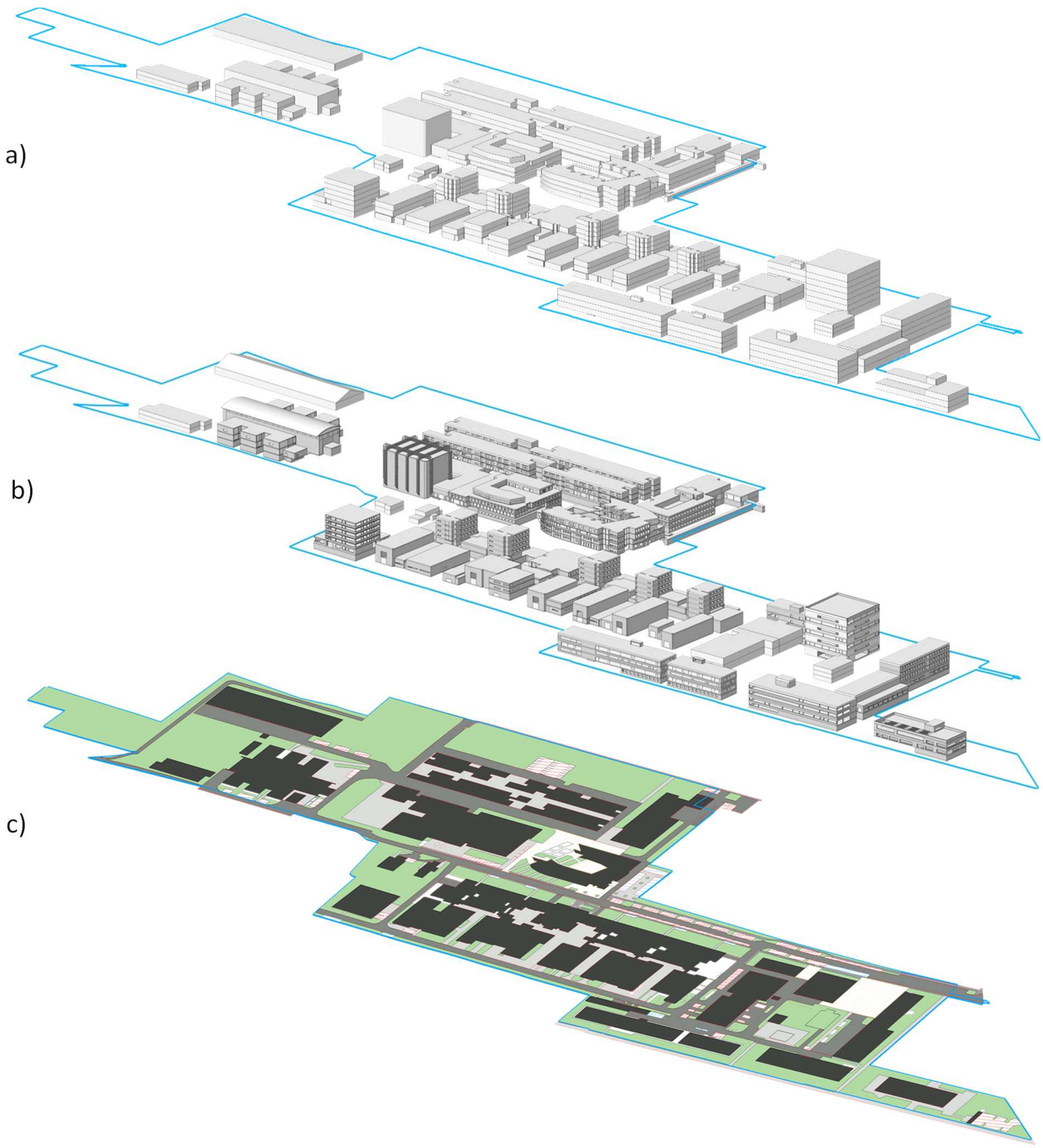

Figure 5: Volume- and gross floor model (a), Envelope and construction model (b), Open Space Model (c)

[18] https://www.computerworks.de/produkte/vectorworks.html

Volume- and gross floor model

The volumes and gross floor areas of all buildings were extracted from planning documents and transferred to the CAD model. The outer surfaces of the building envelope (walls and ceilings or roofs) form the boundary surfaces of the volumes. The floor area of a storey volume is specified as the gross floor area (GFA) and is always at the level of the floor surface. Figure 5 (a) shows a graphical representation. The model was numerically analysed by gross floor area by building and storey. This results in a gross floor area of 141 408 m² for the entire area of the Innovation District Inffeld in 2022. The ground floor clearly dominates in terms of floor space with 45 520 m², followed by the first basement floor with 33 733 m² and the first floor with 28 047 m². The volume and gross floor model is used in applications in which the arrangement of the building volumes is in the foreground, such as in urban building volume studies, shading calculations and for calculating the area-related key performance indicators in the digital energy service RATE (chapter 2.5.3).

Envelope and construction model

In the CAD programme Vectorworks the exterior walls, roofs, basements storey ceilings and the significant interior walls were build up as three-dimensional and geo-referenced objects. Each object is assigned a material whose energy properties are defined in terms of heat conduction and heat storage. The locations and size of all windows and exterior doors were taken from plan material or on-site inspections and integrated into the model. Firstly the structure of each building was defined in one stand-alone file. Subsequently, the individual descriptions were combined into an Envelope and construction model of the entire district Figure 5 (b). The envelope and construction model is used in applications in which the focus is on the physical behaviour of the building, such as energy consumption calculations or efficiency analyses. The Service MODEL in particular uses this information to create simulation models (chapter 2.7).

Open space model

The land consumption at the Innovation District Inffeld for the year 2022 was derived, analysed and documented from the cadastral map and other sources. This information was also entered into the georeferenced CAD data model, which allows descriptive information (attributes) to be assigned to individual drawing objects in the background Figure 5 (c). The total district area (FBG) of 146 230 m² is divided into a three categories. A graphical representation of these categories can be found in Figure 6. 20 % are classified as “Traffic area” and 48 % are classified as “Open space”. These categories area are divided into subcategories. 32 % of the FBG is assigned to the category “Built-up area”. This means that 32 % of the district's land area is occupied by buildings. The calculated degree of sealing of 66.57 % indicates that this proportion of the total area is sealed and no direct absorption of rain water is possible. The open space model is used in applications in which the availability of open spaces is of primary importance, such as analyses of microclimate and building density or densification. Energy planning also requires this information for the positioning of energy components like energy stores, electrical transformers or deep probe fields for heat pumps.

2.1.3 Analysing usable floor space and types of use

The usable floor spaces of all rooms of all buildings at Graz University of Technology are measured as standard by the building administration, transferred to the university's database and made available in the Graz University of Technology's administration system (TU Graz_online [[19]]). In addition, each room area is provided with a data record that provides information on size, type of use, address, room number and other characteristics. The data set, which is continuously adapted to changes and expansions, forms the central basis of numerous facility management activities. In order to ensure consistency, this data set, in its current version, is also used as the basis for the UserGRIDs project.

Each interior space of the Innovation District Inffeld is assigned to an utilisation category in the TU Graz_online database. The categories correspond to the definition given in DIN 277 "Grundflächen und Rauminhalte von Bauwerken im Hochbau (2005)" [[20]]. The abbreviations used for the categories correspond to the original written in German in order to maintain a reference to the standard. The "District area (FBG)" is divided into "Built-up area (BF)" and "Unbuilt area (UBF)". Figure 6 shows that 32 % of the FBG is assigned to BF, which means that 32 % of the district footprint is claimed for buildings. BF is one part of the "gross floor area (BGF)". The gross floor area is the total area of all storeys, limited by the external surfaces of the external facades surrounding each storey. It is divided into the "net floor area (NGF)" and "construction area (KF)". The net floor area is subdivided into "Usable floor space (NF)", Functional floor space (TF)" and "Access floor space" (VF). TF includes floor space for technical facilities for the supply of water, heating, cooling, electricity and similar equipment. VF includes areas for entrance halls, corridors, staircases, shafts and similar uses. Usable floor space (NF) is further divided into sub-categories.

Figure 6 shows a graphical breakdown of the categories occurring in the Innovation District field. The list refers to the usable areas of interior spaces, which is why outdoor usable areas such as balconies, terraces, etc. listed in the TU Graz_online database are not taken into account. The "Unbuilt area" (UBF) is not subdivided further in the classification according to DIN 277. At this point, the illustration shows the structure of the Open Space Model (chapter 2.1.2).

Including the temporary container office building IN28, which is not listed in TU Graz_online, the evaluation results in a net floor area (NF) of 120 547 m². The utilisation category NF3 (Production) accounts for the largest percentage of the available usable space with 27.1 %. This is due to the high proportion of workshops and laboratories. At 22.8 %, the VF (Access) category is the second largest use of space, closely followed by 20.5 % for the NF2 (Office) use category. 9.4 % of the space is used for technical facilities (Facility) and 7.5 % for NF4 (Storing). The Education (6.3 %), Others (3.9 %) and Residential (2.5 %) categories require the smallest proportions of space.

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[19] https://www.campusonline.tugraz.at/home/
[20] http://architekturverzeichnis.blogspot.com/2011/06/din-277-ermittlung-von-grundflachen-und.html

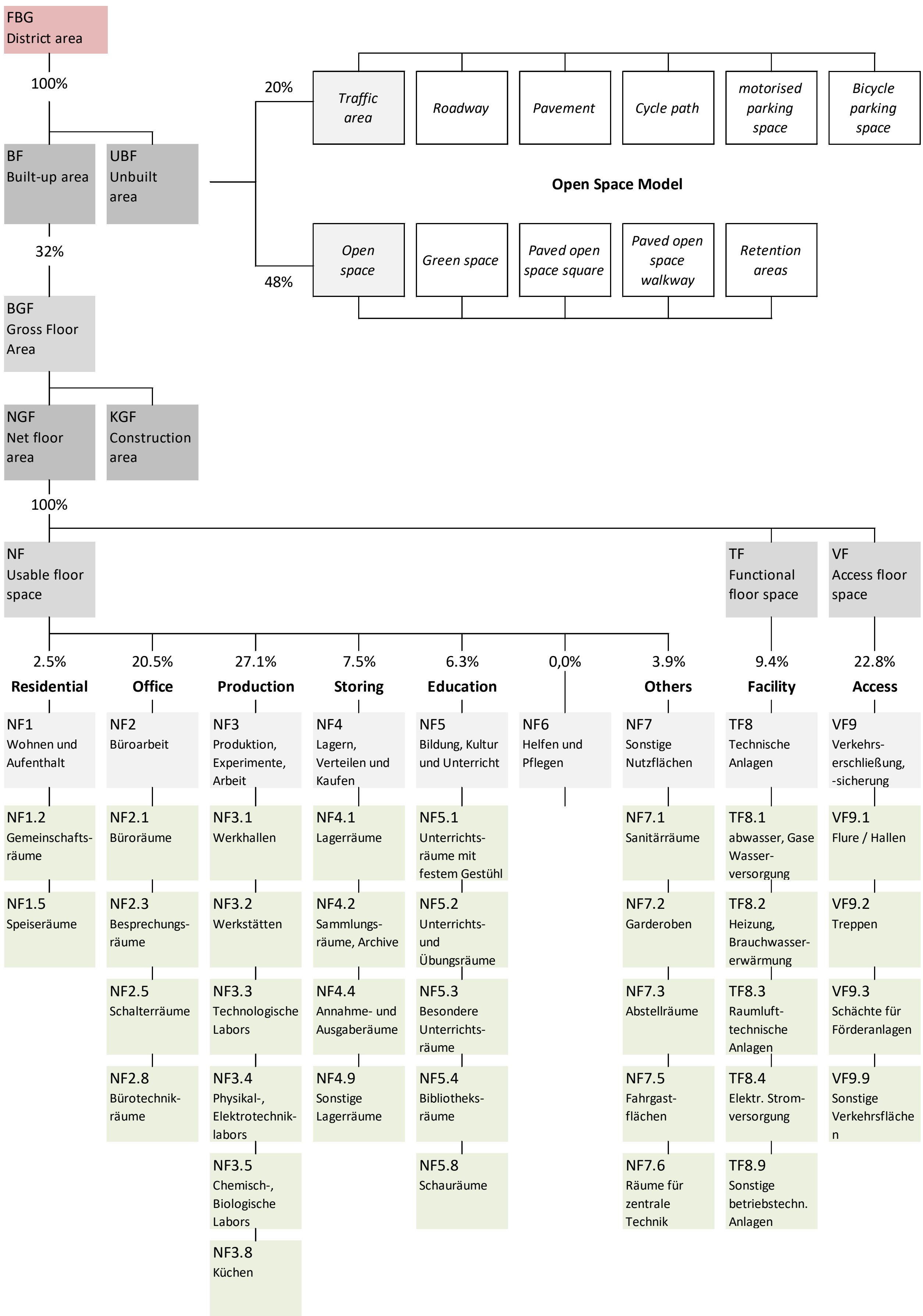


Figure 6: Use classification according to DIN 277 extended by the classifications of the open space model

2.1.4 Energy equipment of the interior spaces

The equipment of the individual interior spaces of the district with energy infrastructure was described in a large number of separate plans. This initial situation is presumably similar to most comparable districts. The high degree of fragmentation of the data and the individual nomenclature of the information make a machine-readable evaluation impossible. For this reason, an on-site assessment was initiated. During an inspection of each individual interior room, the energy technology equipment was recorded and compared with the plans and the knowledge of the responsible service technicians. The room list from TU Graz_online was used as a basis, which was expanded to include additional attributes. The energy-relevant infrastructure was divided into the categories of heating, cooling, ventilation and lighting.

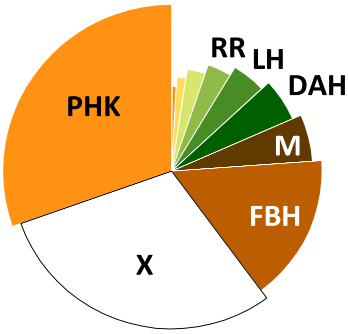
For each category, a distinction is primarily made between the absence and presence of corresponding conditioning devices (unheated/heated, uncooled/cooled, unventilated/ventilated, unlighted/lighted). In the case of presence, in each category there is a range of energy equipment to choose from. Figure 7 shows an analysis in which the usable floor space (NF) available in the entire district in the reference year 2022 was analysed as a percentage according to this scheme. Indoor spaces can also have several systems within a category (e.g. air heating and radiant ceiling panels in the test halls). Accordingly, several attributes of one category can be assigned to an indoor space.

It can be seen that 29.8 % of the usable floor space (NF) is not heated. This can be explained by the proportion of space occupied by car parks, storerooms, technical rooms and similar uses. The largest proportion of heated areas, 30.4 %, is supplied with heat by panel radiators (PHK). This category is dominated by buildings constructed in a period in which district heating was used as standard. The newer buildings equipped with heat pump systems are the main reason for the 16.0 % share of floor heating (FBH). Other heat supply systems such as thermal ceiling heating (DAH) and air supply heating (LH) are in the lower percentage range. 59.4 % of the usable floor space is not equipped for active summer room cooling in the reference year 2022.

Floor cooling (FBK) is the predominant form of room cooling in terms usable floor space (14.6 %), followed by fan coil water driven (FC), which cools 12.8 % of the usable floor space. Other systems for room cooling, such as thermal ceiling cooling (DAK) or ceiling cooling panels (KS), together take up only 6.8 %. The supply of fresh air is realised via window openings (FL), which account for 31.5 % of the usable floor space. Supply and exhaust air systems are mainly used in laboratories and lecture theatres. As expected, almost the entire usable area (98.7 %) is equipped with artificial lighting. Light emitting diodes (LED) already account for 34.4 % of the usable floor space. The categories fluorescent lamps T5 (TF) and fluorescent lamps T8 (TA) together still make up the largest group of lighting systems with 55.3 %.

The analyses are used to quantify the energy reference areas per building for heating (A_{FSH}) and cooling (A_{FSC}), or electrical energy (A_{FSE}). In the RATE service, these are used to calculate the consumption per building. In addition, the definition of the simulation scenarios in the service MODEL is based on the allocation of the heating and cooling systems.

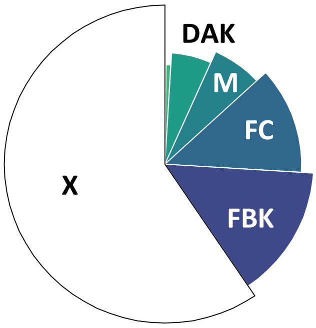
Heating



X - unheated – 29.8 %

PHK - panel radiator – 30.4 %
FBH - floor heating – 16.0 %
M - co-heated surface – 5.4 %
DAH - thermal ceiling heating – 5.3 %
LH - air supply heating – 4.5 %
RR - ribbed radiator – 3.4 %
DSP - ceiling heating panels – 2.8 %
KO - convection radiator – 1.5 %
DE - stationary electric heater – 0.8 %
ME - mobile electric heater – 0.1 %
WH - thermal wall heating – 0.0 %

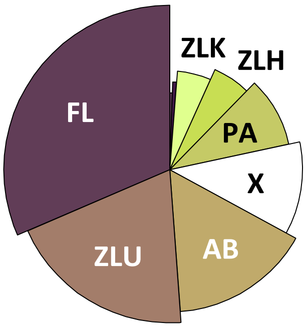
Cooling



X - uncooled – 59.4 %

FBK - floor cooling – 14.6 %
FC - fan coil water driven – 12.8 %
M - cooled surface – 6.5 %
DAK - thermal ceiling cooling – 5.8 %
MK - mobile cooling unit – 0.7 %
SPL - split unit – 0.2 %
WK - thermal wall cooling – 0.0 %
KS - ceiling cooling panels – 0.0 %

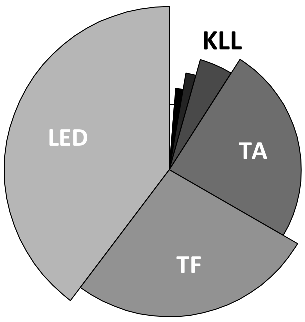
Ventilation



X - unventilated – 11.4 %

FL - window openings – 31.5 %
ZLU - ventilated supply air – 19.6 %
AB - ventilated exhaust air – 15.8 %
PA - process exhaust air – 9.3 %
ZLH - air supply heated – 5.6 %
ZLK - air supply cooling – 5.5 %
DIG - digestory – 0.7 %
BF - humidification – 0.5 %
EF - dehumidification – 0.0 %

Lighting



X - unlighted – 1.3 %

LED - light emitting diodes – 34.4 %
TA - fluorescent lamps T8 – 28.0 %
TF - fluorescent lamps T5 – 27.3 %
KLL - compact fluorescent lamp – 5.4 %
HL - halogen lamp – 1.9 %
GL - incandescent lamp – 1.7 %

Figure 7: Distribution of energy-related equipment on the usable floor space of the Innovation District Inffeld in the 2022 reference scenario; abbreviated forms derived from the German wording

2.1.5 Describing urban energy networks

On the one hand, superordinate energy networks connect energy sources (power and heating plants) with the innovation district infrastructure. On the other hand, energy grids connect the subsystems located in the district with each other. From this, the district's internal grid structure can be divided into connection points to the higher-level grids, the internal pipeline network and the distribution and transfer nodes. All elements must be clearly and comprehensibly described with regard to the essential technical parameters of their utilisation. The descriptive data was extracted from extensive planning material and supplemented by on-site inspections. In cases where neither was possible, particularly due to a lack of accessibility (e.g. underground pipes), assumptions had to be made. In the reference year 2022, three different grid-bound energy networks are in operation: the district heating grid, the district cooling grid and the district electricity grid. The data for describing the three networks was integrated into the CAD model as three independent domain models.

District Heating Grid

In 2022, the majority of buildings in the district are supplied with heat via two district-internal pipe grids (Figure 8). These are each connected to the higher-level Urban Heating Grid via a District Heating Station. At these two points, thermal energy from the Graz district heating network is transferred to the district heating grid and measured.

The **heating pipe network** was subdivided into individual pipes, with the start and end points of each section being georeferenced. In the network structure shown, a line represents the forward flow and opposite return flow. For further description, the following parameters were stored in the integrated database for each heating pipe.

- inner diameter pipe [mm], *di_pipe*
- outer diameter pipe [mm], *do_pipe*
- outer diameter pipe insulation [mm], *do_insu*
- pipe spacing (center/center) [mm], *spacing_pipe*
- installation depth pipe [mm], *depth_pipe*
- installation location pipe (ground or shaft), *loc_pipe*

Heating grid heat exchangers are the interface between the district's pipe network and the building internal systems for supplying heat. The location of the heat exchangers is geo-referenced in the model and stored with the following information.

- unique identifier of the heat exchanger, *ID_HXh*
- heat exchanger performance [kW], *P_HXh*
- inlet temperature heat exchanger primary side [°C], *t_in_pri*
- outlet temperature heat exchanger primary side [°C], *t_out_pri*
- mass flow primary side [kg/hr], *m_dot_pri*
- inlet temperature heat exchanger secondary side [°C], *t_in_sec*
- exit temperature heat exchanger secondary side [°C], *t_out_sec*
- mass flow secondary side [kg/hr], *m_dot_sec*

The measuring points are always located on the secondary side, i.e. at the start of the lower-ranking network. The measured values transmitted and analysed in RATE therefore always correspond to the heat supplied to the lower-ranking system. This applies to the district heat stations as well as to all heat exchangers implemented to supply individual buildings.

Figure 8: Georeferenced and attributed components of the District Heating Grid in 2022

District Cooling Grid

The cooling infrastructure to be found at the Innovation District Inffeld in 2022 has grown gradually over the course of several years. Initially, individual buildings were provided with decentralised cooling supplies, which are gradually being developed into a cooling network due to the requirements in terms of maintenance and reliability (Figure 9). The cooling energy is provided by several **chillers** (CH), which are positioned decentrally at different points in the network. The respective locations were geo-referenced in the CAD model and each chiller was described in more detail using several parameters.

- unique identification of the chiller, *ID_CH*
- power of the chiller [kW], *P_CH*
- chiller inlet temperature [°C], *t_in_CH*
- chiller outlet temperature [°C], *t_out_CH*
- mass flow chiller [kg/hr], *m_dot_CH*
- number of chillers defined above, *Count*
- possibility of free cooling [True / False], *Free_Cool*

The network of cooling pipes is broken down into individual **cooling pipes** in the same way as heating pipes. The parameters for describing the cooling pipes and the associated identifiers correspond to the descriptions of the heating pipes. The consumers in the cooling grid are also connected to the grid via heat exchangers. The location of the **cooling grid heat exchangers** (CG-HE) is geo-referenced in the model and stored with the following information.

- unique identifier of the heat exchanger, *ID_HXc*
- heat exchanger performance [kW], *P_HXc*
- inlet temperature heat exchanger primary side [°C], *t_in_pri*
- outlet temperature heat exchanger primary side [°C], *t_out_pri*
- mass flow primary side [kg/hr], *m_dot_pri*
- inlet temperature heat exchanger secondary side [°C], *t_in_sec*
- exit temperature heat exchanger secondary side [°C], *t_out_sec*
- mass flow secondary side [kg/hr], *m_dot_sec*

Figure 9: Georeferenced and attributed components of the District Cooling Grid in 2022

District Electricity Grid

The Innovation District Inffeld is connected to the public distribution grid via grid level 5 at two grid connection points. The electrical energy in the district is distributed via an underground **20 kV cable network**, also at grid level 5, and sub-distribution via a **low-voltage grid** (grid level 7). The 20 kV distribution grid is operated as an open ring in the default operating state, which can be closed if necessary. This may be necessary for maintenance, expansion or conversion work or in the course of repairing electrical faults.

The transformers connected to the 20 kV distribution grid (grid level 6) transform the electrical energy to a lower voltage (0.4 kV or 0.69 kV). The electrical energy must be of a high quality due to the equipment installed at the Innovation District Inffeld, which is primarily required for research and laboratory operations. For this reason, the low-voltage grid is separated into a “clean grid” and an “unclean grid” via several transformers for EMC (electromagnetic compatibility) reasons. Equivalent to the procedure for thermal networks, the electrical 20 kV grid was mapped geometrically. The 20-kV-cables and the high/low voltage **transformers** were geo-referenced and included into the model. The following parameters were recorded for each transformer and assigned to the georeferenced locations in the model.

- year of construction
- type (core transformer, leg transformer)
- cooling type (e.g. AN, ONAN)
- vector group (e.g. Dyn5)
- rated apparent power (Sr in kVA)
- short circuit voltage (ukr in %)
- open circuit power losses (P0 in W)
- short circuit power losses (Pk in W)

The **cables** of the 20 KV electrical network were also georeferenced in their positions. The following parameters were recorded and implemented in the model:

- diameter of conductor cross section (mm^2)
- conductor material (e.g. CU)
- type of insulation (e.g. VPE)

The equipment with **measuring sensors** is well developed. Two measuring points are located at the district electricity feed-in points, which are used as billing metering points. In addition, measuring points are located behind nearly each transformer at the entrance to the low-voltage grid. To summarise, it can be said that the status of grid levels 5 and 6 can be measured and stored almost completely in 15-minute intervals.

2.1.6 Characterizing photovoltaic plants

In urban locations, such as the Innovation District Inffeld, the available space on the roofs is the main limiting factor concerning the implementation of PV systems. At the beginning of year 2022, one PV system was in operation on buildings IN11, one across all buildings on IN16, IN16a, IN16b and IN16c and one on the roof of IN26. In total, a number of 2002 PV modules were in use, which, with a total area of 3314 m², achieved a combined peak output of 577 kWp. Four further PV systems went into operation during the reference year. A second system was installed on the roof of building IN26, as well as to the roofs of the IN23, IN24 and IN10 buildings. That increased the installed module area to 5331 m² and a peak output of 966 kWp with an additional 1198 modules. With the PV system of the "Silicon Austria Labs" and "Data House" buildings commissioned in 2023, the peak output installed in the district is 1.03 MWp (Figure 10).

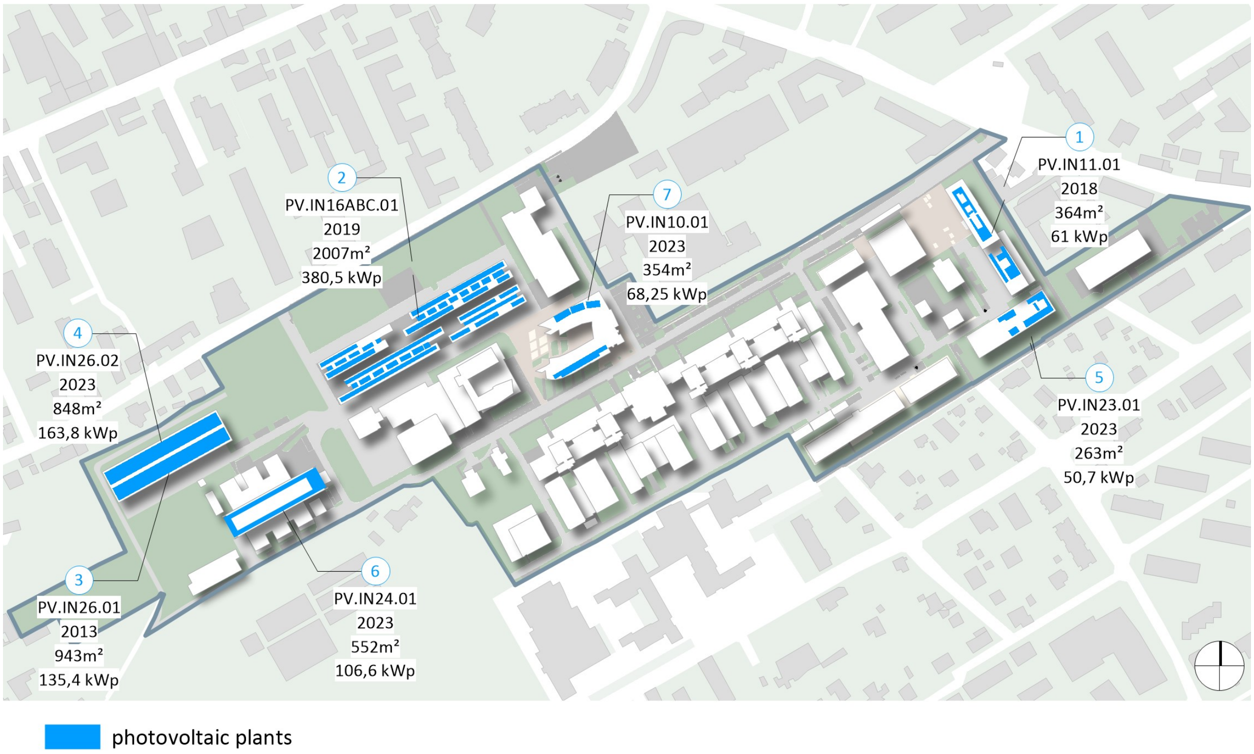


Figure 10: Implemented PV sytems at Innovation District Inffeld in the year 2023

The technical plant descriptions associated with the plants are distributed across different data formats and data sources, sometimes in several planning variants. In order to create a centralised and consistent data source, a compilation was developed in the project that contains all information relevant for yield models. This contains information on the type, size, orientation, number and performance of the modules. The networking of the individual panels into strings and the assignment of the strings to inverters is also described. This common database was used in the digital energy service PROGNOSE to create the forecast models (chapter 2.4.1). In the RATE service, the evaluation of the PV systems is based on this description (chapter 2.5.4) and the detailed simulation models in the MODEL service were also built on this basis.

By 2042, the module area is expected to be expanded to 7560 m² and an output of around 2.37 megawatts peak (MWp) will be achieved. The installed PV area in the **year 2042** was calculated on the basis of the planned gross floor areas and number of storeys in 2042 and the installation densities of 29.7 % (m² PV module area / m² roof area) achieved in the PV systems currently realised. The first three PV systems (577 kWp), which were already running continuously in the reference year 2022, generated an annual yield of around 620 MWh of electrical energy. If the expected development materialises, this yield could increase to just over 3000 MWh per year by 2042. This significant increase in annual yield is mainly due to the increased module area, as it can be assumed that all new buildings added in the district by then will be consistently equipped with PV systems. A small part of the increase is due to the further development of PV technology, with an assumed improvement in efficiency from approx. 17 % to 22 % in 2042.

2.2 ORGANIZE

Sensor data are indispensable for analysing energy-related processes in urban districts, providing information on energy-relevant status variables. Real-time operating data is required in order to implement functions such as fault detection, evaluation, forecasting and control optimisation. When designing data transmission, it is important to bear in mind that data-transmitting and data-processing systems have undergone rapid development and technological change in recent decades. As a result, a variety of transmission technologies and data formats can be found in sensors and actuators in mature urban areas. Establishing communication between the various sensors and actuators and digital energy services requires a great deal of maintenance and is associated with errors as a result of the increasing pace of change. One solution identified by the "State of the Art" research (chapter 1.4) is the central bundling and organisation of all data flows between the energy systems and the digital services. This results in the following objective for the digital energy service ORGANIZE.

The **target** of this service is to enable and bundle bidirectional communication and data exchange between the district energy systems and the digital energy services.

The Digital Energy Service ORGANIZE is a central point of contact for data streams from the district's energy control systems (Figure 11).

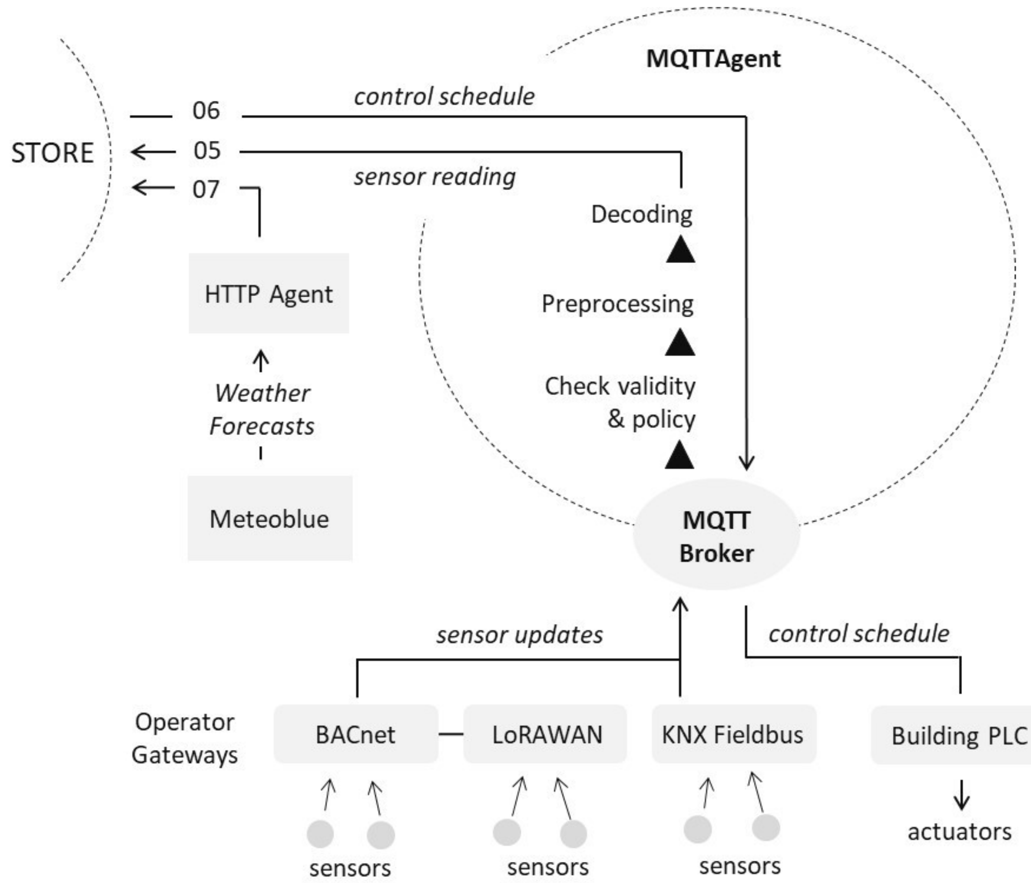


Figure 11: Functional scheme of digital energy service ORGANIZE

Relevant sensor values are transmitted from the control systems via operator gateways to an MQTT broker and then forwarded to the MQTT agent. After passing through several process steps (check, pre-processing, decoding), the sensor values can be transmitted to the STORE service (05). On the other hand, the schedules from the CONTROL service are forwarded by STORE to the building control actuators via the MQTT broker (06). An HTTP agent also transmits climatological forecast data from the external provider Meteoblue to STORE, where it is stored (07). The work described in chapters 2.2.1 to 2.2.4 was carried out to develop the structure shown in Figure 11 and to set up and test the hardware and software at the Innovation District Inffeld.

2.2.1 Identification and analysis of existing data sources

In the year 2022 the responsibility for the energy system operation and the associated data management is held by the department "Buildings and Technical Support" (TU Graz). The sensors and actuators devices are maintained by different operating companies, responsible for different segments of the energy supply system. In a first step the following data sources and data holders were identified to be relevant to the accessibility and use of energy operational data at the district:

novaNet

... is a control system for building technology from Sauter [[21]] based on a two-wire bus system. Four subsystems (Sys1 - Sys4) are operated at the district on the basis of this technology. The system was installed until 2010 and is constantly being upgraded to newer technology. The connection with the IoT platform is transferred to the BACnet bus system via a separate gateway.

enteliWEB

... is a software package [[22]] for controlling energy systems based on the BACnet protocol (Building Automation and Control Networks), on the basis of which the energy systems running in the district are controlled and monitored. This system mainly uses sensor values to analyse the thermal energy supply (heating energy, cooling energy, heating outputs, cooling outputs, mass flows, etc.). To a lesser extent, however, electrotechnical measured values are also transmitted.

KNX

... is a field bus system in the field of building automation [[23]], which is mainly used at the district in the area of electricity supply. KNX stands for the word "Konnex" (Latin connexio: to connect). This system is used almost exclusively to transmit sensor data for analysing electrical energy and power.

[21] https://www.sauter-controls.at/
[22] https://deltacontrols.com/de/products/enteliweb/
[23] https://www.knx.org/knx-de/fuer-fachleute/

2.2.2 Complementing internal and adding external data sources

Based on the analysis of existing data sources, additional required data sources were identified. In relation to the intended functionality of the IoT platform the following data sources hat to be built up:

Climate Station

Since local and current climate data are essential for most of the digital energy services to analyse energy performance, a climate station was set up and put into operation as part of the project. Situated on top of the building Inffeldgasse 13 it provides local measurements of outdoor air temperature (sensor TEMP-UM-2.0 [[24]]), relative humidity and solar global and diffuse radiation (Sunshine Pyranometer SPN1 [[25]]).

LoRaWAN

A LoRaWAN [[26]] network (Low Power Wide Area Network) was set up in the building Inffeldgasse 21b to provide support for user-integrated control (see chapter 2.6.2). It is used to transmit measurement data relating to indoor air and component temperatures, indoor air humidity, CO_2 concentration and other relevant parameters to analyse energy performance and thermal comfort.

Meteoblue AG

... is a Swiss company from CH-4058 Basel that specialises in the analysis, processing and provision of meteorological data [[27]]. As part of the project, data packages (basic-1h, solaqr-1h, wind-1h, clouds-1h) were procured for a period of two years (2022-03-01 to 2024-02-29). Forecast data for the main meteorological values (air temperature, relative humidity, global radiation, diffuse radiation, etc.) are transmitted via an interface (API). The forecasts refer to the coordinates of the centre of the nearest grid cell (location coordinates: 47.07, 15.45). The forecast period is one week and is updated or retrieved once an hour.

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[24] https://delta-t.co.uk/wp-content/uploads/2016/10/Temperature-Sensors-User-Manual-v2.0.pdf

[25] https://delta-t.co.uk/product/spn1/

[26] https://www.lora-wan.de/

[27] https://docs.meteoblue.com/en/weather-apis/packages-api/introduction

2.2.3 Connecting data sources to the IoT Platform

The sensors mainly record thermal and electrical energy quantities and power, but also temperatures, mass flows, humidity, irradiation values, CO_2 concentrations and other parameters that describe the status. The sensor values are transmitted via the various gateways (BACnet server, KNX fieldbus, LoRaWAN) to the digital energy service ORGANIZE, where an MQTT broker forms the data entry point into the IoT framework (Figure 11).

The mosquitto **MQTT Broker** [[28]] (Message Queuing Telemetry Transport [[29]]) is able to provide a uniform access for a wide range of sensors and third-party systems. It is a lightweight publish/subscribe network protocol that transports messages between devices. In the survey conducted, it was cited by more than 90 % of the experts as an essential means of communication. The protocol usually runs over TCP/IP (TCP: Transmission Control Protocol, IP: Internet Protocol), however, any network protocol that provides ordered, lossless, bi-directional connections can support MQTT. The solution is compatible with NGSI-LD, which is an information model and API (Application Programming Interface) for publishing, querying and subscribing to context information. NGSI-LD has been standardized by ETSI (European Telecommunications Standardization Institute [[30]]) and is a core aspect of the FIWARE project [[31]].

The MQTT broker is queried for updates by a Python-based paho-mqtt client, which is subsequently referred to as the **MQTT agent**. In the event of a sensor update, the agent executes a demultiplexer, which performs the necessary decoding and pre-processing steps. However, if the agent receives queries that do not contain any user data, these are not processed by the MQTT agent. Two data formats are supported in this process. One is the "Ultralight 2.0 protocol", a text-based format based on key/value pairs, whereby keys and values are separated by a pipe symbol. The decoding was implemented with string splitting and indexing operations in Python. The native library provided by Python is used to decode JSON user data. The decoded user data is forwarded to the databases in the digital energy service STORE.

In addition to data transmission via MQTT Broker and MQTT Agent, another dockerised client is used to transmit data to the services. An HTTP agent queries an external web API (Application Programming Interface) from Meteoblue AG for climatological forecast data. This data is forwarded to STORE at the same time as all other incoming data and stored there. A more detailed description of the transmission of different sensor data and actuator data to the IoT platform, from internal and external sources, was presented and published by the project team at SMART'22 in Lazio (Italy) in November 2022:

► *Schranz, T.; Alflouji, Q.; Hirsch, T.; Schweiger, G.; An Open IoT Platform: Lessons Learned from a District Energy System, 2022 Second International Conference on Sustainable Mobility Applications, Renewables and Technology (SMART)*

[28] https://mosquitto.org/
[29] https://mqtt.org/
[30] https://www.etsi.org/
[31] https://www.fiware.org/

2.2.4 Iterative editing of sensor readings and service functionalities

Once the data sources had been identified and the IT transmission structure had been set up, the sensor values required in the services were integrated. A balance had to be found between the data requirements of the services and the availability of data and the associated procurement costs. An iterative pattern emerged in the course of the step-by-step implementation (Figure 12).

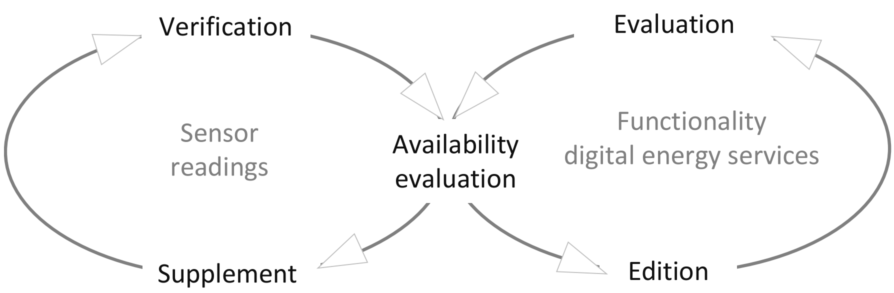

Figure 12: Sample process for implementing sensor values

The **first step** was to identify the sensor values essential for the functionality of the planned digital energy services. After the preliminary evaluation of the service functionality, in the **second step**, the corresponding sensor data had to be checked with regard to their availability. For each sensor value the importance for the service functionalities and the expected costs and time expenditures had to be taken into account.

In the case of positive procurement evaluation, the data sources had to be defined and the corresponding measuring points supplemented. After implementation, the newly supplemented sensor values had to be verified with respect to their transmission values. If, on the other hand, the availability of requested measured values was judged negatively, then the corresponding service had to be edited to manage without these values. Consequently, a new evaluation had to be carried out with regard to given validity of the service.

If it turned out that the functionality was insufficient, then the acquisition of the required senor values had to be reassessed. This led to the tapping into data sources und implementation of supplemental sensor readings. The result was a permanent match between data requirements and data availability, which lead to creation of additional data sources.

For example, a local climate station had to be established as soon as it became clear that reliable local climate data were not be available with existing facilities. This iterative process was repeated several times to achieve the best possible match between service functionalities, data requirements and data supply.

2.3 STORE

When analysing complex energy systems, it is not only the current status of the energy flows that is of great interest, but also the energy-related behaviour over different periods in the past. To do this, the current values must be stored in time series data bases. Each time series must also contain semantic data about the respective data points. This contains localisation of the measuring point, type of measuring method, units and post-processing applied. These are essential information in this context in order to be able to correctly interpret and classify measured values and the evaluations or statements generated from them. In addition, access to the stored data must be made possible for further processing and the traceability of this data. The target of the STORE service results from these considerations.

The **target** of this service is to store time series and semantic data of sensor data from the district energy systems, as well as from external sources, and to make them available for all other digital energy services.

The digital energy service STORE developed in the UserGRIDs project receives updates of the sensor values (05), (06), (07) from the digital energy service ORGANIZE, which are stored in an 'Ontology Database' (MongoDB) (Figure 13).

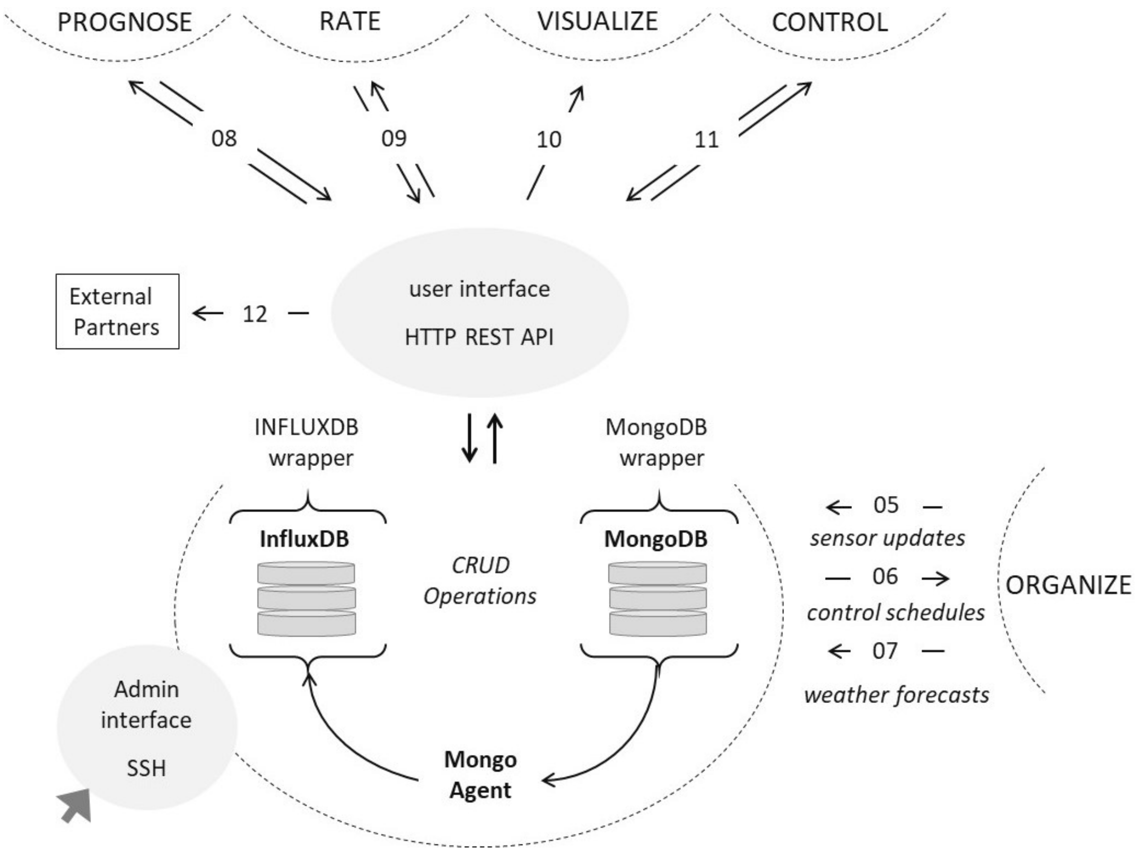

Figure 13: Functional scheme of digital energy service STORE

A Mongo Agent requests the sensor values at 15-minute intervals and, if a new value is available, writes it to the 'Time Series Database' (InfluxDB). Data can be read from this database via a user interface in order to make it available to other services PROGNOSE (08), RATE (09), VISUALIZE (10), CONTROL (11). Data generated by these digital services can in turn be stored in the databases. External partners can also be granted reading rights for individual sensor values (12). The maintenance of this system by administrators is enabled by the admin interface (Figure 13). The work described in chapters 2.3.1 was carried out to develop the structure shown in Figure 11 and to set up and test the hardware and software at the Innovation District Inffeld.

2.3.1 Implementation of ontology and time series databases

The 'Ontology Database' is implemented as MongoDB and thus belongs to the NoSQL databases (Not only SQL). In contrast to the widely used relational databases, these do not use a fixed table schema and can be described as a 'document-orientated' database management system. MongoDB [[32]] can manage JSON (JavaScript Object Notation), which is a compact data format in text form that can be read by both humans and machines.

The 'Time Series Database' is implemented as InfluxDB [[33]]. InfluxDB is a high-performance database for real-time data developed by the company influxdata. As an 'open source' product, InfluxDB is widely used in the 'open source developer community'. Wrappers were developed to execute CRUD operations. CRUD stands for the abbreviations 'Create, Read, Update and Delete', i.e. the basic actions for operating a database. This structure ensures that the current databases can be easily replaced by other databases with little processing effort in the course of further development.

2.3.2 Handling different measurement and transmission methods

Most of the processes in the energy control systems at the Innovation District Inffeld work on the basis of the BACNET 'change of value' (COV) principle. The functionalities of the digital energy services, on the other hand, are largely based on the 'equidistant time series' principle.

- Change of value: The sensors measure at short time intervals and compare the measurement results with the previous measured value. If the difference between the previous measured value and the current measured value exceeds a defined limit, the current measured value is used for further processing.

- Equidistant time series: Time series that are divided into discrete equidistant time steps. Each time step is assigned a unique value that represents either an actual individual value at a defined point in time within the time step, or an average of several individual values that occurred within the time step.

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[32] https://www.mongodb.com/de-de
[33] https://www.influxdata.com/products/influxdb/

To obtain the required 'equidistant time series', a service called 'MongoAgent' is implemented. This checks at 15-minute intervals whether new energy-related sensor values have arrived in the MongoDB and transfers them to the InfluxDB. The time resolution was selected so that it meets the requirements of E-Control [[34]] for intelligent measuring devices [[35]]. If the respective data source is updated at intervals of 15 minutes (or less), time series of energy-related sensor values with a time resolution of 15 minutes are stored in the InfluxDB. A time resolution of 15 minutes is detailed enough for most of the measured energy-related processes. All other measured values (temperatures, CO_2 concentration, window contacts, etc.) remain in principle 'change of value' and are passed on from the MongoDB to the InfluxDB and stored there each time the 'Operator Gateways' are updated.

2.3.3 Labelling of sensor data streams

The sensor data that is transmitted to the service STORE comes from various sources. These can be assigned to different specialist areas and are used for different purposes. Each provider of data naturally uses designations that correspond to the respective department or are adapted to the respective environment. As a result, the names of the sensor values or data series that are transmitted to the service STORE have a wide variety of syntactic and semantic structures. The choice of names for the transmitted data or data ranges is within the sphere of influence of the data provider and can typically only be influenced to a very limited extent (Figure 14 – column a).

Data streams with different nomenclatures must therefore be bundled and stored in STORE on the IoT platform. To ensure uniqueness in this context and exclude duplicate designations, the individual data streams are assigned unique 'identifiers' (Figure 14 - column b). The structure of the identifier is based on NGSI-LD, an information model and interface for processing context information, developed and standardised by ETSI [[36]], a European Standards Organisation focusing on the creation of standards in the area of 'Communication Networks and Services'. Accordingly, each entry in the databases requires a unique identification in the format of the NGSI-LD (internal designation: influxDB_id). This must consist of a prefix, a type designation and an alphanumeric identification, each separated by a colon.

Data from a wide range of disciplines and contexts is processed within digital energy services. The sensors are therefore labelled with names that correspond to external nomenclatures from different contexts. In MongoDB, it must therefore be possible to assign further different names to each uniquely identified sensor value. The established designations (Figure 14 - column c) are also given to enable the responsible technicians to relate the familiar designations to the different sensor names.

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[34] https://www.e-control.at/

[35] https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20007497

[36] https://www.etsi.org/

An independent, coherent nomenclature for the energy technology sector had to be developed for the RATE service, which is shown in Figure 14 - column d. In addition, each sensor is assigned context information in relation to characteristic and location (Figure 14 - column e - j). This provides information on technical specifications, data provision and localisation of the sensors.

Sensor Identficators								Sensor Characteristic				Sensor Localisation	
a	b	c	d					e	f	g	h	i	j
			Rating										
Data source to MQTT	InfluxDB _id	ENERGO+	Area Code	Address Code	Component Code	Direction Code	Domain Code	Unit	Resolution	Timestep [min]	Source	District Name	Building Address
20_120210	urn:ngsi-ld:Energy:20_120210	IN12-H05	IN	_ IN12	_ DHS	_ out	_ HE	MWh	0,001	15	KNX-Wild	Inffeld	Inffeldgasse 12
20_160210	urn:ngsi-ld:Energy:20_160210	IN16AC-H06	IN	_ IN16	_ DHS	_ out	_ HE	MWh	0,100	15	KNX-Wild	Inffeld	Inffeldgasse 16
20_999100	urn:ngsi-ld:Energy:20_999100	IN11-SHSP05i	IN	_ IN11	_ DES	_ out	_ EE	kWhe	1,000	15	KNX-Wild	Inffeld	Inffeldgasse 11
20_000100	urn:ngsi-ld:Energy:20_000100	IN12-SHSP02i	IN	_ IN12	_ DES	_ out	_ EE	kWhe	1,000	15	KNX-Wild	Inffeld	Inffeldgasse 12
20_100120	urn:ngsi-ld:Energy:20_100120	IN10-ST2	IN	_ IN10	_ ET20	_ out	_ EE	kWhe	0,001	15	KNX-Wild	Inffeld	Inffeldgasse 10
In1In11K1_E930_S94_P10_Nrg	urn:ngsi-ld:Energy:IN11_ST1	IN11-ST1	IN	_ IN11	_ ET1	_ out	_ EE	kWhe	0,001	15	BACNET-EAM	Inffeld	Inffeldgasse 11
In1In11K1_E930_S94_P11_Nrg	urn:ngsi-ld:Energy:IN11_ST2	IN11-ST2	IN	_ IN11	_ ET20	_ out	_ EE	kWhe	1,000	15	BACNET-EAM	Inffeld	Inffeldgasse 11
In1In11K1_E930_S94_P15_Nrg	urn:ngsi-ld:Energy:IN11_ST3	IN11-ST3	IN	_ IN11	_ ET30	_ out	_ EE	kWhe	1,000	15	BACNET-EAM	Inffeld	Inffeldgasse 11
20_120110	urn:ngsi-ld:Energy:20_120110	IN12-ST1	IN	_ IN12	_ ET1	_ out	_ EE	kWhe	0,200	15	KNX-Wild	Inffeld	Inffeldgasse 12
20_130120	urn:ngsi-ld:Energy:20_130120	IN1319-ST2	IN	IN13	_ ET2	_ out	_ EE	kWhe	0,200	15	KNX-Wild	Inffeld	Inffeldgasse 13
20_160110	urn:ngsi-ld:Energy:20_160110	IN16AC-ST1	IN	_ IN16A	_ ET1	_ out	_ EE	kWhe	0,500	15	KNX-Wild	Inffeld	Inffeldgasse 16
20_160115	urn:ngsi-ld:Energy:20_160115	IN16AC-ST1R	IN	_ IN16A	_ ET1R	_ out	_ EE	kWhe	0,500	15	KNX-Wild	Inffeld	Inffeldgasse 16
20_160120	urn:ngsi-ld:Energy:20_160120	IN16AC-ST2	IN	_ IN16A	_ ET2	_ out	_ EE	kWhe	0,010	15	KNX-Wild	Inffeld	Inffeldgasse 16
20_180130	urn:ngsi-ld:Energy:20_180130	IN18-ST3	IN	_ IN18	_ ET3	_ out	_ EE	kWhe	0,010	15	KNX-Wild	Inffeld	Inffeldgasse 18
IN1IN21K1_A310__P011_Nrg	urn:ngsi-ld:Energy:IN21_ST1	IN21-ST1	IN	_ IN21	_ ET1	_ out	_ EE	kWhe	1,000	15	BACNET-EAM	Inffeld	Inffeldgasse 21
IN1IN21K1_A300__P008_Nrg	urn:ngsi-ld:Energy:IN21_ST2	IN21-ST2	IN	IN21	_ ET2	_ out	_ EE	kWhe	0,250	15	BACNET-EAM	Inffeld	Inffeldgasse 21
IN1IN21K1_A310__P010_Nrg	urn:ngsi-ld:Energy:IN21_ST3	IN21-ST3	IN	_ IN21	_ ET3	_ out	_ EE	kWhe	0,500	15	BACNET-EAM	Inffeld	Inffeldgasse 21
IN1IN21K1_A300__P051_Nrg	urn:ngsi-ld:Energy:IN21_ST5	IN21-ST5	IN	_ IN21	_ ET5	_ out	_ EE	kWhe	1,000	15	BACNET-EAM	Inffeld	Inffeldgasse 21
IN1IN21K1_A300__P052_Nrg	urn:ngsi-ld:Energy:IN21_ST6	IN21-ST6	IN	IN21	_ ET6	_ out	_ EE	kWhe	1,000	15	BACNET-EAM	Inffeld	Inffeldgasse 21
20_230110	urn:ngsi-ld:Energy:20_230110	IN23-ST1	IN	_ IN23	_ ET1	_ out	_ EE	kWhe	0,200	15	KNX-Wild	Inffeld	Inffeldgasse 23
20_240110	urn:ngsi-ld:Energy:20_240110	IN24-ST1	IN	_ IN24	_ ET1	_ out	_ EE	kWhe	0,100	15	KNX-Wild	Inffeld	Inffeldgasse 24
20_240125	urn:ngsi-ld:Energy:20_240125	IN24-ST2_RPV	IN	_ IN24	_ ET2R	_ out	_ EE	kWhe	0,100	15	KNX-Wild	Inffeld	Inffeldgasse 24
20_251110	urn:ngsi-ld:Energy:20_251110	MA-ST1	IN	_ IN25A	_ ET1	_ out	_ EE	kWhe	0,001	15	KNX-Wild	Inffeld	Inffeldgasse 25A
20_251102	urn:ngsi-ld:Energy:20_251102	MA-ST3	IN	_ IN25A	_ ET3	_ out	_ EE	kWhe	1,000	15	KNX-Wild	Inffeld	Inffeldgasse 25A
20_252115	urn:ngsi-ld:Energy:20_252115	MB-ST1_R	IN	_ IN25B	_ ET1R	_ out	_ EE	kWhe	0,001	15	KNX-Wild	Inffeld	Inffeldgasse 25B
20_252125	urn:ngsi-ld:Energy:20_252125	MB-ST2_R	IN	_ IN25B	_ ET2R	_ out	_ EE	kWhe	0,001	15	KNX-Wild	Inffeld	Inffeldgasse 25B
20_256110	urn:ngsi-ld:Energy:MF_ST1	MF-ST1	IN	_ IN25F	_ ET1	_ out	_ EE	kWhe	0,200	15	KNX-Wild	Inffeld	Inffeldgasse 25F
20_256125	urn:ngsi-ld:Energy:20_256125	MF-ST2_R	IN	_ IN25F	_ ET2R	_ out	_ EE	kWhe	0,200	15	KNX-Wild	Inffeld	Inffeldgasse 25F
20_130132	urn:ngsi-ld:Energy:20_130132	IN1319-SWP2	IN	_ IN13	_ HP2	_ in	_ EE	kWhe	0,020	15	KNX-Wild	Inffeld	Inffeldgasse 13
20_230121	urn:ngsi-ld:Energy:20_230121	IN23-SWP1	IN	_ IN23	HP1	_ in	_ EE	kWhe	0,020	15	KNX-Wild	Inffeld	Inffeldgasse 23
20_230122	urn:ngsi-ld:Energy:20_230122	IN23-SWP2	IN	_ IN23	HP2	_ in	_ EE	kWhe	0,020	15	KNX-Wild	Inffeld	Inffeldgasse 23
20_330121	urn:ngsi-ld:Energy:20_330121	IN33-S_WP	IN	_ IN33	HP1	_ in	_ EE	kWhe	0,001	15	KNX-Wild	Inffeld	Inffeldgasse 33
20_136121	urn:ngsi-ld:Energy:20_136121	PE136-SWP1	IN	_ PE136	_ HP1	_ in	_ EE	kWhe	0,010	15	KNX-Wild	Inffeld	Petersgasse 136
20_136122	urn:ngsi-ld:Energy:20_136122	PE136-SWP2	IN	_ PE136	_ HP2	_ in	_ EE	kWhe	0,010	15	KNX-Wild	Inffeld	Petersgasse 136
...	...	...	...	_ ...	_ ...	_ ...	_ ...	...	...	...	...	...	...

Figure 14: Extract from the sensor list with identification, characteristic and location of the sensor values

2.3.4 Integrating interfaces for management and access

Access to the administration of the databases (admin interface) is set up via SSH (Secure Shell) network protocol. Operators and administrators can create, edit, update, delete or export entities in MongoDB. It can also be used to insert, change and delete access authorisations for the MQTT broker (API keys).

The access to the data of the data bases (user interface) is implemented via an HTTP REST API. This 'Representational State Transfer Application Programming Interface' enables users to access the data of both databases. The interface was developed based on 'Swagger' [[37]]. These enable the creation and documentation of the API and its operation in a cloud solution. Information is essentially transmitted via the interface in the description language JSON (JavaScript Object Notation) [[38]]. The 'Inframonitor API' [[39]] developed for this purpose provides information on the set of rules to be applied for the correct transmission of data. In this way, data from energy meters and the climate station can be transmitted as individual data series or entire packets of data series. Data series from the weather forecast (see chapter 2.2.2) and other sources can also be read from the databases. Also the data processed by the RATE and CONTROL services (e.g. operationPlan) is also transferred to the databases. Metadata on the sensors and their ontology can also be accessed via the API.

[37] https://swagger.io/
[38] https://www.json.org
[39] https://inframonitor.tugraz.at:3000/v2/ui/

2.4 PROGNOSE

With the expansion of volatile energy sources such as solar and wind energy, other parts of the energy systems need to become more flexible to match the available energy from renewable resources with demand in terms of location, time, and quantity. To enable this, various demand-side management (DSM) measures are needed. DSM comprises a range of measures aimed to change end users' demand patterns, including the adoption of energy efficient appliances, reducing energy consumption, shifting consumption to off-peak times, and applying dynamic pricing mechanisms. Predicting loads is central to many of these applications: model predictive control needs reliable predictions as boundary conditions to derive optimal control strategies, peak-shave applications to estimate potential flexibilities, and fault detection to provide a reliable baseline to detect faults. Fault detection gets its importance because complex energy systems depend on a high number of different system variables. Their multitude, constant fluctuations and multiple interactions far exceed human diagnostic capabilities. Digital methods, and in particular prognostic technology, can be used to diagnose complex systems almost in real time. The following target resulted from this background.

The **target** of this service is to provide models for predicting energy yield and energy consumption in order to automatically detect faults.

A digital framework was implemented for the Innovation District Inffeld in which different data-driven and physical forecasting models can be developed and tested for the Innovation District Inffeld (Figure 15).

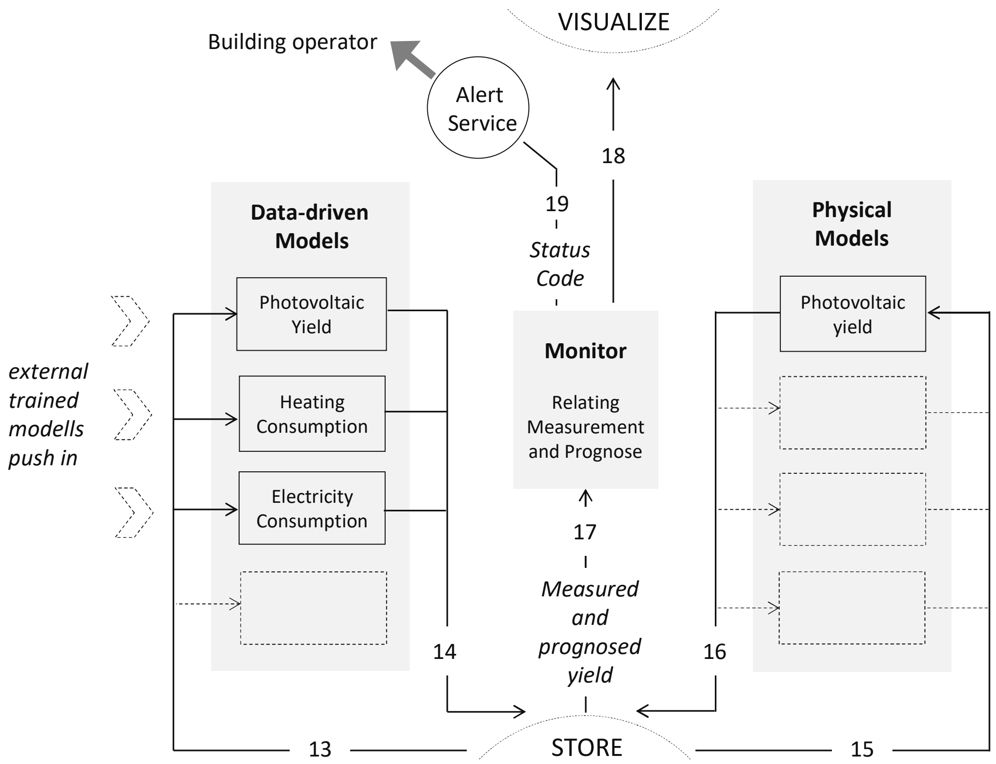

Figure 15: Functional scheme of digital energy service PROGNOSE

Data on energy consumption, PV generation and climatological forecast values are transmitted hourly from the service STORE to the 'data-driven models' (13) and to the 'physical models' (15). In both the energy yields of three photovoltaic systems are predicted and saved in the STORE service (14) (16). The forecast results are automatically transmitted to the monitor (17), where they are compared with real-time measurement data and visualised in a dashboard (18). If there is too great a deviation between the forecast values and the measured values, an error message is sent to the person responsible for the system via the 'Alert Service' (19).

The time horizon for load projections is usually divided into short-term, medium-term, and long-term categories, and the specific time horizon for each category varies. In UserGRIDs, we consider a timeframe of one hour to a few days as short-term, and everything beyond as long-term.

2.4.1 Energy yield prediction of PV facilities

At the beginning of 2022, three photovoltaic systems are in operation at the Innovation District Inffeld; Inffeldgasse 11 (PV.IN23.01), Inffeldgasse 26 (PV.IN26.01) and Inffeldgasse 16-16c (PV.IN16ABC.01); see Figure 10). The yield forecasts for these systems were carried out using two fundamentally different approaches, based on data driven models and on the basis of physical models. The models use the basic data on the PV systems determined in the service structure (see chapter 2.1.6)

The data-driven forecasting models developed are based on the neural network. The networks are trained using historical data in an external, infrastructure and stored in a "forecast model directory". The global and diffuse irradiation measured by the weather station, as well as several parameters describing the calculated position of the sun, are used as inputs. The models have been made publicly available on GitHub [40].

The physical modelling corresponds to the basic plant structure of the real systems. The individual module groups are each assigned to an inverter. The solar irradiation on the modules and the associated loss factor IAM (incident angle reflection) is calculated according to the "ASHRAE IAM Model" [41]. The dependence of the yield on the temperature of the module is calculated according to Fuentes [42]. In this method, the module temperature is calculated as a function of the climatic parameters of air temperature and wind speed. The type of installation, module dimensions, module orientation and module radiation properties are also included. AC, DC and losses are determined using the PVWatts method [43]. The DC model calculates the electrical DC power as a function of the irradiation and the cell temperature and the AC model describes the efficiency of the inverter as a function of the capacity utilisation.

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[40] https://github.com/tug-cps/datamodels

[41] https://pvpmc.sandia.gov/modeling-steps/1-weather-design-inputs/shading-soiling-and-reflection-losses/incident-angle-reflection-losses/ashre-model/

[42] http://www.bwilcox.com/BEES/docs/Fuentes%20-%20PV%20Arrays.pdf

[43] https://www.nrel.gov/docs/fy14osti/62641.pdf

The "monitor" service analyses deviations between predicted and measured values, generating alerts when these deviations exceed predefined thresholds. Figure 16 shows the forecast and measured PV consumption over one year (aggregated daily values) and Figure 17 exemplarily for one week.

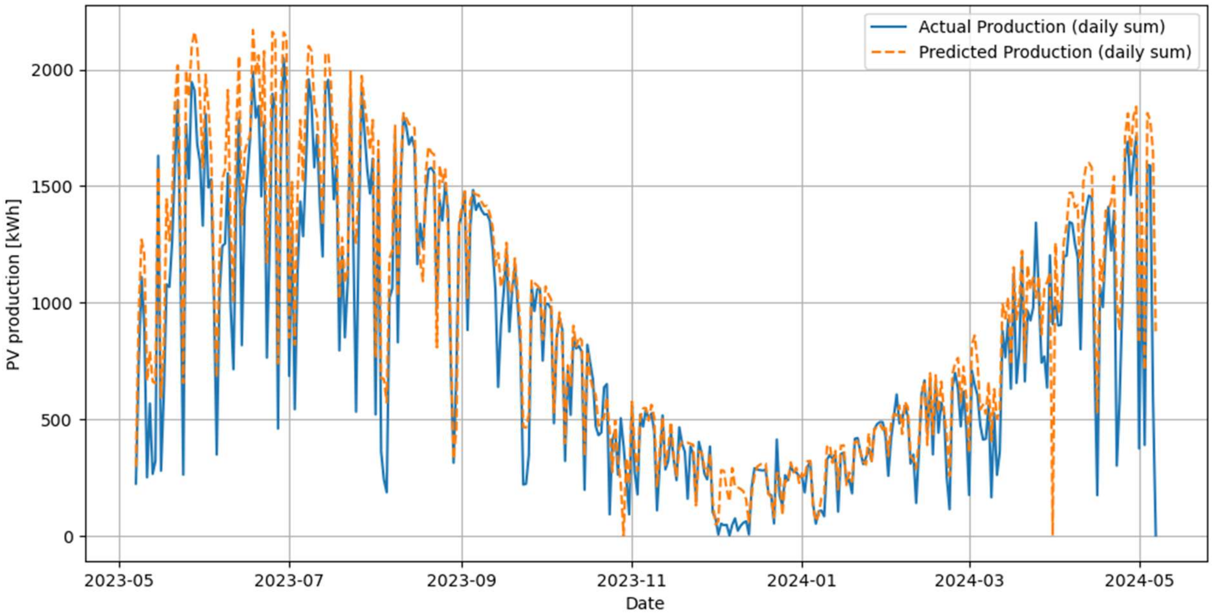


Figure 16: Comparison of actual production (PV.IN16ABC.01) with predicted production over one year (daily sum).

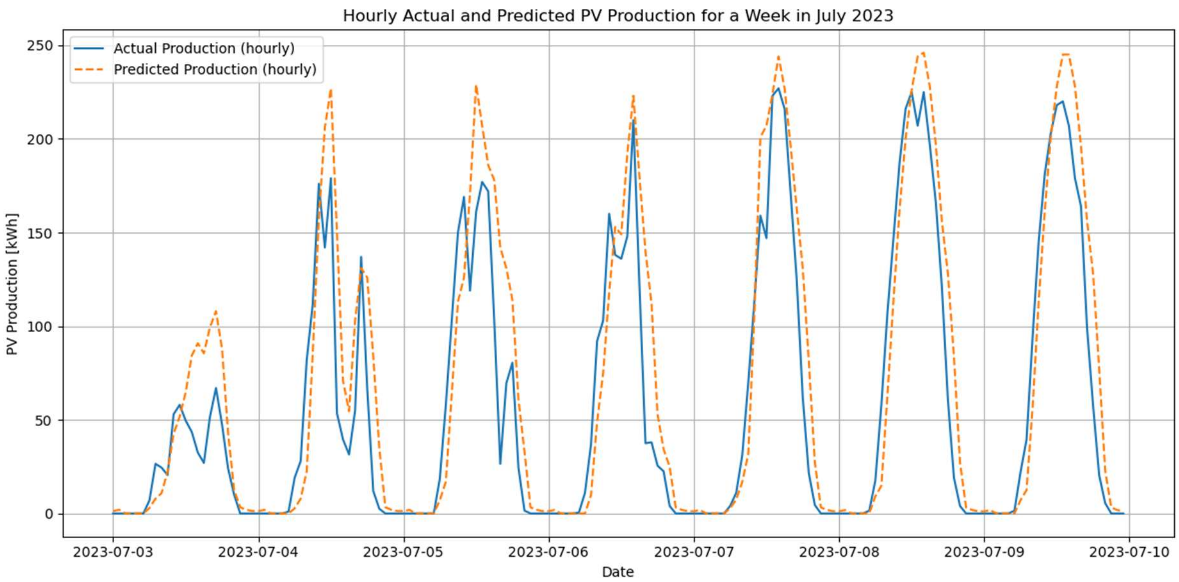


Figure 17: Comparison of actual production (PV.IN16ABC.01) with predicted production over the course of a week in summer 2023 (hourly values).

Dashboards have been developed for visual monitoring, which are displayed in the VISUALISE service (see chapter 2.8.3). The PV diagnosis service has been online for more than a year. No significant deviations occurred during this period, and therefore no faults were reported.

2.4.2 District energy: short-term prediction

The Innovation District Inffeld has different types of buildings and usages, ranging from offices, study halls, classrooms, gastronomy, and labs (see Figure 6). A particular challenge is the unpredictable energy consumption patterns from **high energy demand labs**. The question of how to deal with these special performance peaks led to a series of investigations in UserGRIDs. While these loads appear to be purely stochastic from a historical data analysis point of view, they are planned and scheduled events in the real world (Figure 18). This scheduling information is usually available before the actual experiments are undertaken. We developed ML models for short-term prediction incorporating consumption data from previous hours and long-term prediction models capable of producing predictions over any period with a consistent error rate by relying solely on average climate data.

Lab	Peak (kW)	Connected devices
1/9	372	Server room; Heat pumps (cooling + heating)
2/9	390	Large engine centre (test hall); research centre
3/9	430	Server room; Heat pumps (experiment); Climate chamber
4/9	2426	Thermal turbo-machinery (big compressors)
5/9	2256	Server room; Heat pumps (cooling)
6/9	2003	turbo-machinery compressors
7/9	2003	Heat pumps (cooling + experiment)
8/9	2365	Heat pump (cooling + experiment); engines and test benches
9/9	365	Heat pumps (cooling + heating); Clean room

Figure 18: Lab loads

Whenever the power consumption of a laboratory/special load exceeds its mean by more than 0.15 times its standard deviation, we assume the special load to be active. The resulting binary vectors form our representation of laboratory/special loads scheduling information. The models used in our experiments can be split into two categories, based on the approach to the problem, utilized feature sets, and temporal scope. The first category is formed by short-term prediction models that predict the next time step's energy consumption in a recurrent manner based on the previous values. The second consists of long-term prediction models that predict the consumption for any given time in the future, based only on general information. The base features used in both model categories are shown in Figure 19.

Workday - Binary value being 1 for Monday until Friday, and 0 for Saturday and Sunday
Class day - Binary value being 1 for workdays during the semester, 0 for weekends, holidays and lecture-free periods
Day of Week - Cyclic encoding of the day of week (0-6)
Month - Cyclic encoding of the month (0-11)
Time of day - Cyclic encoding of the time in hours (0-23)
Temperature - Outside temperature in degrees Celsius
Lab Schedule - Binary value for each of the nine laboratories being 1 if the special load is in use and 0 otherwise

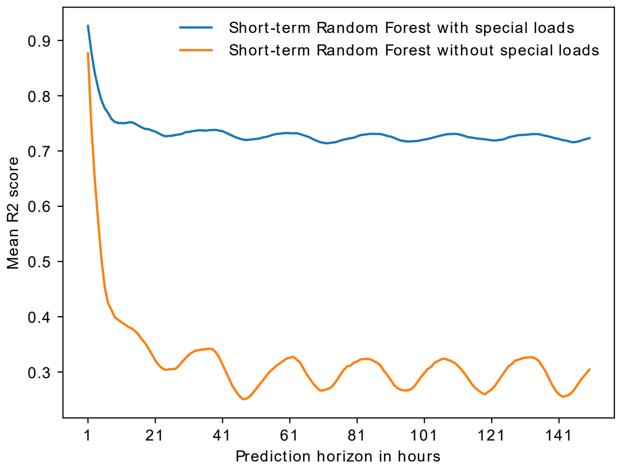
Figure 19: base features

Short-Term Prediction Models have the last N hours of energy consumption as additional features and predict the consumption of the next hour. To perform predictions over longer periods, the models are applied recurrently, with the prediction for time T being fed back into the model as a feature to predict the next timestamp T +1. The weather information (temperature) used in this class of models is based on weather forecasts obtained at T =0. Figure 20 shows the R2 scores of cross-validation for a prediction horizon of up to five hours. The linear regression and random forest model perform best for predicting the energy consumption of the upcoming hour. As to be expected, model performance decreases towards longer prediction horizons. This is due to the prediction error accumulating as the output of the model for one prediction step is fed back into the model as a feature for predicting the next step. Beyond a prediction horizon of five hours, linear regression is outperformed by the DNN. The random forest performs best overall and is chosen for further experiments.

Model	Prediction horizon in hours				
	1	2	3	4	5
XGBoost	0.90	0.85	0.81	0.78	0.76
Linear Regression	0.91	0.85	0.81	0.79	0.79
Elastic Net	0.46	0.43	0.41	0.41	0.41
Decision Tree	0.84	0.79	0.75	0.72	0.69
Random Forest	0.92	0.88	0.85	0.82	0.79
Bayesian Ridge	0.91	0.85	0.81	0.79	0.79
ANN	0.88	0.83	0.80	0.79	0.78
DNN	0.91	0.85	0.82	0.80	0.79

Figure 20: Mean R2 scores from time-series cross validation

Figure 21 (left) shows the energy consumption prediction when including or excluding lab schedule information from the feature set. We can observe that the models integrating heavy load scheduling information strictly outperform the models without. Furthermore, the prediction performance of models without scheduling information very quickly deteriorates to impractical levels, dropping below R2 ≤ 0.5 within 4 hours, while the models incorporating this information continue performing at or above R2 ≥ 0.7. We conclude that models substantially benefit from the scheduling information for special loads.



Model	MSE [MWh]	R2	MAE [kWh]	MAPE
XGBoost	161	0.75	250	0.11
Linear Regression	149	0.78	263	0.12
Elastic Net	407	0.41	396	0.18
Decision Tree	151	0.76	246	0.11
Random Forest	119	0.80	220	0.10
Bayesian Ridge	145	0.79	257	0.12
ANN	157	0.78	251	0.11
DNN	177	0.75	305	0.11

Figure 21: left: Mean R2 scores from time-series cross validation, right: mean scores of long-term prediction

2.4.3 District energy: long-term prediction

Long-Term Prediction Models use only the base features described above to predict the energy consumption for an arbitrary point in the future. The weather information (temperature) used in this class of models is based on climate data collected from past years and represented as monthly means. Figure 21 (right) shows the cross-validation results of the long-term energy prediction models utilizing special load scheduling information. As the used models do not rely on loads for previous time steps, the reported scores are the result of averaging the prediction performance of all points in time within the cross-validation test splits (test split sizes ranging in size from 88 to 112 days). Again, Random Forest models perform best at the task of load prediction in all metrics (e.g., R2 = 0.80). The Bayesian Ridge model achieves the second-best performance in terms of MSE and R2 (MSE = 145, R2 = 0.79).

2.4.4 District energy: Prediction using ensemble models

Ensemble Models means that we select the best-performing model from each category, short- and long-term, and use their outputs as features for a custom Voting Regressor model producing a final prediction. The input of this Voting Regressor consists of the predictions of the short-term model for a period of N =150 hours starting at time T, and the predictions of the long-term model for the same period predicted from start time T. A Logistic Regression model is used as a Voting Regressor to combine the benefits of the short- and long-term models.

Figure 22 shows scores of the Voting Regressor together with the underlying short- and long-term. The performance of the Ensemble across the transition point, where the long-term model is starting to outperform the recurrent model, is substantially better than what can be achieved by switching short-term and long-term models depending on the current prediction horizon (R2 = 0.85 vs. R2 = 0.82 for a 4-hour prediction). Also for mid- and long-term predictions after the transition point, the Voting Regressor performs better than the long-term model alone (R2=0.81 vs. R2 = 0.80 for a 72-hour prediction).

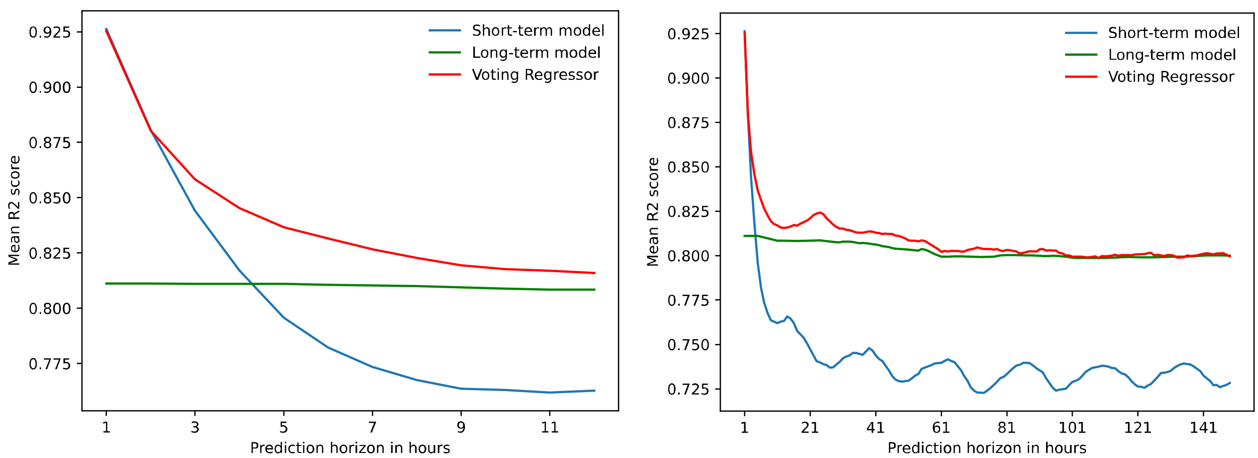


Figure 22: left: Comparsion of the best performing short- and long-term models (both Random Forests), right: R2 scores from cross-validation of the Voting Regressor, short- and long-term models over a prediction horizon of 150 hours.

Figure 21 shows the prediction result of our Ensemble for a 150-hour prediction horizon with, and without lab schedule information. Again, we can observe that load prediction without scheduling information is infeasible due to the stochastic nature of these heavy loads. Peaks are even predicted for points in time where no peak exists. This figure shows that the inclusion of lab plan information is crucial for prediction accuracy. In the future, discussing how this information can be provided effectively will be necessary. This will first require discussions with individual lab operators to determine the extent to which they have such data in advance (days? weeks?) and how frequently last-minute changes are made to these plans. The proposed solution must then be seamlessly integrated into existing scheduling systems (e.g., simple calendars) to minimize the burden on lab staff.

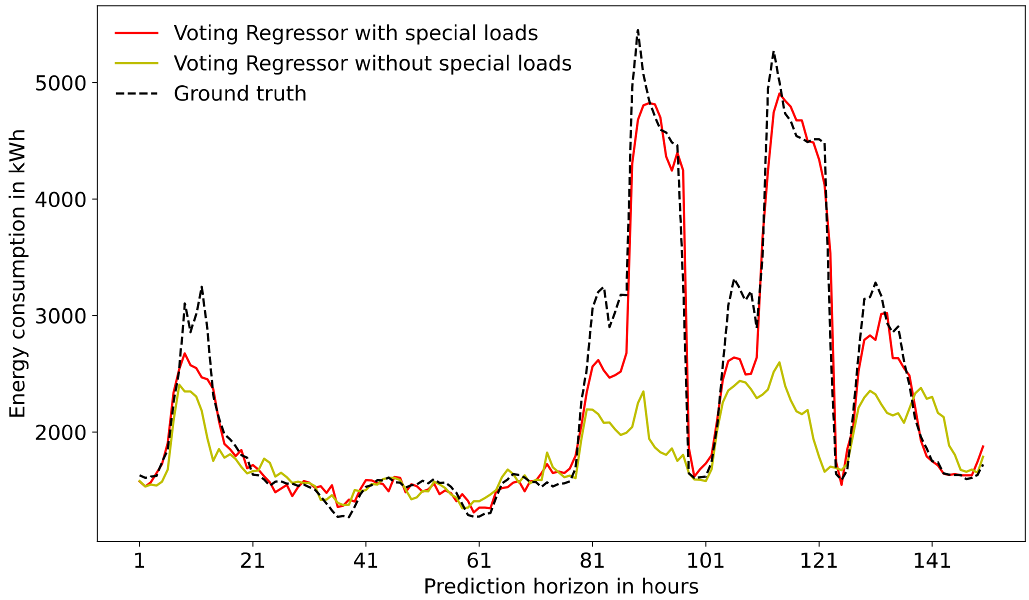


Figure 23: Prediction using the Voting Regressor with and without lab schedule information for the next 150 hours

2.5 RATE

The evaluation of energy systems can be divided into different aspects. The first question is often whether the energy consumption is in good correlation with the benefits achieved, i.e. the question of energy efficiency. Then it is necessary to clarify which energy sources (heat, electricity, gas) are used to cover the consumption and in what quantities. This in turn allows the costs and environmental impact to be assessed. If costs, energy quantities and environmental impacts are processed into meaningful values in a defined manner, these are referred to as key performance indicators (KPIs). These can represent absolute values or be related to basic parameters in order to enable comparative assessments of different systems. The target for the Service RATE is derived from these correlations.

The **target** of this service is to evaluate the energy-relevant measurement data and to provide assessments on the basis of comprehensive Key Performance Indicators (KPIs).

The digital energy service RATE receives energy-related sensor data for heat quantities and electrical energy consumption from STORE (20) via the user interface and transmits this to the aggregation routine (Figure 24). There, the sensor values are combined into thermal and electrical energy flows with a time step of one hour.

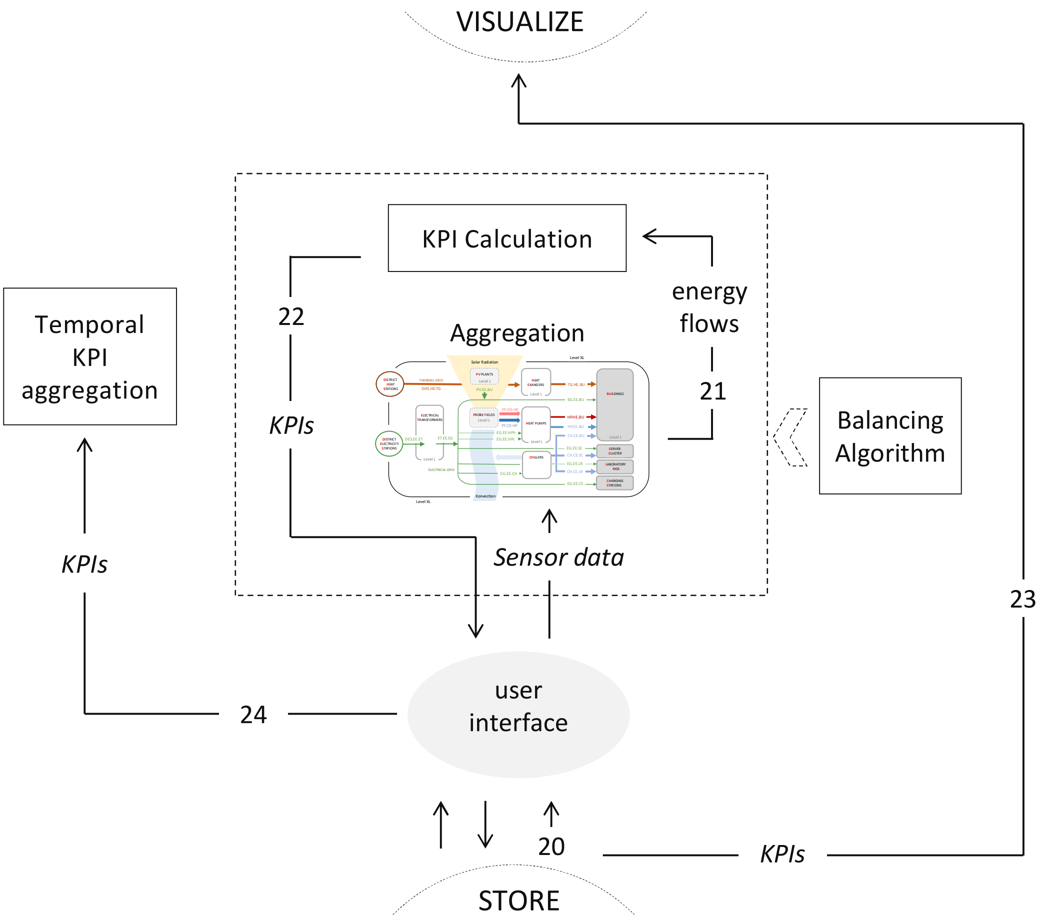


Figure 24: Functional scheme of digital energy service RATE

These are in turn processed into hourly key performance indicators (KPIs) to evaluate the energy performance (21). The hourly KPIs are then transferred to STORE via the user interface, where they are stored in time series (22). From STORE, the KPIs stored on an hourly basis can be read out for temporal aggregation (23) in order to create monthly and annual analyses. In parallel or in addition, the hourly KPIs are forwarded to VISUALIZE to be displayed in dashboards (24).

2.5.1 Structuring the energy supply system

The energy supply structure must be analysed as the basis for evaluating the performance of the energy supply (Figure 25). The Innovation District Inffeld is supplied with heat via two DISTRICT HEATING STATIONS. This is transported in a THERMAL GRID (see Figure 8) and delivered to the BUILDINGS via HEAT EXCHANGERS. Two DISTRICT ELECTRICITY STATIONS supply the district with electrical energy at a voltage of 20 KV. An internal DISTRICT ELECTRICITY GRID (level 5) feeds ELECTRICAL TRANSFORMATORS in which the voltage is reduced. The individual loads are supplied with electrical energy from the TRANSFORMATORS via a DISTRICT ELECTRICITY GRID (level 7). PV PLANTS also feed into this distribution grid. Some of the buildings are heated and cooled by HEAT PUMPS coupled with PROBE FIELDS. In addition, a number of CHILLERS provide room cooling and process cooling. The majority of energy consumption is caused by BUILDINGS. In spatial terms, these also include SERVER CLUSTER, LABORATORY RIGS and CHARGING STATIONS. In energy balancing, particularly energy-intensive systems in these functional groups are balanced independently and not allocated to the respective building.

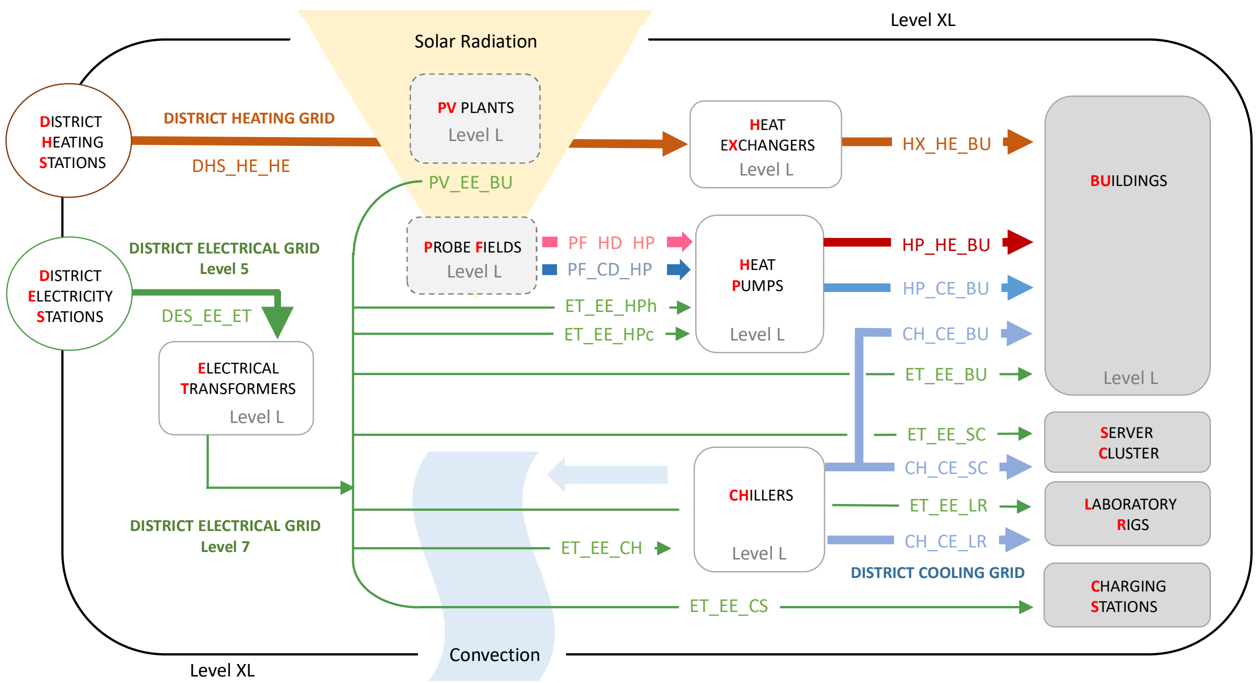


Figure 25: Visualisation of the basic energy supply structure at the district and energy flows on level L

The energy supply system of the Innovation District Inffeld contains a large number of subsystems and components. A **hierarchical object-oriented three level structure** (Level M, L and XL) was developed to systematise the real system in such a way that it allows to assess energy performance and greenhouse gas emissions. The structure was designed as expandable upwards (e.g. further districts), as well as downwards, in order to enable more detailed analyses (Figure 25).

- The top level (**level XL**) represents the entire Innovation District Inffeld. It forms the sum of subsystems, components and energy flows that are located inside of the district borders. It also considers energy flows crossing the district borders (district electricity supply, district heat supply, solar radiation and air convection).
- The level below (**Level L**) clusters all subsystems and components that relate to the same kind in functional groups. The functional groups are electrical transformers, PV plants, probe fields, heat exchangers, heat pumps, chillers, buildings, server clusters, laboratories and charging stations.
- In the most detailed level (**Level M**) each functional group is divided in its actual subsystems. For example the functional group buildings is broken down into twenty-seven individual buildings, each of which forms its own accounting system.

The structuring is supported by a **nomenclature**. This enables the clear identification of each subsystem and each energy flow in the M, L and XL levels. The naming system was designed to include key information about the properties in the name itself, which is intended to facilitate intuitive use. The labelling of the address code (AC) is composed by a two letter abbreviation of the street name, followed by the house number (e.g. IN11 for building Inffeldgasse 11). So each building of the district is assigned a unique abbreviation.

Each functional group at level L is to be seen as the sum of all subsystems of the same kind. For example, the subsystem "Electrical Transformers" is the sum of all electrical transformers at the District. Each subsystem of level L is abbreviated by two or three letters (DHS…district heat station, DES …district electricity station, ET…electrical transformer, PV…photovoltaic plant, PF…probe field, HX…heat exchanger, HP…heat pump, CH…chillers, BU…building, SC…server cluster, LR…laboratory rig, CS…charging station).

The labelling of energy flows on level L follows a Syntax containing three parts. The left part shows the abbreviation for the component the energy flow comes from (e.g. HP for heat pump). The middle part shows the abbreviation for the type of energy (EE for electrical energy, HE for heating energy, CE for cooling energy). The right part shows the abbreviation for the component the energy flow goes to (e.g. BU for building, SC for Server Cluster, LR for laboratory rig).

The labelling of the energy flows of level M is based on the nomenclature of level L. Basically, the same three-part system (abbreviation energy source_abbreviation energy carrier_ abbreviation energy sink) is used, but supplemented with specifications with regard to the addressed respective subsystem (e.g. IN13 for building with the address Inffeldgasse 13).

2.5.2 Aggregation of sensor values to calculate energy flows

The sensors documented in STRUCTURE and their measured values form the basis for determining assessments of the energy flows. These are transmitted to ORGANIZE from the various systems in the real district, stored in STORE and made available to RATE. In the first step of the evaluation, all sensor values that arrive from the various systems with different designations are brought into a standardised designation scheme. This ensures that the subsequent calculations can be organised in a clearly structured and comprehensible way. The balancing algorithm (phyton script) that was developed on the basis of the pipe structure and the position of the sensors aggregates the sensor values into energy flows. The calculation rules are translated into the programming language YAML (Ain't Markup Language [44]). YAML is a human-readable language and is therefore suitable for checking the balancing algorithm directly by humans. The next step automatically checks whether all the sensor values required to combine the energy flows can be called up or whether corresponding error messages are displayed. The energy flows calculated in this way are transferred to the database in STORE via an interface, where they are stored for further processing into key performance indicators and, in some cases, displayed in the VISUALIZE dashboards.

2.5.3 Calculation of Key Performance Indicators

At the Innovation District Inffeld, up to five different categories of energy supply can be consumed in each building. Figure 26 shows these: (1) district heating, (2) electricity for heat pump heating, (3) electricity for heat pump cooling, (4) electricity for chillers, (5) electricity for non-thermal use.

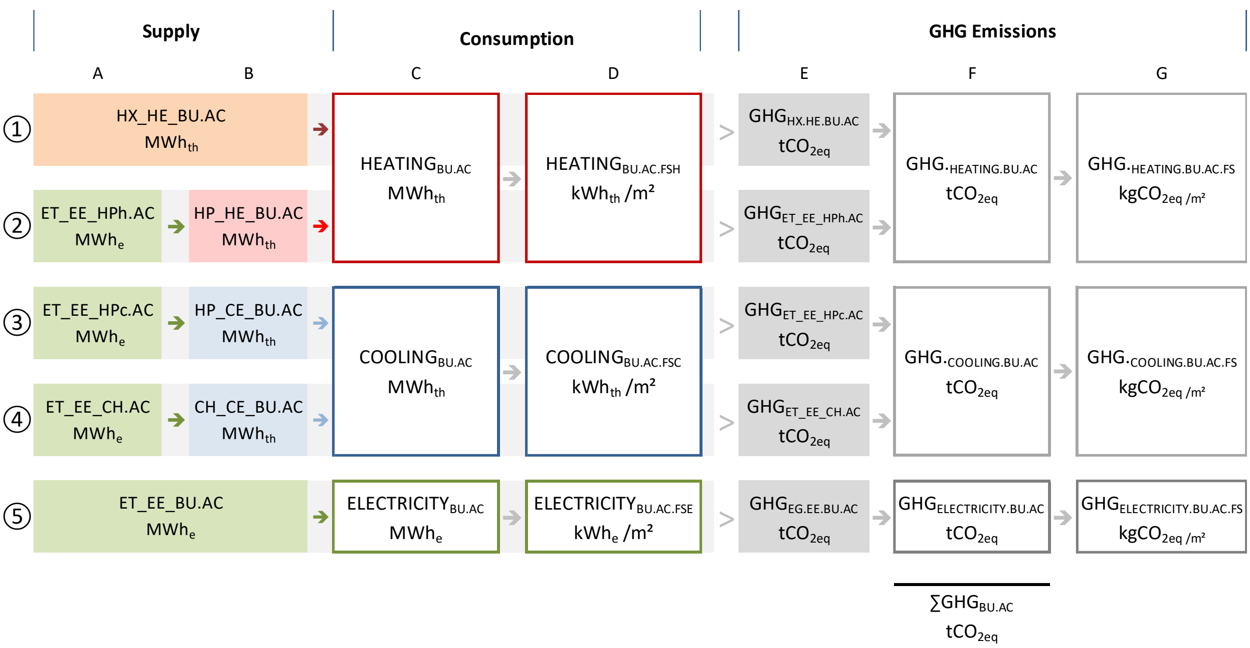


Figure 26: Energy flows that are brought into buildings from different sources and consumed there

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[44] https://yaml.org/

Two groups of key performance indicators (KPIs) are associated to the energy that ensures the energy supply of the building (Supply containing column A and column B). In order to make them comprehensible, they are presented in Figure 27 accompanied by an explanatory definition.

Labelling of energy supply	Definition
$\mathrm{HX\_HE\_BU.AC} \quad [MWh_{th}]$	heating energy (HE) supplied by an heat exchanger (HX) to heat a building (BU) with the address code (AC)
$\mathrm{ET\_EE\_HPh.AC} \quad [MWh_{e}]$	electrical energy (EE) supplied by an electrical transformer (ET) to a heat pump (HP) to generate heating energy which is consumed by a building with the address code (AC)
$\mathrm{HP\_HE\_BU.AC} \quad [MWh_{th}]$	heating energy (HE) supplied by an heat pump (HP) to heat a building (BU) with the address code (AC)
$\mathrm{ET\_EE\_HPc.AC} \quad [MWh_{e}]$	electrical energy (EE) supplied by an electrical transformer (ET) to a heat pump (HP) to generate cooling energy which is consumed by a building with the address code (AC)
$\mathrm{HP\_CE\_BU.AC} \quad [MWh_{th}]$	cooling energy (CE) supplied by a heat pump (HP) to cool a building (BU) with the address code (AC)
$\mathrm{ET\_EE\_CH.AC} \quad [MWh_{e}]$	electrical energy (EE) supplied by an electrical transformer (ET) to a chiller (CH) to generate cooling energy which is consumed by a building with the address code (AC)
$\mathrm{CH\_CE\_BU.AC} \quad [MWh_{th}]$	cooling energy (CE) supplied by a chiller (CH) which is consumed by a building (BU) with the address code (AC)
$\mathrm{ET\_EE\_BU.AC} \quad [MWh_{e}]$	electrical energy (EE) supplied by an electrical transformer (ET) to meet purposes in a building (BU) with the address code (AC) that cannot be assigned to heating or cooling functions

Figure 27: Listing, labelling and definitions of energy flows used to calculate the KPIs

The KPI **Consumption** provides information on the quantities of energy consumed in a building per category. Both the energy quantities per building (column C) and the specific values related to the respective reference areas are calculated. If the energy quantities are to be broken down according to the basic functions of heating, cooling and electricity for non-thermal purposes, then the respective energy quantities used for a function must be added together (column C).

$$\mathrm{HEATING_{BU.AC}} = \mathrm{HX\_HE\_BU.AC} + \mathrm{HP\_HE\_BU.AC} \quad [MWh_{th}]$$

$$\mathrm{COOLING_{BU.AC}} = \mathrm{HP\_CE\_BU.AC} + \mathrm{CH\_CE\_BU.AC} \quad [MWh_{th}]$$

$$\mathrm{ELECTRICITY_{BU.AC}} = \mathrm{ET\_EE\_BU.AC} \quad [MWh_{e}]$$

If the energy consumption is related to the corresponding reference areas for heating (A_{FSH} ... floorspace area heated), cooling (A_{FSC} ... floorspace area cooled) and electricity (A_{FSE} ... floorspace area electricity), the corresponding specific KPIs are obtained (column D). Floor space is the usable floor area in the interior rooms (excluding construction areas).

$$\mathrm{HEATING}_{\mathrm{BU.AC.FSH}} = \frac{\mathrm{HEATING}_{\mathrm{BU.AC}} \cdot 1000}{A_{FSH}} \quad \left[\frac{kWh_{th}}{m^2}\right]$$

$$\mathrm{COOLING}_{\mathrm{BU.AC.FSC}} = \frac{\mathrm{COOLING}_{\mathrm{BU.AC}} \cdot 1000}{A_{FSC}} \quad \left[\frac{kWh_{th}}{m^2}\right]$$

$$\mathrm{ELECTRICITY}_{\mathrm{BU.AC.FSE}} = \frac{\mathrm{ELECTRICITY}_{\mathrm{BU.AC}} \cdot 1000}{A_{FSE}} \quad \left[\frac{kWh_{th}}{m^2}\right]$$

The KPI **GHG emissions** show the greenhouse gas emissions associated with the production of this energy. Starting with the year 2017, a greenhouse gas balance for Graz University of Technology was drawn up and published at regular intervals [[45]]. The "ClimCalc" assessment tool used by the "Alliance of Sustainable Universities in Austria" [[46]] publishes the corresponding emission factors for the forms of energy used in Austria every year. In order to ensure consistency between the projects at Graz University of Technology, the UserGRIDs project uses the same data source. As the calculation bases are only available after the end of a reporting period, the emission factors (EF) are published in chronological order. Figure 28 shows the published emission values for previous years.

	Emission Factors (EF) per year				
[kg CO_{2eq} / MWh]	Year 2021	Year 2020	Year 2019	Year 2018	Year 2017
Electric energy RL UZ 46	12.4	13.9	13.9	16.3	16.3
Electric energy	226.0	202.6	218.7	268.4	257.3
PV Yield internal consumption	40.0	39.8	39.8	39.8	62.0
District heat Graz	250.0	309.0	307.8	310.7	348.7

Figure 28: Emission factors (EF) relevant for the assessment in the last accounting periods (years)

The calculation of GHG emissions (Figure 26 - column E) is based on the quantified consumption of district heating and the electrical energy required for the heat pumps, chillers and other functions. The consumption is multiplied by the respective emission factors (EF) from Figure 28 and this leads to the induced GHG emissions in t CO_{2eq}.

[45] https://pure.tugraz.at/ws/portalfiles/portal/40459447/THG_Bilanz2020_Bericht.pdf
[46] https://nachhaltigeuniversitaeten.at/arbeitsgruppen/co2-neutrale-universitaeten/

$$\mathrm{GHG}_{\mathrm{HX\_HE\_BU.AC}} = \frac{\mathrm{HX\_HE\_BU.AC}}{10^6} \cdot \mathrm{EF} \quad [tCO_{2eq}]$$

$$\mathrm{GHG}_{\mathrm{ET\_EE\_HPh.AC}} = \frac{\mathrm{ET\_EE\_HPh.AC}}{10^6} \cdot \mathrm{EF} \quad [tCO_{2eq}]$$

$$\mathrm{GHG}_{\mathrm{ET\_EE\_HPc.AC}} = \frac{\mathrm{ET\_EE\_HPc.AC}}{10^6} \cdot \mathrm{EF} \quad [tCO_{2e}\ ]$$

$$\mathrm{GHG}_{\mathrm{ET\_EE\_CH.AC}} = \frac{\mathrm{ET\_EE\_CH.AC}}{10^6} \cdot \mathrm{EF} \quad [tCO_{2eq}]$$

$$\mathrm{GHG}_{\mathrm{ET\_EE\_BU.AC}} = \frac{\mathrm{ET\_EE\_BU.AC}}{10^6} \cdot \mathrm{EF} \quad [tCO_{2eq}]$$

If the greenhouse gas emissions are to be categorised according to the basic functions of heating, cooling and electricity for non-thermal purposes (column F), the following equations are obtained.

$$\mathrm{GHG}_{\mathrm{HEATING.BU.AC}} = \mathrm{GHG}_{\mathrm{HX\_HE\_BU.AC}} + \mathrm{GHG}_{\mathrm{ET\_EE\_HPh.AC}} \quad [tCO_{2eq}]$$

$$\mathrm{GHG}_{\mathrm{HEATING.BU.AC}} = \mathrm{GHG}_{\mathrm{ET\_EE\_HPc.AC}} + \mathrm{GHG}_{\mathrm{ET\_EE\_CH.AC}} \quad [tCO_{2eq}]$$

$$\mathrm{GHG}_{\mathrm{HEATING.BU.AC}} = \mathrm{GHG}_{\mathrm{ET\_EE\_BU.AC}} \quad [tCO_{2eq}]$$

The greenhouse gas emissions categorised according to the basic functions are related to the respective reference areas (A_{FSH}, A_{FSC}, A_{FSE}). This gives specific emissions per square metre of floorspace (column G) and associated function (heating, cooling and electricity).

$$\mathrm{GHG}_{\mathrm{HEATING.BU.AC.FSH}} = \frac{\mathrm{GHG}_{\mathrm{HEATING.BU.AC}} \cdot 1000}{A_{FSH}} \quad \left[\frac{kgCO_{2eq}}{m^2}\right]$$

$$\mathrm{GHG}_{\mathrm{COOLING.BU.AC.FSC}} = \frac{\mathrm{GHG}_{\mathrm{COOLING.BU.AC}} \cdot 1000}{A_{FSC}} \quad \left[\frac{kgCO_{2eq}}{m^2}\right]$$

$$\mathrm{GHG}_{\mathrm{ELECTRICITY.BU.AC.FSE}} = \frac{\mathrm{GHG}_{\mathrm{ELECTRICITY.BU.AC}} \cdot 1000}{A_{FSE}} \quad \left[\frac{kgCO_{2eq}}{m^2}\right]$$

If the individual functions of separately calculated GHG emissions (column F) are added together, the total induced greenhouse gas emissions of a building are obtained.

$$\sum \mathrm{GHG}_{\mathrm{BU.AC}} = \mathrm{GHG}_{\mathrm{HEATING.BU.AC}} + \mathrm{GHG}_{\mathrm{COOLING.BU.AC}} + \mathrm{GHG}_{\mathrm{ELECTRICITY.BU.AC}} \quad [tCO_{2eq}]$$

2.5.4 Photovoltaic yield assessment

At the beginning of the reference year 2022, three PV systems were in operation at the Innovation District Inffeld, and seven at the end of 2022 (view chapter 2.1.6). The basis for the assessment of the photovoltaic systems is the quantification of the electrical energy generated which is called electrical energy yield. This is the electrical energy (kWh_e) that is measured cumulatively on the AC voltage side of the PV inverter. It represents the generated electrical energy minus the line losses up to the inverter and its inverter losses. The electrical energy yield generated by the PV functional group forms the energy flow PV_EE_BU (Figure 25), which is formed from the sum of the electrical energy yields of all PV systems. Figure 29 shows the designation and correlation in the Yield Identifier column. The assessment of induced greenhouse gas emissions (GHG-Emissions$_{PV}$) is based on the quantified electrical yield, multiplied by the emission factor to be applied to PV systems in Austria (Figure 28), and thus shows the associated GHG emissions in kg CO_{2eq} (Figure 29).

	PV Plants		Yield			Emission		
	Name	Identifier	Energy flow identifier	Unit				GHG-Emissions$_{PV}$
Subsystems Level M	PV Plant Inffeldgasse 11	PV.IN11.01	PV.IN11.01_EE_BU	kWh_e	X	Emission factor PV [ClimCalc]	=	kg CO_{2eq}
	PV Plant Inffeldgasse 26	PV.IN26.01	PV.IN26.01_EE_BU					
	PV Plant Inffeldgasse 16	PV.IN16A.01	PV.IN16A.01_EE_BU					
Level L	**Functional Group PV**		**PV_EE_BU**					

Figure 29: Composition and evaluation of the PV functional group

Various **key performance indicators** (KPIs) can be defined to evaluate the electrical yield of PV systems [[47]]. The amount of electrical energy generated is usually related to the module area, the design power or other parameters of the system. KPIs thus establish a connection between the basic benefit of a PV system, the electrical energy generated and the effort required to generate this benefit. As they relate to basic parameters describing the system in terms of time, energy technology and geometry (h, kW or m²), they make it possible to compare the yield of a system with empirical values or with other PV systems.

Efficiency (η_{PV}) is the quotient of the Electrical Energy Yield (PV_EE_BU) and the incident radiant energy (H_G) on the module surface. This shows what proportion of the available solar energy is converted by the system into use, i.e. usable electrical energy. As shown below, the efficiency can be calculated for the entire function group or for each system.

$$\eta_{PV} = \frac{PV\_EE\_BU}{H_G} \quad \left[\frac{kWh/a}{kWh/a}\right]$$

[47] Mertens K. (2022): Photovoltaik - Lehrbuch zu Grundlagen, Technologie und Praxis, Carl Hanser Verlag München

Specific Module Area Yield (SMY) is the Electrical Energy Yield (PV_EE_BU), divided by the module area (AM). This indicates how much electrical energy is generated per square meter of module area. In this way, installation costs and module requirements are related to the benefit of the electrical energy harvested.

$$SMY = \frac{PV\_EE\_BU}{A_M} \quad \left[\frac{kWh/a}{m^2}\right]$$

Specific Peak Final Yield (Y_F) is the Electrical Energy Yield (PV_EE_BU) divided by the nominal peak power (P_{STC}) under standard test conditions STC (irradiance: 1000 W/m², module temperature 25 °C, standard light spectrum AM 1.5). This indicates the extent to which the performance of the system is utilised in relation to standardised conditions and how much electrical energy is generated per installed kW_p. This KPI can be interpreted as equivalent to the specification of full load hours for electrical power plants.

$$Y_F = \frac{PV\_EE\_BU}{P_{STC}} \quad \left[\frac{kWh/a}{kW_p}\right]$$

Reference System Yield (Y_R) is defined by relating the specific real irradiation sum (H_{G_spec}) on the inclined orientated surface to the maximum irradiance (E_{STC}) of the sun under STC conditions (i.e. 1.0 kW/m²). The reference system yield therefore indicates the number of hours that the sun would have to shine on the PV system with full solar radiation in order to generate the radiant energy (H_{G_spec}). The reference system yield therefore represents the solar full load hours at module surface level per year.

$$Y_R = \frac{H_{G\_spec}}{E_{STC}} \quad \left[\frac{kWh/(m^2 a)}{kW/m^2}\right]$$

Performance Ratio (PR) is the quotient of Specific Peak Yield (Y_F) and the Reference System Yield (Y_R) of a PV system. Thus, it compares the energy yield of a PV system with the yield of a system operated under standardised laboratory conditions. The performance ratio summarises the energy performance of all components (module, inverter, cabling, etc.) of the system. As specific conditions are equalised, different systems can be compared.

$$PR = \frac{Y_F}{Y_R} = \frac{\frac{PV\_EE\_BU}{P_{STC}}}{\frac{H_{G\_spec}}{E_{STC}}} \quad \left[\frac{\frac{kWh/a}{kW_p}}{\frac{kWh/(m^2 a)}{kW/m^2}} = \frac{\frac{h}{a}}{\frac{h}{a}}\right]$$

Specific Footprint Yield (SFY) is the Electrical Energy Yield (PV_EE_BU) divided by the roof or façade area required for the PV modules, referred to as the Footprint (A_F). This indicates how much electrical energy is generated per square metre of roof or façade area. This provides an indication of how well the available installation area is utilised.

$$SFY = \frac{PV\_EE\_BU}{A_F} \quad \left[\frac{kWh/a}{m^2}\right]$$

2.5.5 District evaluation analysis

The energy-related sensor values recorded and stored by the IoT platform can be used for a wide variety of analyses. The focus is on the task of understanding and quantifying energy-related processes. This chapter shows examples of some of these analyses, which are able provide information about on specific building (energy consumption and KPIs). Other analyses show the distribution of heat by source or consumption of electricity by functional groups (see Figure 25). Furthermore, waste heat potential is presented as well as transformer losses which are unavoidable in the provision of electrical energy.

Consumption and KPIs per building

In order to obtain an overview of the energy requirements of the individual buildings, corresponding key performance indicators (KPIs) were developed in chapter 2.5.3. For this purpose, an evaluation platform was created to generate KPIs for buildings. Figure 30 shows an example providing key performance indicators for heating, cooling and other purposes. The annual values and KPIs (absolute and specific) are presented from supply, to consumption to caused CO_2 emissions. The building required roughly the same amount of heating (48 kWh/m²a) and cooling (60 kWh/m²a) in the year 2020. The consumed electricity was 78 kWh/m²a as the sensory equipment was only implemented step by step during the project, some values had to be estimated by means of calculations (calc).

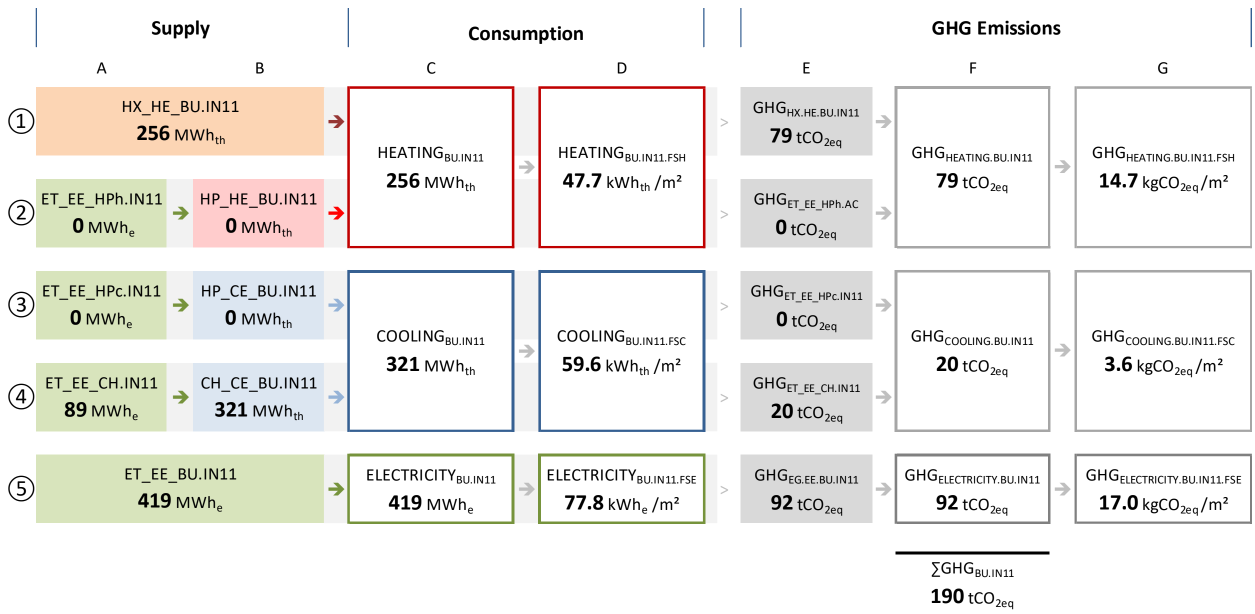

Figure 30: Energy demand per energy consumption areas (see Figure 7) and KPIs for one building

Supply and distribution of heat

The Innovation District Inffeld is connected via two District Heat Stations (heat exchangers) to the district heating network of the City of Graz (see Figure 25). In the course of the project, it was possible to draw up a building-specific balance sheet of the heat requirements. This is shown in Figure 31 in the form of an energy flow diagram for the year 2023. District supply station I transfers 80 % of the district heat and district supply station II transfers the remaining 20 %.

District heating accounts for around 89 % of total heat consumption. Five newer buildings are supplied with heat from brine-to-water heat pumps with geothermal probes (approx. 11 % of heat consumption). Figure 31 shows the supply of district heating to the buildings from left to right. The buildings supplied with heat from heat pump systems are shown from right to left.

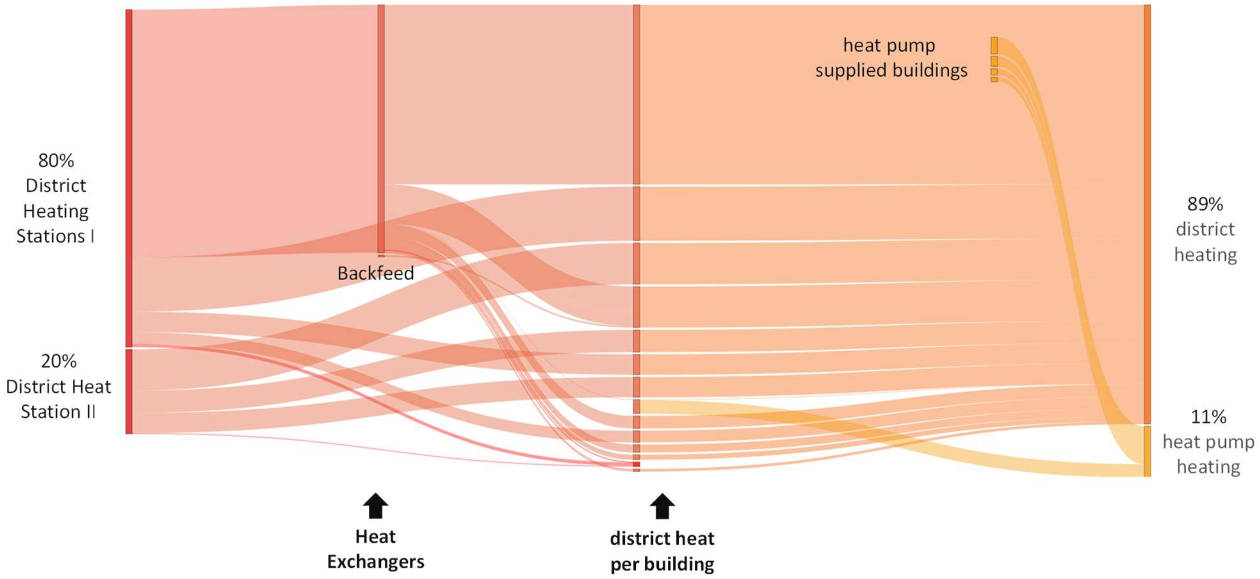

Figure 31: Illustration of the heat demand per building, from the heat sources district heating and heat pump

Supply and consumption of electrical energy

The district is supplied with electrical energy via two District Electricity Stations and transformers convert to the usable voltage level. Around 40 % of the district's electric energy was required by buildings. The laboratories use 44 % of the total electricity and 6 % is used to operate the servers. The losses on the part of the transformers and the power grid are close to 10 % (Figure 32).

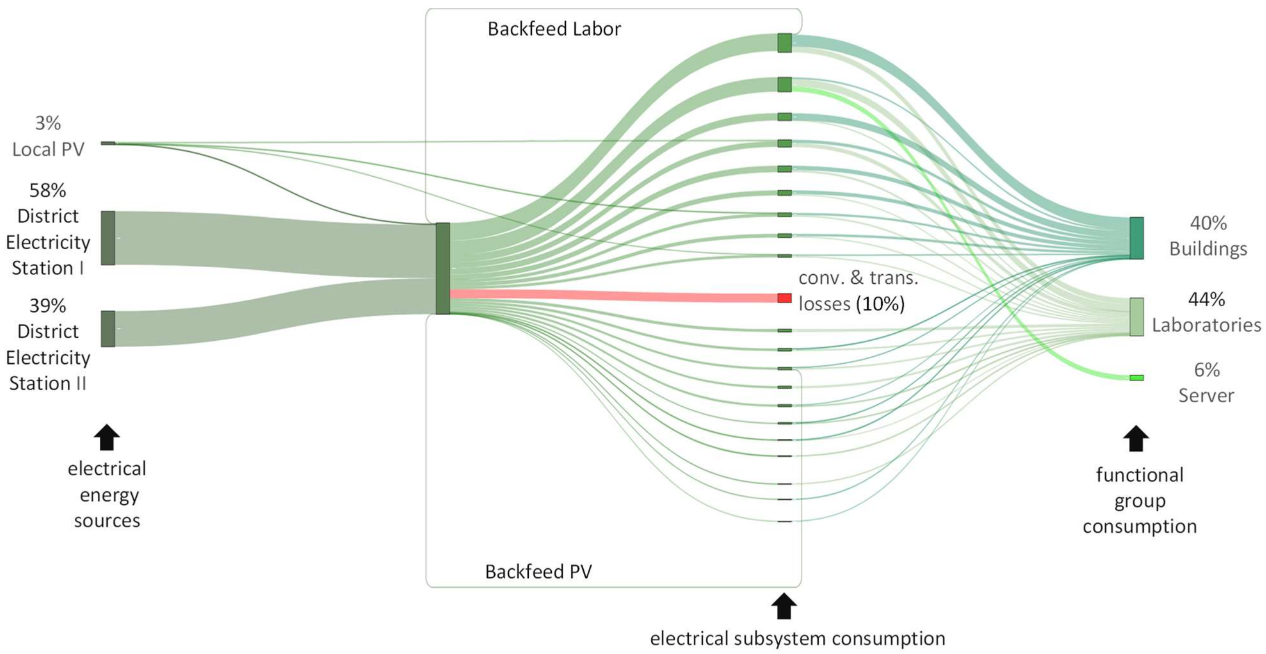

Figure 32: Illustration of electricity demand per functional group, in the Innovation District Inffeld (06.2022 – 06.2023)

Large electricity consumers and their waste heat potential

To determine the waste heat potential, measuring points of relevant consumers were analysed with regard to their electricity consumption. This showed that some consumers have relevant but volatile power consumption. These are mainly test benches cooled by compression chillers. Two other electricity consumers, on the other hand, show a more usable curve in terms of duration and output. If the electricity demand is converted to usable waste heat, this results in a waste heat generation presented in Figure 33. It shows that the potentials of servers and dry cooler are the most useful sources. All other sources show extremely volatile behaviour with significant power peaks. This results in a sensible waste heat potential of between 400 and 1200 kW_{th}. The temperature level of the waste heat sources is between 25 and 40 °C, depending on the time of the year. These waste heat sources provided by the district's large consumers can be used as a heat source for a large heat pump in order to decarbonise the heat supply.

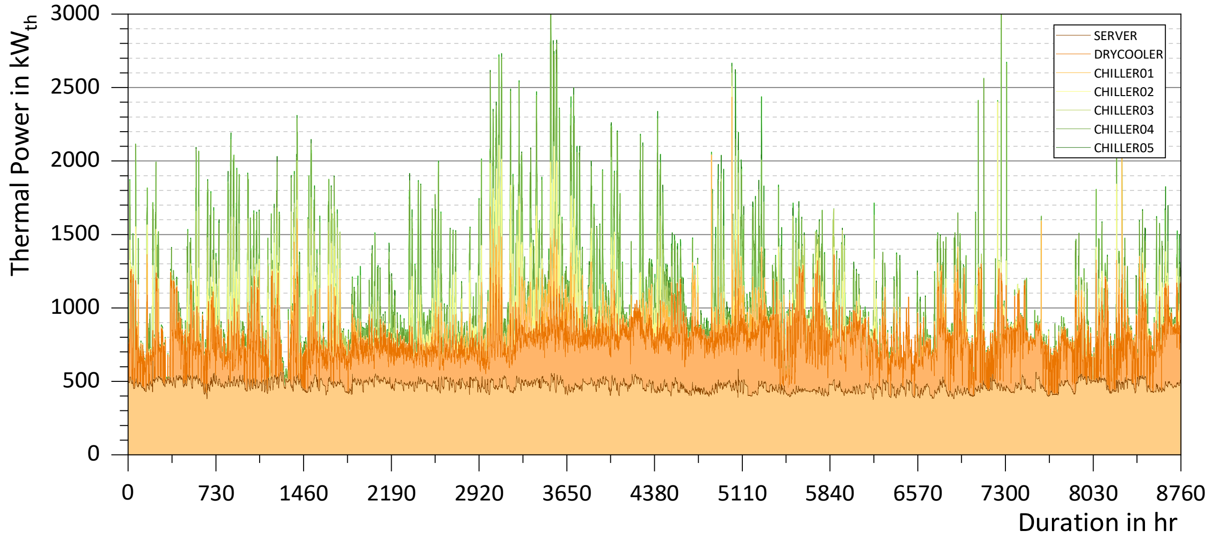

Figure 33: Waste heat potential from relevant large electricity consumers in the district

Transformer losses in the district power grid

The energy losses indicated by the transformation of the electrical voltage are an important parameter for the efficiency of the electricity grid. The transformer losses, which are made up of the no-load losses and the load-dependent losses, were calculated for the Innovation District Inffeld on the basis of the recorded transformer data and the measured load profiles. The transformer losses are independent of the load flow direction. They occur both during consumption and feed-in (e.g. from a PV system). As an example, Figure 34 shows the load-dependent losses of a transformer to which a 145 kWp PV system is connected on the low-voltage side. If energy is fed into the 20-kV grid from the PV system, the power is negative; if electricity is drawn from the grid, it is positive. The minimum power loss is determined by the no-load losses of the transformer (approx. 2.3 kW shown in Figure 34). Regardless of the load flow direction, the load-dependent losses add up depending on the transformer load. Overall, the transformation losses on the electrical side of the grid in the Innovation District Inffeld amount to around 3.8 % of total electrical energy consumption.

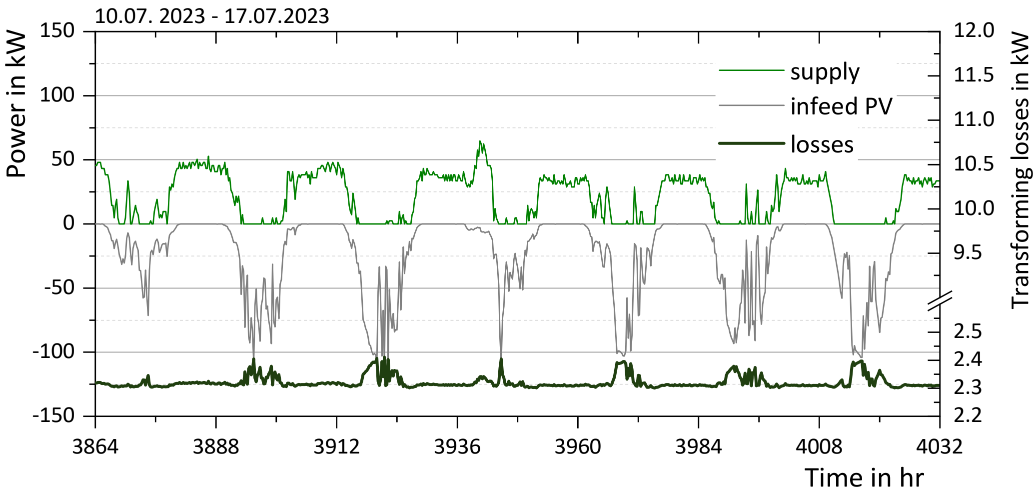

Figure 34: Transforming losses during one week (PV system - 145 kWp)

Photovoltaic yield evaluation

Three photovoltaic systems (with 587 kWp) supplied 0.485 MWh in 2023. The descriptions of the KPIs can be found in chapter 2.5.4. The analyses show that the Specific Peak Yield (Y_F) of 650-960 kWh/(kW$_p$·a) lags behind newly constructed, perfectly orientated systems. The performance ratio (PR) shows a similar picture; only IN26 can achieve a typical value (75 % to 85 % [47]) with a yield ratio of around 75 %. The Specific Footprint Yield (SFY) shows how well the available area could be utilised. In the case of IN11, 30 % of the roof area is occupied by the PV system. In the case of the system in IN26, 71 % of the roof was utilised. These differences are mainly due to the architecture and utilisation of the roof areas. The electrical energy generated by the PV systems per month for the year 2023 is shown in Figure 35 below.

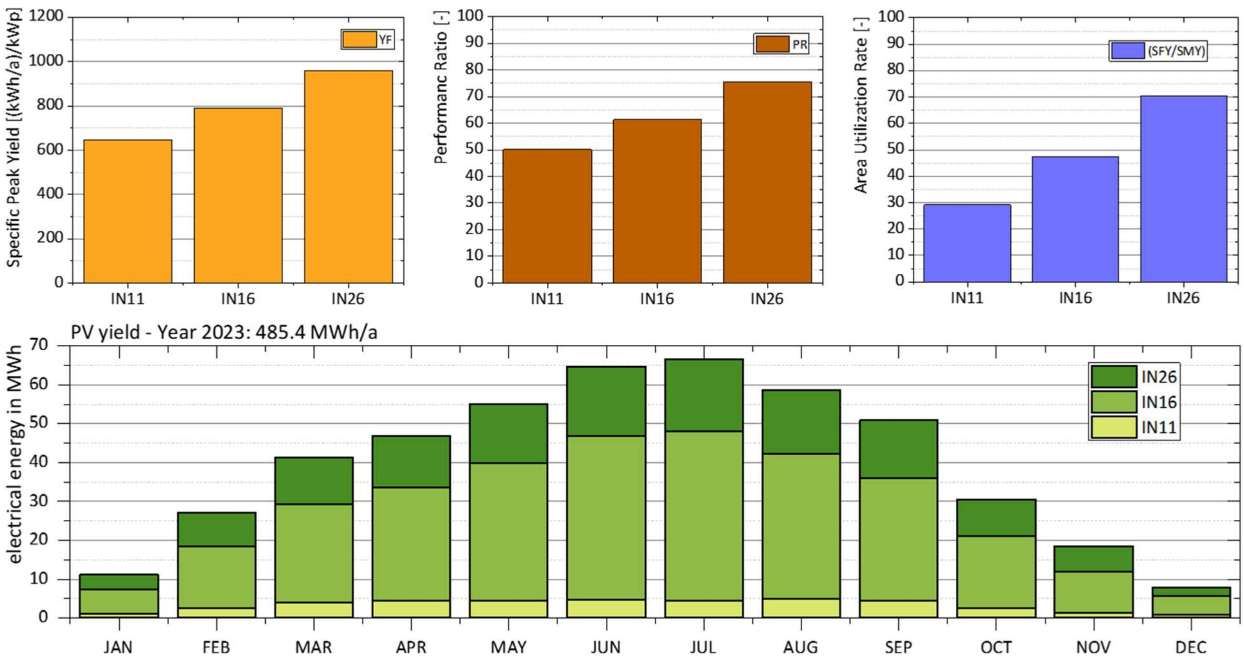

Figure 35: PV key performance indicators YF, PR, SFY/SMY and monthly yield of the PV systems (year 2023)

2.6 CONTROL

Based on the energy system design, the control methods determine energy consumption, greenhouse gas emissions and thermal comfort. In this context, predictive control strategies can make a significant contribution to increasing system efficiency. Energy savings and emission reductions can be quantified on the basis of measurements and simulations. Ultimately, however, the quality of the thermal comfort achieved is assessed by users. The target for the CONTROL service is based on these contexts.

The **target** of this service is to process system settings from the district energy systems, optimise them with regard to an ecologically and comfort-related defined target function to send optimized control schedules back to the district energy systems.

The digital energy service CONTROL is demonstrated for an office building (Inffeldgasse 21B). Sensor data (room air temperature, building component temperatures, etc.), control signals (valve positions), weather data as well as user feedback from an online comfort survey are used for the real-time control (Figure 36).

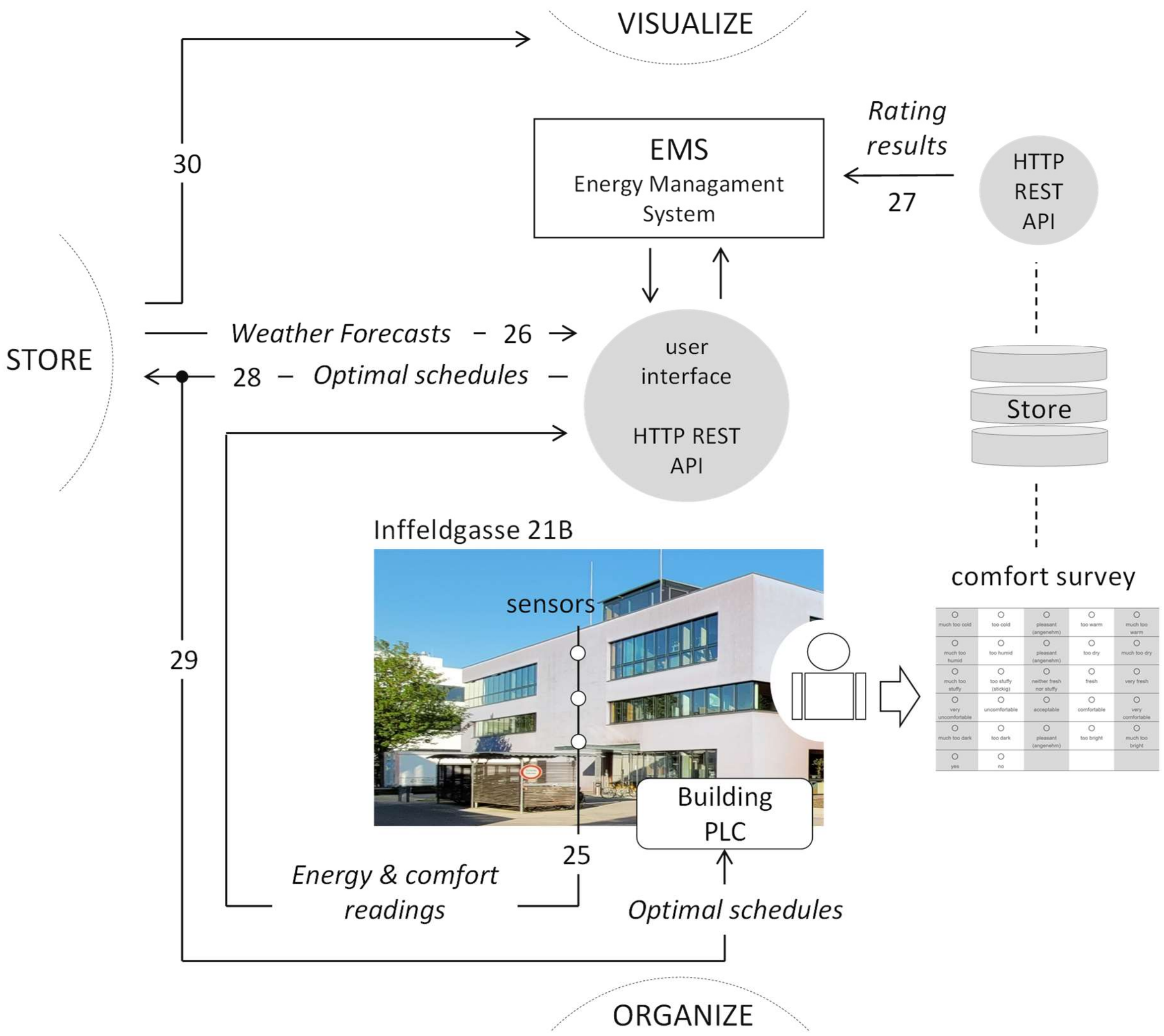

Figure 36: Functional scheme of digital energy service CONTROL

The digital energy service CONTROL (EMS) is based on the method of model predictive control (MPC). This method repeatedly solves optimization problems in real-time, where the objective function is such that energy consumption in the heating and cooling operation of buildings is penalized while maintaining a high level of comfort is rewarded. In addition to sensor data, the EMS also processes hourly climatological forecast data (26). The thermal comfort achieved in the test building is evaluated on the basis of the sensor data. The feedback from the comfort survey provided by the building users with regard to temperature, humidity and other comfort parameters flow directly into the control specification by the EMS (27). This is transmitted to STORE in the form of optimum schedules at fifteen-minute intervals (28) and is updated every fifteen minutes. From there, the optimal schedules are sent to the building control unit (Building PLC) (29), where the control signals directly control the valve position for the heating and cooling circuits in test building. At the same time, predictions of the most important parameters, e.g., air temperatures and valve positions are transferred to VISUALIZE for visualisation in a dashboard (30).

2.6.1 Optimal control on building level based on prediction

The Inffeldgasse 21B property was selected as a demonstrator of the building-related control concept. This is largely heated and cooled via thermally activated concrete ceilings. Only the sanitary facilities were equipped with underfloor heating. The flow temperature for the building, which is connected to the district heating network, is controlled by one mixing circuit for the whole building. The mass flow of the flow and return can be set for each storey using a valve. The original control strategy is based on the flow temperature, which depends on the outside air temperature, and manual adjustment of the storey valves. If the moving average of the outside air temperature falls below 14 °C, the system is in the heating mode; if it rises above 17 °C, the system switches to the cooling mode.

The implemented **energy management system (EMS)** is based on model predictive control (MPC). For this purpose, the entire energy system must be formulated in a mathematical model that is simple enough to be solved in real time. The EMS is based on mixed-integer linear programming (MILP), i.e. linear optimisation problems. The implementation is carried out in the programming language 'Julia' [[48]], whereby the solution runs on a Linux machine and is determined using IPOPT [[49]]. A calculation run is carried out every 15 minutes, in which a prediction horizon of 72 hours is established. The first 24 hours are forwarded to the building control system as a schedule. The schedules created by the EMS, i.e. the setting values of the mixing circuit and the storey valves, are transmitted to the REST API user interface (view chapter 2.3.4), stored in STORE and forwarded from there to the systems of the Inffeldgasse 21B building. In the event of a communication failure in which no schedules can be transmitted, the current schedule is executed for a further 24 hours, even if it is not renewed. If no new schedule is transmitted during this period, the standard control system takes over control operation.

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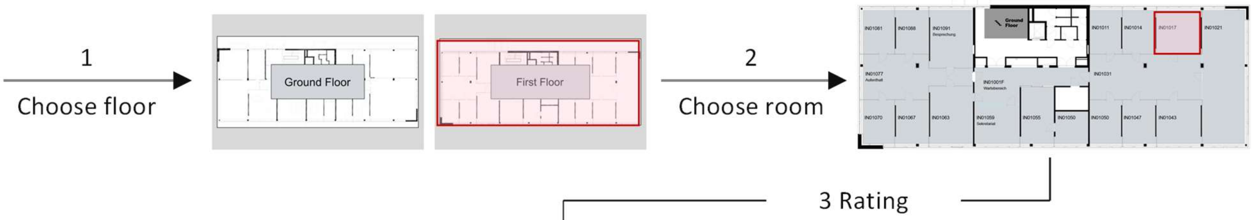
[48] https://julialang.org/

[49] On the implementation of an interior-point filter line-search algorithm for large-scale nonlinear programming, http://link.springer.com/10.1007/s10107-004-0559-y

As an entire storey is controlled via a valve in this case, the resulting four thermal zones correspond to the four storeys of the building. The thermal zones are considered independently of each other because the thermal coupling via the storey ceilings is estimated to be negligible.

2.6.2 Implementing user feedback on thermal comfort in the control loop

The purpose of heating, ventilation and air conditioning technology is to provide the user with thermal comfort in the interior of buildings. In addition to temperatures, humidity, convection, solar radiation and air quality also play decisive roles. All these aspects can be measured and analysed by means of sensors. Ultimately, however, the users, i.e. the people present in the respective interior at a given time, remain the decisive criterion. An app was developed in the project UserGRIDs to record the subjectively perceived thermal comfort and to be able to allocate it to time and space [50]. After selecting the relevant floor (step 1) and interior (step 2), six aspects contributing to thermal comfort can be evaluated. In the background, the answers given are time-stamped and stored in a database for further processing.



How would you rate the indoor climate in the room IN01014 right now?

How would you rate the temperature in the room right now?	much too cold	too cold	pleasant (angenehm)	too warm	much too warm
How would you rate the humidity in the room right now?	much too humid	too humid	pleasant (angenehm)	too dry	much too dry
How would you rate the air in the room right now?	much too stuffy	too stuffy (stickig)	neither fresh nor stuffy	fresh	very fresh
What is your overall comfort level right now?	very uncomfortable	uncomfortable	acceptable	comfortable	very comfortable
How adequate is the light (natural and artificial) in the room right now?	much too dark	too dark	pleasant (angenehm)	too bright	much too bright
Do you feel an unpleasant draught (Luftzug) in the room right now?	yes	no			

4 Transmission to database

Figure 37: Procedure of the comfort survey via app

50 https://usergrid-in21-monitoring.best-research.eu/

In the context of model predictive control (MPC) an optimization problem is solved in real-time. For this a so-called objective function must be formulated mathematically. In the specific case, a key aspect of the objective function is to minimise the energy costs for heating and cooling. However, thermal comfort must be ensured, as otherwise the ‘optimum solution’ would be not to heat or cool at all. Therefore, the objective function was supplemented by the condition that the room air temperatures must lie within a specified range, a temperature band, which is enforced via penalty costs. OENORM EN ISO 7730 [[51]] was used as the basis for defining this temperature range. This is labelled A, the best of three comfort levels. Up to one degree Kelvin deviation upwards or downwards forms Comfort Level B and up to a deviation of two degrees Kelvin upwards or downwards forms Comfort Level C. In addition, the standard distinguishes between different requirements in the heating or cooling season and proposes different reference temperatures depending on the outside air temperature. The ratings given in the comfort survey are taken into account by assigning offsets [°K] to the reference temperatures, which shifts the temperature bands of the comfort levels. The feedback is given at irregular intervals and is potential inconsistent, which must be considered.

2.6.3 Evaluation of the pilot operation phase

The predictive control scheme for the Inffeldgasse 21b started its pilot phase in January 2023. At this point, the question arose as to how to proceed with a comprehensive evaluation. The years 2021 and 2022 had to be excluded because usage was significantly restricted in these two years due to the pandemic and was therefore not suitable. For the comparison, similar years are chosen in terms of heating and cooling season, and 2023, when the proposed controller was operational. The selection was performed based on degree days. The base temperature for heating and cooling is 23 °C and 18.3 °C, respectively. The threshold for heating and cooling is 15 °C and 18.3 °C, respectively. The estimated long term (over the last 10 years) heating degree days (HDD) and cooling degree days (CDD) for Graz are $HDD = 4045$ and $CDD = 240$. The degree days for heating and cooling are $HDD_{2019} = 3884$ and $HDD_{2023} = 3745$ and $CDD_{2021} = 298$ and $CDD_{2023} = 242$. At the end for heating 2019 and for cooling 2021 where chosen since they were most similar in terms of degree days to 2023. Both were years where the reference control scheme was employed. The reference control scheme did not actuate the valves of the building at all and only the feed temperature was varied, based on a static heating curve. In terms of performance, the thermal comfort and energy consumption is considered. These are opposing goals. The zone temperature shows less overheating (23 - 25°C vs. 25 - 27°C) with the predictive control scheme than with the reference control scheme.

A quantitative comparison of the performance in terms of thermal comfort is done via the time spent at each comfort level, summed up over the whole building. Figure 38 (top section) shows the comparison of the hours (for one year) spent at each comfort level.

[51] OENORM EN ISO 7730 (2006). Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria (ISO 7730:2005)

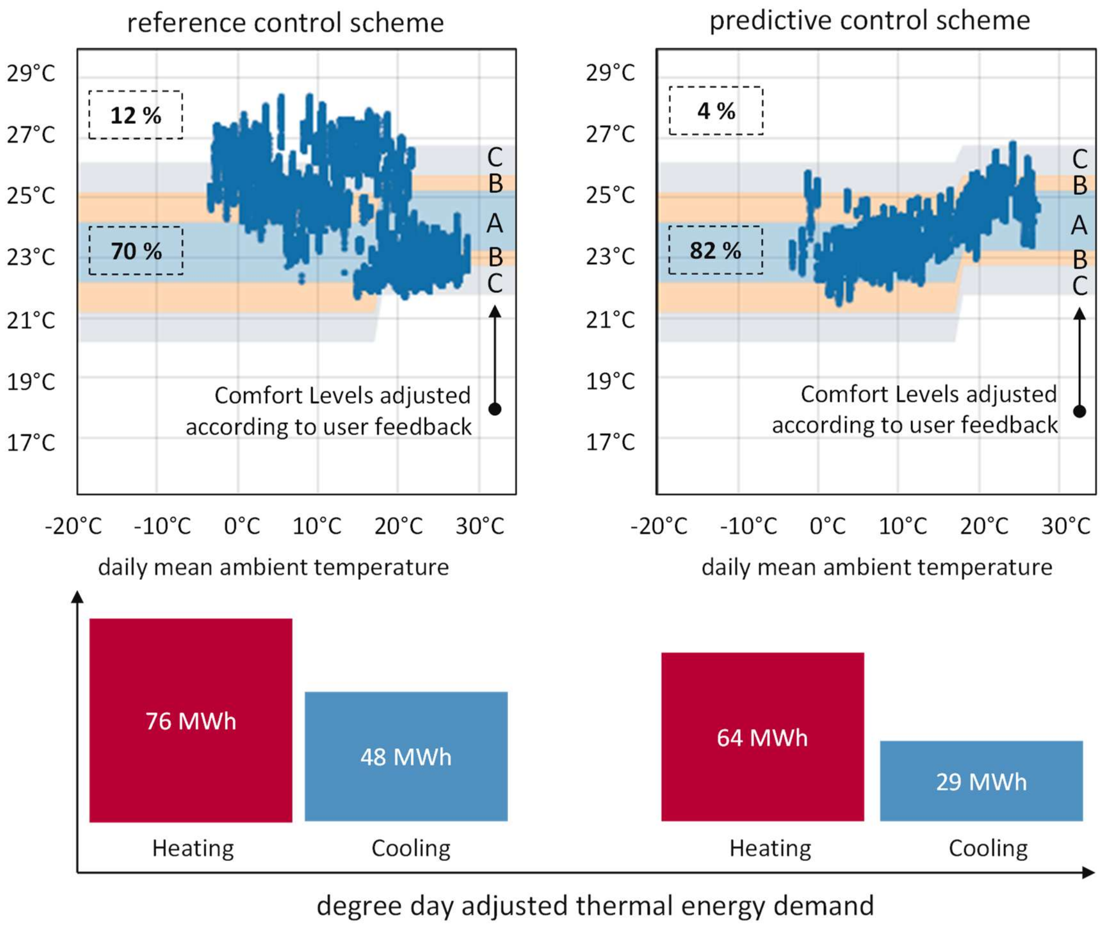


Figure 38: Zone air temperature of the first floor for the reference control scheme (top left) with the predictive control scheme (top right) in the reference timespan of one year. Comparision of heating and cooling energy (bottom).

For the reference control scheme, about 70 % of the time is spent in category A, for the new predictive control scheme this is increased to about 82 %. The time outside of comfort category C is reduced from 12 % to 4 %. Additionally, to the evaluation in terms of thermal comfort, the energy consumption of the building is evaluated. Unfortunately, there was no heat meter installed until early 2023; hence, an estimate has to be used. Fortunately, the heat and cooling demand can be reliably estimated from the valve openings and the common feed and return temperatures of the building. Figure 38 (bottom section) shows the degree day adjusted thermal energy for heating and cooling for the reference control and the proposed predictive control. For a fair comparison, the thermal demands have to be adjusted using the degree days for heating and cooling. The predictive control scheme was able to reduce the degree day adjusted thermal energy for heating from 76 MWh to 64 MWh and from 48 MWh to 29 MWh for cooling – a 25 % improvement overall. The project partners describe this work in a scientific article:

► *Kaisermayer, V., Muschick, D., Gölles, M., Schweiger, G., Schwengler, T., Mörth, M., Heimrath, H., Mach, T., Herzlieb, M., Horn, M., Predictive Building Energy Management with User Feedback in the Loop, Journal Smart Energy*

2.6.4 Comparing Optimization-based EMS and AI-based EMS

As an alternative to the optimization-based EMS described in chapter 2.6.1, control approaches based on machine learning or AI methods were also considered. A study was therefore carried out in which the optimisation-based EMS was compared with an alternative method that is currently being developed by a project partner.

The simulation study considers the four-story office building Inffeldgasse 19 (INF19). For this study it is assumed that the building INF19 has its own energy centre with heat pumps and cooling machines. The main component of the energy system are the electrical heater and chiller, both air-to-water heat pumps. On the electrical side a 50 kWh battery and a PV system with 75 kWp is present. The thermal demand is split into the thermal zones, i.e. the offices, and uncontrollable thermal demand such as laboratories. To interpret the results correctly, it is important to know that no additional thermal energy storage is present and only the thermal mass of the building is utilized. The electricity demand of the building itself, i.e. appliances and lighting is not taken into account, and only the electricity demand for heating and cooling systems is considered. For the simulation study a variable price for importing electricity from the grid and a monthly variable price for exporting electricity to the grid is assumed.

A predictive **optimisation-based building energy management system (EMS)** (Figure 36) was implemented based on the same modular framework which also was used for Inffeldgasse 21b. In contrast to the one implemented for Inffeldgasse 21b, the components of the energy supply (thermal district grid, heat pump, PV system) and an electrical battery were also integrated into the control scheme.

For the **AI-based EMS** a training model was needed that is fast enough to be evaluated many thousand times during training in a reasonable amount of time. As the model developed in the IDA ICE simulation programme (Figure 43) is not suitable for this due to its high level of detail, a surrogate was developed based on the detailed model. The development of this surrogate model was published in:

► *Kefer, K., Haijes, S., Mörth, M., Heimrath, R., Mach, T., Kaisermayer, V., Zemann, C., Muschick, D., Burlacu, B., Winkler, S., & Affenzeller, M. (2023). Evaluating Machine Learning and Heuristic Optimization Based Surrogates as a Replacement for a Complex Building Simulation Model. Proceedings of the International Workshop on Simulation for Energy, Sustainable Development and Environment, SESDE, 2023-September.*

The developed model was then used for training the AI-based EMS. It is based on symbolic regression, i.e. non-linear equations, describing the actual control strategy in terms of input signals. Some of the inputs are actual measurements of the building, some are computed features, such as the cosine of the hour of day or an indicator if it is a working day or holiday. Coming up these features is tricky and a lot of insight is needed. Finding the optimal non-linear equations for the AI-based EMS, is done using a genetic algorithm. The idea is to iteratively combine existing equations, and slightly mutating them, evaluating their performance against an objective function (similar to the optimization-based EMS) and favouring the equations that performed best in the next iteration. The result is an executable that was used for evaluation of the approach in a detailed co-simulation with the IDA ICE model of the building Inffeldgasse 19.

In terms of cost, the AI-based EMS achieves 4 % lower costs compared to the optimization-based EMS. However, energy costs and comfort are opposing goals, hence the comfort has to be evaluated too. The comparison of the thermal comfort is based on the ISO7730, where three comfort levels are distinguished. In terms of thermal comfort, the optimization-based EMS is able to increase the overall time spent in the highest comfort level and decrease the time outside of all comfort levels. It can be seen, that the reason for the cost reduction is a large loss of comfort. The time outside the comfort norm is 16 % for the AI-base EMS and only 2 % for the optimization-based EMS.

A common key performance indicator for PV-systems is the degree of self-sufficiency (Figure 39). It can be seen that the optimisation-based EMS has a lower degree of self-sufficiency than the AI-based EMS. Summarizing, the optimization-based EMS is able to achieve higher comfort levels, with a small cost increase. Comfort and cost are opposing goals, hence only one or the other can be minimized. The AI-based EMS archives a higher degree of self-sufficiency; however, this has not been part of the objective function of the optimization-based EMS. Only cost and comfort were part of it.

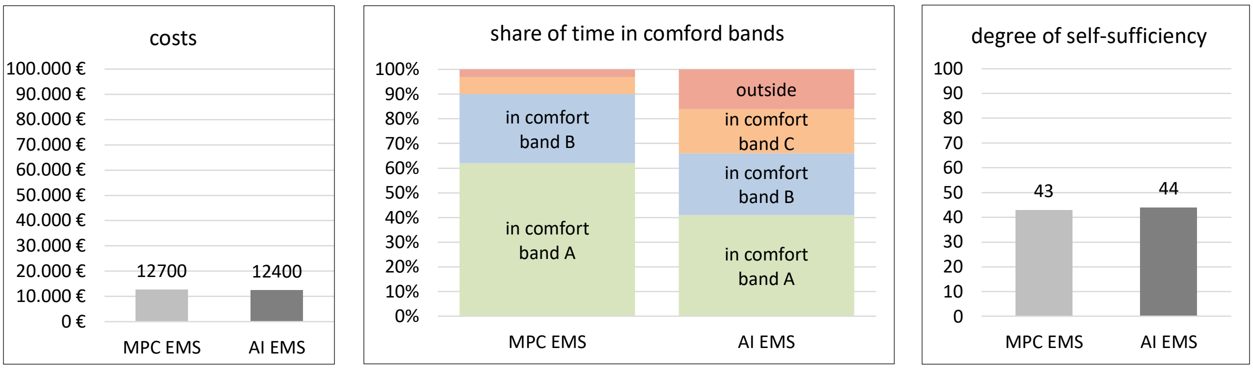


Figure 39: Comparison of the results of AI-base EMS with results of optimization-based EMS

2.6.5 Approaches of optimised energy control of a district

To create an optimization-based energy management system (EMS) for an entire district, it is necessary to consider the energy system of all buildings, including their thermal zones, as well as all energy generation systems, such as heat pumps, energy storages, and PV systems. However, due to the large scale of this optimization problem, real-time control may not be feasible. Therefore, a hierarchical approach is proposed, in which a central planning EMS considers a simplified model of the Campus' energy system, but with a longer prediction horizon.

For individual buildings, separate EMSs are implemented, which have a more detailed model of their corresponding energy system, possibly even considering the thermal zones of the building to enable thermal demand-side management. The planning EMS is responsible for considering the boundary conditions of the campus, such as the electricity price, total electricity consumption, and total thermal demand that must be supplied by the district heating network.

While the underlying building EMS can also consider the electricity price, it cannot consider more elaborate costs and constraints, such as power prices or limitations on the total demand. Only a high-level EMS is able to consider such costs and constraints.

Coordinating such a hierarchical structure, however, is challenging. One promising approach is distributed optimization. The idea is to divide a larger optimization problem into smaller ones and ensure coupling constraints via an iterative algorithm. The algorithm would iterate three steps: First, the planning EMS would compute so called shadow prices and communicate these to the underlying low-level EMS. Second, the low-level EMS have to consider those price signals and compute an optimal schedule for their energy system. Third, the new schedules are sent back to the planning EMS, which in turn would update the shadow prices. Figure 40 shows the hierarchical structure of the proposed concept for predictive control of the whole campus.

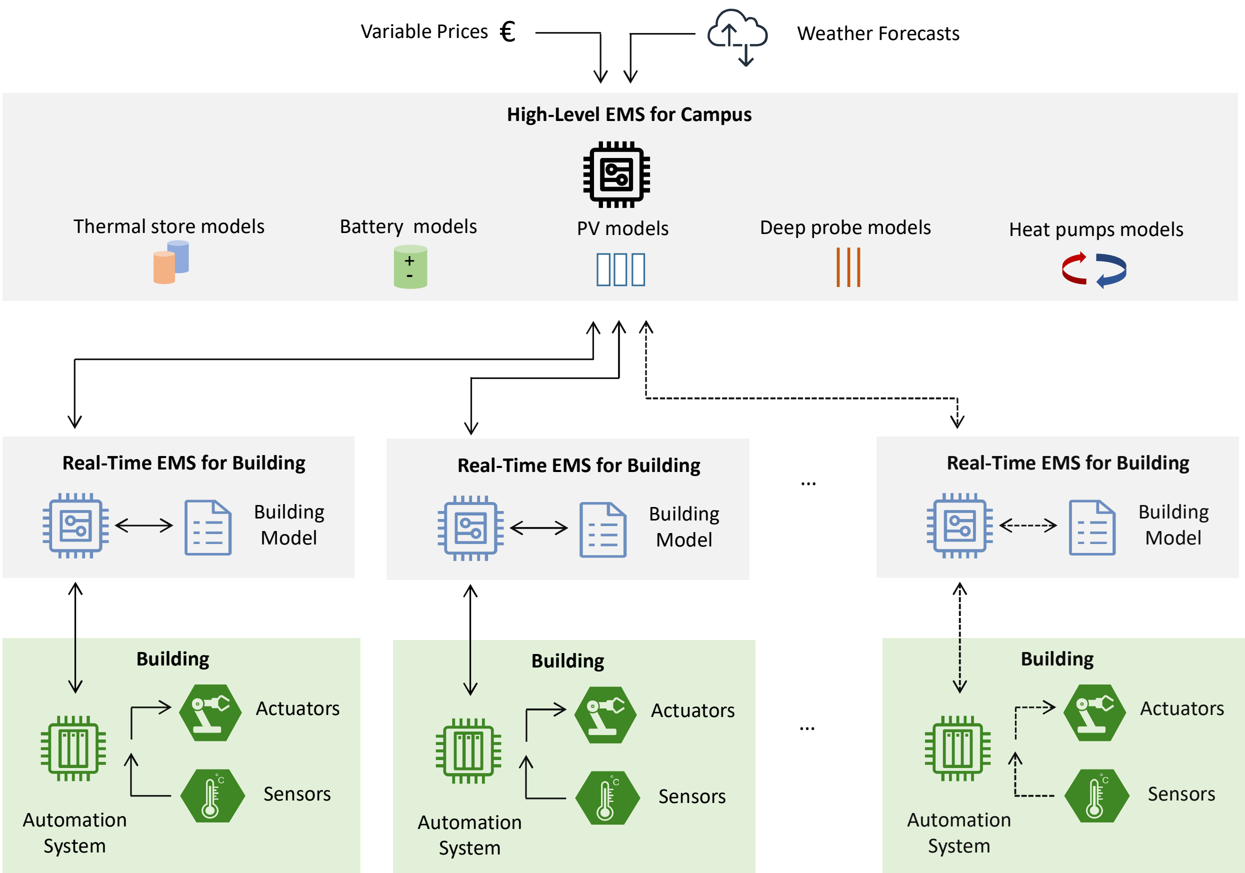


Figure 40: hierarchical structure of the proposed concept for predictive control of the whole campus

For the implementation of such a system several parts are needed. The high-level EMS for the campus which bases on individual component models in order to describe the energy systems for the EMS. In UserGRIDs models for thermal stores, batteries, PV systems, deep probes and heat pumps have been implemented. As well as a working implementation of the EMS for individual buildings, that are able to consider variable prices, detailed building and energy system models. And last but not least an algorithm and communication protocol for interconnecting them.

2.7 MODEL

Energy systems of urban areas are subject to constant transformation. Changes in use, new buildings, extensions and demolitions, as well as activities to increase energy efficiency cause permanent change. As a basis for every change measure, design options and planning variants must be evaluated and further developed with regard to their functionality, efficiency, environmental impact and costs. A tool is therefore required that can be used to model, evaluate and optimize structural, energy-related, climate-related and usage-related transformation projects for complex energy systems. The fundamental objectives are, on the one hand, to prepare the basis for decisions on the selection of the most suitable consumption and supply infrastructure and, on the other hand, to test and develop the most effective operating mode. This results in the following objective for the digital energy service MODEL.

The **target** of this service is to model the status quo as well as possible development scenarios of urban energy systems by means of detailed numerical simulation.

The digital energy service MODEL is a sequential combination of processing steps and different modelling and simulation methods (Figure 41). In MODEL, data from the STRUCTURE service is used to create a thermoelectric simulation model of the entire Innovation District Inffeld.

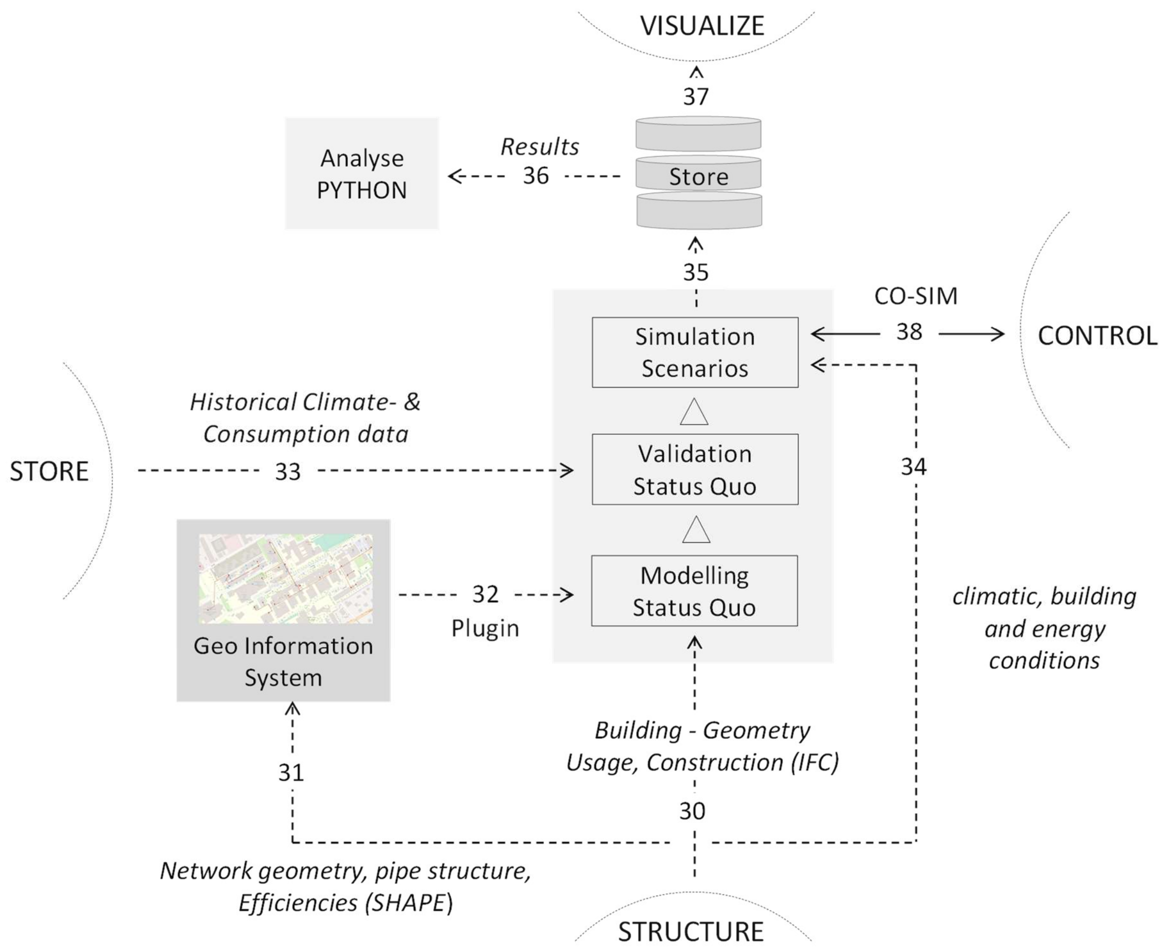


Figure 41: Functional scheme of digital energy service MODEL

Building geometries, construction structures and user data are exported semi-automatically (IFC) to the IDA ICE simulation environment (30) and further processed into a district building model. Data describing the thermal and electrical urban energy supply infrastructure is exported georeferenced to a geoinformation system (31) and also transferred to a simulation model via a plugin developed in the project (32). The resulting simulation model of the Innovation District Inffeld is validated using measured values, for which historical climate- & consumption data is used (33). Possible future developments are formulated as simulation scenarios based on the information available in STRUCTURE (34). The results are transferred to a database (35), analysed (36) and displayed in VISZUALIZE (37). The scenario models are also used in a co-simulation (C-SIM) by the Digital Energy Service CONTROL as a virtual test bed for developing control strategies (38).

2.7.1 Semi-automated generation of building models

Urban energy systems can be understood as a collection of individual energy subsystems and the energy grids that connect the subsystems. In addition to large energy-infrastructural components, such as heating plants or large heat pumps, buildings make up the majority of subsystems. Depending on the task at hand, these building models must be set up in varying degrees of detail. The models of all levels of detail have two fundamental things in common. On the one hand, their creation requires a substantial amount of information about the structure and operation of the buildings to be modelled. This necessity was taken into consideration in UserGRIDs by setting up the STRUCTURE service (chapter 2.1). On the other hand, the creation of building models is associated with a very high input effort, which is both time-consuming and error-prone. For this reason, different methods for semi-automated model creation were developed and tested in UserGRIDs:

A new **semi-automated workflow** (Figure 37, process 30) was implemented to transfer building geometry data to the simulation models of the district. The building descriptions, defined in STRUCTURE and stored in Vectorworks can be directly imported into the simulation program IDA ICE [[52]] via an IFC interface. IFC (Industry Foundation Classes [[53]]) is an open international standard for data exchange in the building industry, which is especially suitable for transferring geometric data. The "Volume and construction model" (chapter 2.1.2) contains information on the georeferenced positioning and geometric extent of all components that define the interior, such as walls, doors, windows, ceilings and floors. Information on the geometric subdivision of the components into individual construction layers is also available. The IFC transport transfers the geometric data and the associated attributes from Vectorworks to the IDA ICE simulation program. In contrast to this successful automation of the transfer of geometric information to the building models, there is still a need for further automation in the transfer of material properties and usage specifications.

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[52] https://www.equa.se/en/
[53] https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/

In addition to the geometric data, different attributes are assigned to elements in STRUCTURE. For example, component layers have an identifier for the material they are made of and interiors have an identifier for the usage category applicable to the room. Further data must be assigned to these attributes individually when creating the model. For example, the material identifier can be assigned specific material parameters from the program's internal material database and the usage type identifier can be assigned different profiles of internal temperatures and other usage-dependent values.

In order **to explore the possibilities of further automation**, a master's thesis was carried out as part of the UserGRIDs project (author F. Profanter - chapter 4.3). In the Revit [[54]] program, the geometry of individual buildings (parts) was already stored in the structural model with material parameters. As a result, an automated transfer of component geometry, including stored material properties, could be found in IDA ICE models. The transfer of geometrically complex components often requires a geometric simplification in the simulation model. For this reason, the effects of different degrees of simplification on the energy-related simulation result were evaluated in the thesis.

In higher levels of detail in the modelling and simulation of buildings, the building's internal energy system components, such as radiators, are also mapped. Another master's thesis (author M. Oboril - chapter 4.3) therefore dealt with the **automation of the transfer of building energy components** from a structural model to a simulation model based on IDA ICE. A method was developed to store energy-related data for radiators in the structural model. The selection of the stored data is based on the requirements of energy-related radiator modelling. A semi-automated transport makes it possible to transfer the radiator with all the necessary energy-related parameters directly into IDA ICE and automatically create an energy-related radiator model there.

2.7.2 Towards semi-automated modelling of the urban energy infrastructure

Energy networks are the connecting elements of urban energy systems. They transport energy so that the tasks of heating, cooling and the supply of electricity and domestic hot water can be fulfilled. On the one hand, they are connected to higher-level hierarchical systems, such as transfer stations for receiving heat or electrical energy from urban energy networks. On the other hand, they connect the individual subsystems (buildings) with each other. In addition, infrastructural subsystems such as large heat pumps or energy storage systems can also be arranged in the networks.

At the same time, the energy models of these networks are the connecting elements between the individual sub-models (building models). The structure of these network models shares the two similarities described above with the sub-models.

[54] https://www.autodesk.de/products/revit/architecture

Here too, a great deal of information is required to create the model, which is then just as time-consuming and error-prone. The consistent data source for this has also been set up in the STRUCTURE service in the UserGRIDs project. Being able to transfer the relevant information from a single source of truth database into simulation models with the least possible time expenditure and susceptibility to errors is of central importance. Such an automated process of data transfer into models has not yet been established either in practice or in the research landscape. As part of the UserGRIDs project, a corresponding method was developed and refined. The method comprises the export of relevant modelling data from STRUCTURE, processes 31 and 32 as well as "Modelling Status Quo" (Figure 37):

Heating and cooling supply data stored in STRUCTURE is exported from Vectorworks using SHAPE files. The Shape data format was developed by the Environmental Systems Research Institute (esri [[55]]) to store and transfer georeferenced data and its associated attributes on the basis of vectors. In the UserGRIDs project, information exported from STRUCTURE on network geometries, pipelines, heat exchangers, chillers and their attributes (chapter 2.1.5) is imported into QGIS. QGIS (Open-Source-Desktop-GIS [[56]]) is the ideal basis for intersecting or relating the information of the respective project with data from the extensive data landscape of geoinformation systems, e.g. GIS Styria [[57]]. Non-imported information on the heating and cooling networks can be added in QGIS. Automatic network generation, which was developed in a previous project [[58]], can also be used to generate network maps. It is also possible to manually draw the network geometries based on street plans and other boundary conditions.

A **user interface** (Figure 42) has been designed to make it easy to build and simulate typical cases, but also offers the advanced user the full flexibility of IDA ICE. To provide both efficiency and flexibility, two user levels are offered: Standard in QGIS and Advanced in IDA. The modelling part in QGIS is split into five plugins:

- Projects can be managed by means of the **Project Handling** plugin. They can be loaded, deleted or created. Versions with sub-versions can be created for each project (Mother/Child principle). In addition, configurations can be set for selected projects, e.g. the reference coordinate system. The data is stored in tables in a PostgreSQL database (DB), which is an open source SQL database with an extensive library for processing georeferenced data.

- The **Data Center** plugin can be used to organize data. Default data can be customized and used all over projects and its versions. To increase productivity, predefined templates for energy supply systems, customers and devices such as heat exchangers, heat pumps, pumps or valves, are provided. Templates can be used or customized and placed on the map.

[55] https://www.esri.com/en-us/home
[56] https://www.qgis.org/de/site/
[57] https://gis.stmk.gv.at/wgportal/atlasmobile/map/Basiskarten/Basiskarte
[58] EnergySimCity, Research Studio Austria, 2014 - 2018

- The **Pre-processing** plugin helps to fill projects with data. A pipe laying algorithm to automatically generate a network between customers and energy plants can be used. Alternatively new network topologies can be created on the QGIS user environment.

- The **Modelling and Simulation** plugin can be used to build a simulation model based on QGIS data, which can be simulated in IDA ICE. The core of the simulation model are finite difference and plug-flow pipe models, which allow bi-directional flow. The user can define the discretization and the boundary of the piping network and can select which output should be logged. Features such as energy plants, customers or devices can be connected together using connection types and pipe bundles. Any number of pipes can be modelled, combining different systems such as cooling and heating networks. Stochastic domestic hot water profiles can be used to represent the occupancy behaviour. Further, decoupling methods can be used to distribute the model to several computing cores to increase performance.

  The buildings are represented by highly simplified models in order to minimise the duration of the simulation calculation, even for complex energy systems. If statements about the energy behaviour within a building are to be analysed, then each simplified model can be removed from the defined interface and replaced by more complex models.

- In order to check the input data or to evaluate the simulation results, visualization is particularly important for modellers as well as for stakeholders. The data can be presented by means of the **Result and Visualization** plugin in 2D categorized in colour codes and displayed with maps. Any number of layers can be overlaid. In the 3D representation, building heights or the elevation model can also be displayed. Results can be presented in the form of heat maps, building-specific results, path reports or animations.

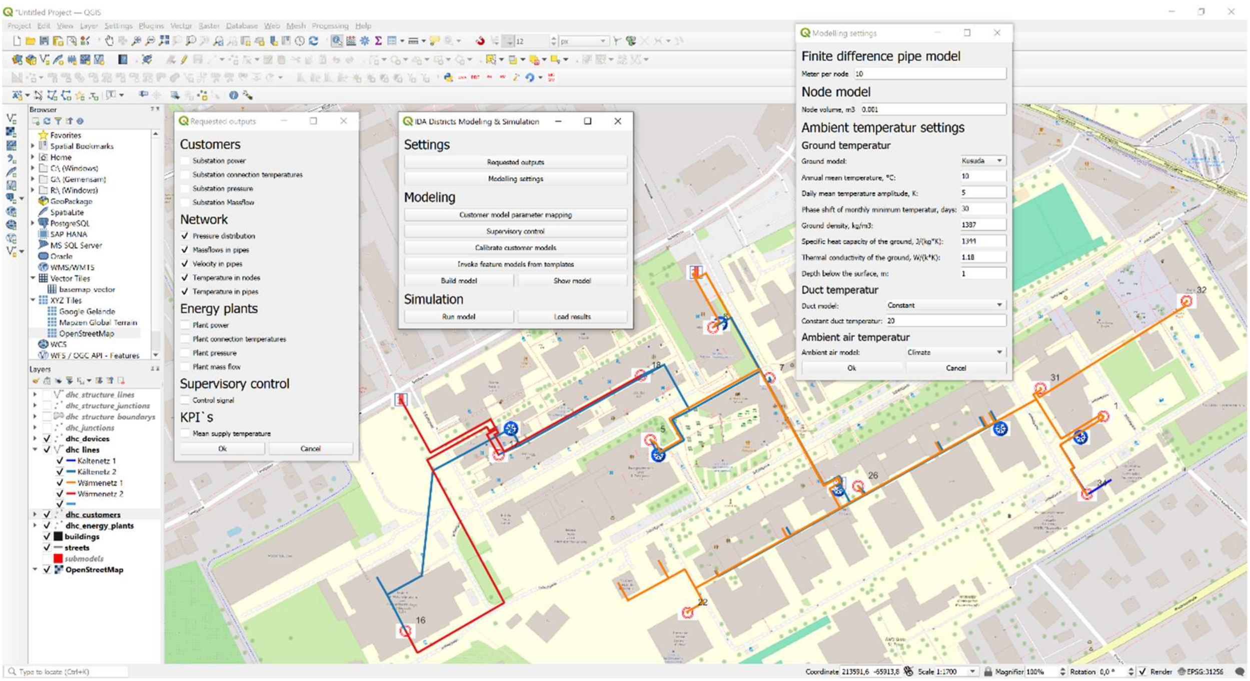

Figure 42: User interface in QGIS showing the case of the Innovation District Inffeld

The increasing complexity of heating and cooling networks requires new modelling and simulation methods that can quickly simulate and clearly visualize even large systems with a large number of components. The new methods are based on a dynamic simulation application to study thermal energy supply strategies of districts. They can be used to simulate the dynamic interactions between supply, storage, distribution and consumers in a coupled manner, which allows an exact coordination of all subsystems as well as sizing of components. The results of these simulations can be visualized as animations, which allows a clear presentation of the overlapping result layers of the buildings and the network. The methods can provide planning security in both, designing a district energy system and operating it. The energy system can be precisely adapted to local conditions and different strategies can be compared. The network topology can be checked or generated automatically. The choice and dimensioning of components can also be facilitated. Furthermore, the pressure-driven modelling allows the evaluation of different operational strategies such as decreasing the supply temperature or demand side management and evaluation of failure scenarios or insufficient heat supply.

2.7.3 Measurement based validation of simulation models

The validation of simulation models is crucial for the credibility of the results and conclusions derived from them. The simulation model developed for the energy system of the Innovation District Inffeld consists of a large number of sub-models. Each sub-model represents one component of the real energy system. In this case, two validation steps are required. In the first step, the functionality of the individual submodels must be checked to ensure that the individual components are correctly represented by the submodels. To this end, all relevant data points were measured, analysed and compared with the simulation results of the submodels using indicators and balances. As a result, validated component models of the buildings, the geothermal probes, the heat pump and the associated energy storage and photovoltaic systems are available. The second step is to ensure that the combination of the individual sub-models behaves in the same way as the combination of the real components in the real overall energy system.

The sub-models of the buildings are available in two different levels of detail. Detailed simulation models were developed for individual buildings (e.g. IN12, IN19, IN21b). These were created in the IDA ICE simulation programme and contain a large number of thermal zones as well as a detailed representation of the building's energy technology. Figure 43 shows, as an example, views and some characteristic values of the simulation model of the building at Inffeldgasse 19. The building was divided into 48 thermal zones, which were classified into different user groups. Each user group has corresponding internal heat inputs from persons and equipment. Constructive structures are modelled in detail, considering the component layers. The shading of external building surfaces, especially windows, by neighbouring buildings is also taken into account. The simulation models were calibrated on a monthly basis using measured heating and cooling energy consumption. The detailed modelling and validation procedure are described in M. Mörth's master's thesis (chapter 4.3).

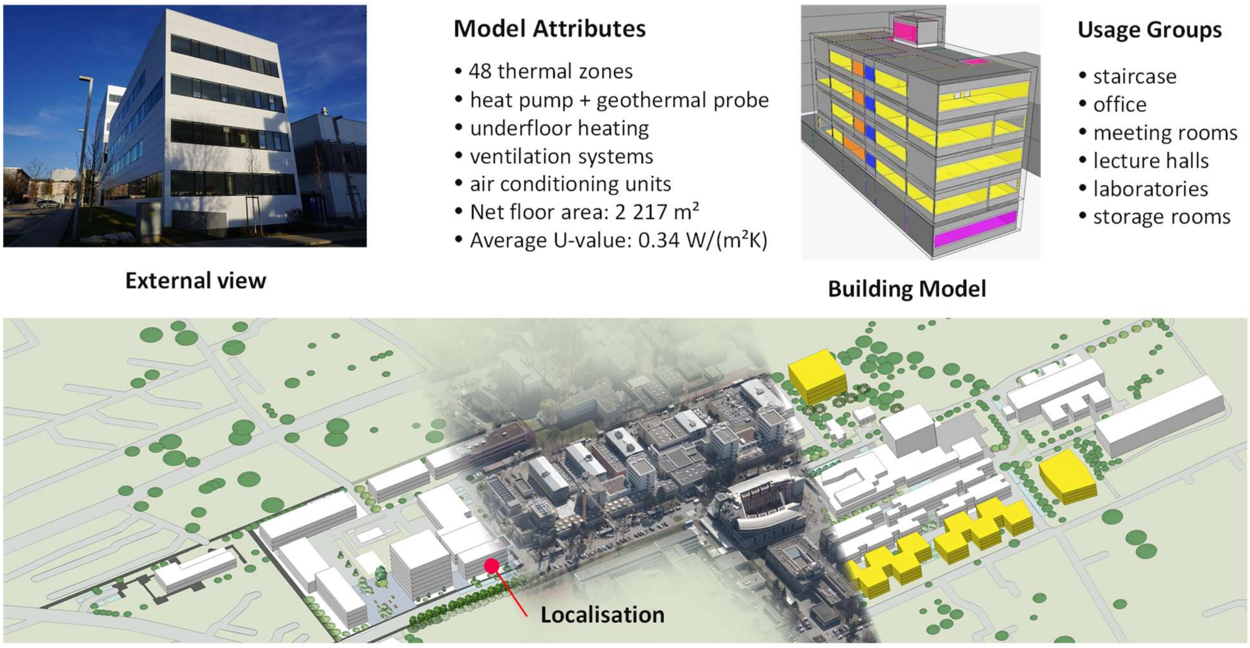

Figure 43: Views and characteristic values of the simulation model of the building at Inffeldgasse 19

At the same time, work was done on significantly **simplified building models**, which should have sufficient accuracy with regard to general issues without causing long simulation computing times. For this purpose, a separate RC-Grey-Box-Model was created and validated. The simulation model of each building consists of two capacitances and three single resistances. The single resistances are represented by physical-mathematical descriptions with the objective of correctly modelling both the heating system and indoor air temperatures. The model was tested via an extensive validation process using a detailed building model and measurement data. The validation shows very good agreement between the simulated return temperatures and the indoor air temperature. In addition, the model can predict monthly and annual energy quantities very accurately. Nevertheless, it should be noted that the use of the model to calculate peak loads is limited. This is mainly due to the simplified representation of solar irradiation and the complex interactions between users and window ventilation.

The **geothermal probe model** was calibrated and validated using the results of a thermal response test carried out at the Innovation District Inffeld. Both the measured and simulated temperature curves were analysed and optimised in order to achieve the best possible agreement. A good agreement was achieved, with the difference in the average borehole heat exchanger temperatures being only minimally overestimated by the model. Calibration of the **heat pump model** was done by comparing the measured and simulated condenser output and the recorded compressor output under various boundary conditions of a real heat pump in the Innovation District Inffeld.

The **photovoltaic model** was analysed and validated in detail using three PV systems in the Innovation District. These submodels were validated in the COOL-QUARTER-PLUS project and published in the associated final report [59].

The **validation of the heat supply and demand of the district** was carried out by comparing the measured and simulated total energy consumption for heat during the last four months of 2022. This selection was made because measured data from both district heating transfer stations was available for this period. There was a good agreement between the measured values and the simulation results. The simulation reacted more sensitively to changes in the ambient conditions, which can be attributed to the reduced complexity of the building modelling (RC-Grey-Box-Model). One noticeable characteristic was the different start of the heating period, which was based on manual interventions in the real system and was not exclusively due to the outdoor temperature (as in the simulation model). Furthermore, the simulated heat demand at higher power levels is slightly higher than the measurements. Due to the constant changes and measures in the real district, it is difficult to achieve 100 % agreement with the measured data. Nevertheless, the agreement achieved can be described as good with reference to the reduced complexity of the modelling (Figure 44).

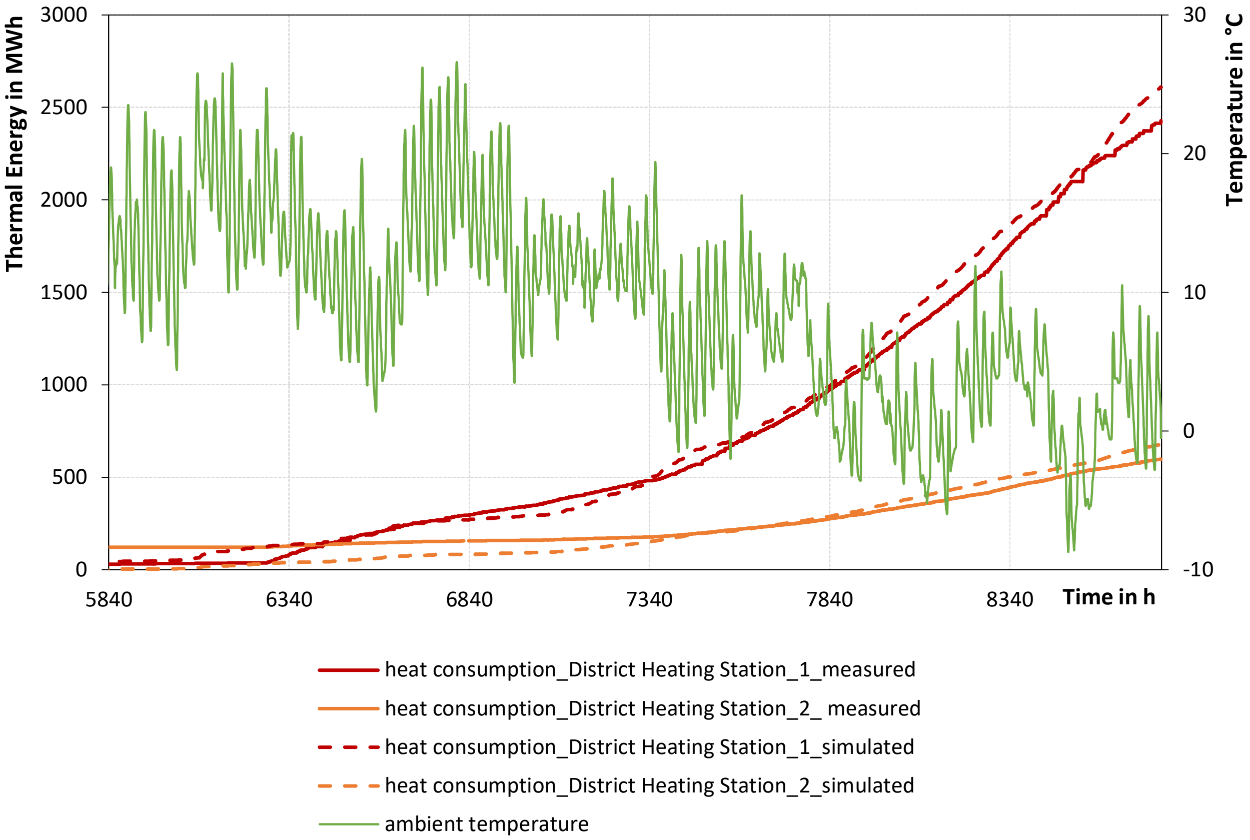

Figure 44: Measured and simulated cumulative heat demand for the last four months of 2022 and the outside air temperature, which can be read off the right-hand ordinate.

[59] COOL-QUARTER-PLUS, THG-neutrale Kühlung von Büro- und Forschungsquartieren, PN 879460, 2020 bis 2024

2.7.4 Evaluation of the utilisation of waste heat through heat pumps

The "Climate Neutral TU Graz 2030" project shows that the supply of district heating to the building's accounts for a relevant proportion of the greenhouse gas emissions caused by TU Graz. At the same time, large amounts of waste heat are generated at the Innovation District Inffeld due to the cooling of server rooms, test benches and interior spaces. These relationships are used to develop a use case for the simulation models created in the course of the project. The aim is a concept in which the available waste heat is to be used by means of a heat pump process to replace part of the district heating utilisation, which in turn should reduce the greenhouse gas emissions.

The central component of the concept is a compression heat pump, designed with two compact screw compressors of type CSH9583-280Y, the refrigerant R1234ze and an economiser. The used compressor has application limits up to condensing temperatures of just over 80 °C. A thermal store with a volume of 180 m³ (hot store) is assumed on the "warm side" of the heat pump. A thermal store with a volume of 80 m³ (warm store) is placed on the "cold side" of the heat pump to store the waste heat from various sources.

For the hydraulic integration into the existing district heating network (Figure 8), a parallel integration (Figure 45 - shaded yellow) and a serial integration (Figure 45 - shaded red) were developed. In both integration variants, the supply temperatures must be reached in order to provide the buildings with sufficient heat and the specifications of the district heating supplier, which define a maximum permissible return temperature in the superordinate urban heating network, must be fulfilled.

In the case of **parallel integration**, the district heating is integrated in parallel with the heat pump. Control is based on the specified supply temperatures to the consumers. If the heat pump cannot reach the required temperature, the district heating is switched on. If the supply temperature into the distribution network is below the required supply temperature, the proportion of district heating is continuously increased.

In the case of **series integration**, the district heating is connected downstream in series. With this type of integration, the return temperature may not meet the specifications of the heat supplier. To counteract this, the district heating return flow is sent through an additional heat exchanger to meet the heat supplier's specification. This is located on the source side ("cold side") of the heat pump. This makes it possible to cool the return flow further and meet the requirements of the heat supplier. It is also possible to use the district heating return as the source temperature. The further cooling of the return flow can have a positive effect on the existing district heating network.

In addition, two different control strategies for the heat pump are considered with both integration variants on the "hot side". In addition, two different control strategies for the heat pump are considered. In one variant, the admixing circuit (Figure 45 - shaded green) is not activated; in the other variant, premixing is carried out up to the required supply temperature to the customers. This means that the heat pump mixes until the required supply temperature is reached.

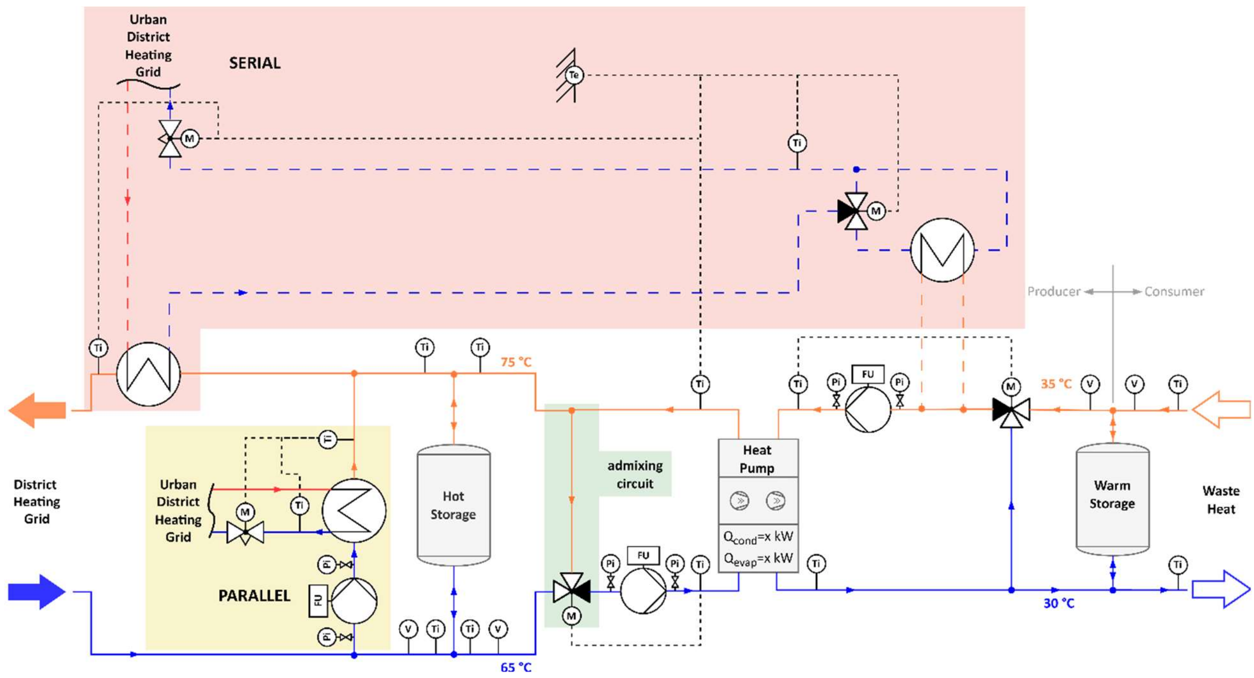

Figure 45: Possible system integration of the heat pump into the district heating grid of the Innovation District Inffeld

It is necessary to define key figures for a comprehensive analysis. The seasonal performance factor 2 (SPF) [60] is used as an efficiency indicator. This not only refers to the COP of the heat pump (coefficient of performance), but also includes the energy consumption of the pumps and the thermal losses of the storage tanks. In most cases, focussing only on the annual capital costs is not sufficient for an economic analysis. For this reason, the payback period [61] is also calculated, which indicates the time until the investment is fully refinanced. Furthermore, the internal rate of return [61] is calculated, at which the present value of the investment becomes zero. This enables potential investors to estimate the annual returns. The specific costs per MWh are also determined. In addition to the total CO_2-emissions, the specific emissions and the thermal self-sufficiency rate for heating energy of the urban quarter are also calculated. This indicates what proportion of the heat supply in the "Innovation District Inffeld" is covered by the heat pump.

The boundary conditions described in Figure 46 are used for the analysis. The investment costs of the heat pumps were taken from a study by Agora [62], as were the maintenance costs and the interest of capital. The specific costs for electrical and thermal energy are based on the net procurement costs of Graz University of Technology. The environmental costs were assumed according to ClimCalc [63] for the year 2021. The emissions for electricity are based without certification according to eco-label UZ 46 [64].

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[60] M. Erb, P. Hubacher und M. Ehrbar, Feldanalyse von Wärmepumpenanlagen FAWA 1996-2003, Schlussbericht., Apr. 2004, https://www.fws.ch/wp-content/uploads/2018/06/FAWA_Auszug_deutsch.pdf
[61] U. Terstege, M. Bitz und J. Ewert, Investitionsrechnung klipp & klar, Springer 2023, ISBN: 978-3-658-38655-9
[62] Roll-out von Großwärmepumpen in Deutschland: Strategien für den Markthochlauf in Wärmenetzen und Industrie, https://www.agora-energiewende.de/publikationen/roll-out-von-grosswaermepumpen-in-deutschland
[63] Erreichbar unter: https://nachhaltigeuniversitaeten.at/arbeitsgruppen/co2-neutrale-universitaeten/
[64] Richtline UZ 46, Grüner Strom, https://oekostrom.at/zertifizierung-in-oesterreich/

Investment Costs	Operating Costs	Environmental Costs
water-to-water heat pump: 1000 €/kW air-to-water heat pump: 700 €/kW	maintenance: 3 % of invest interest of capital: 3 % of invest price increases: 0 % of invest imputed service life: 20 years capital value factor: 10.19 % residual value: 0 €	urban district heat: 250 kgCO_2/MWh electrical energy: 226 kgCO_2/MWh

Figure 46: Boundary conditions applied for the analysis

Four scenarios were defined on the basis of boundary conditions. Two scenarios with serial integration and two scenarios with parallel integration were modelled, each with and without admixing circuit. The analysis of the results showed that admixing to the desired flow temperature leads to a decrease in the SPF, as the heat pump operates on average with higher condensing temperatures compared to the variant without admixing. The use of serial integration has advantages in terms of a higher SPF and is therefore more resource-efficient with exergy, as the heat pump has a lower average temperature on the condenser side. In addition, this integration offers the possibility of optimizing the district heating network. For further investigations and optimisations, the serial integration of the heat pump without admixing was therefore selected.

In the next step, optimisation is used to determine the optimum size of the heat pump. For that several target variables were transformed into a weighted objective function. One ecological, one economic and one performance-specific key figure are used as target functions, namely the thermal self-supply ratio , the internal rate of return and the SPF.A total of three scenarios are analysed. In the "**waste heat scenario**”, an attempt is made to achieve the maximum benefit from the assumed and available waste heat flow. The weighting is equally distributed (w_1=w_2=w_3). In the "**air-to-water heat pump scenario**”, it is assumed that an additional heat source in the form of an air-to-water heat pump is installed on the “cold side” of the heat pump. This corresponds to the worst-case scenario, in which no further waste heat sources can be tapped and the construction of a brine-to-water heat pump coupled with a geothermal probe field is not possible. It is assumed that a further expansion of the internal heat supply by means of a heat pump is necessary to enable a CO_2-neutral Innovation District Inffeld. Once again, the optimisation is carried out using equally distributed weighting factors. The "**self-supply scenario**" is based on the air-to-water heat pump scenario, except that the self-supply ratio weighting factor is set to 0.6 and the internal rate of return and SPF factor are both set to 0.2.

In the final step, the models of the three scenarios are confronted with different climatic and structural boundary conditions. To enable a comparison with internationally recognised framework conditions, the ASHRAE [65] climate data set "IWEC2" for Graz Thalerhof in Austria is used in the first scenario (suffix: **IWEC2**). This climate data represent a typical year.

[65] IWEC2 (International Weather for Energy Calculations, Version 2) is a database provided by the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). It contains typical annual meteorological data for a large number of locations worldwide and is frequently used to simulate energy requirements under standardised weather conditions.

The second scenario follows conditions that correspond to the buildings and weather in the reference year 2022 (suffix: **year 2022**). In the third scenario, future conditions are assumed in which the insulation of four buildings is improved (U-value by 10 %) and climate data for the year 2042 are used. They were created on the basis of RCP scenario 8.5 (suffix: **year 2042**). Further information on the climate data used can be found in chapter 2.1.1. Figure 47 shows a comparison of the key performance indicators calculated on the basis of the simulation results.

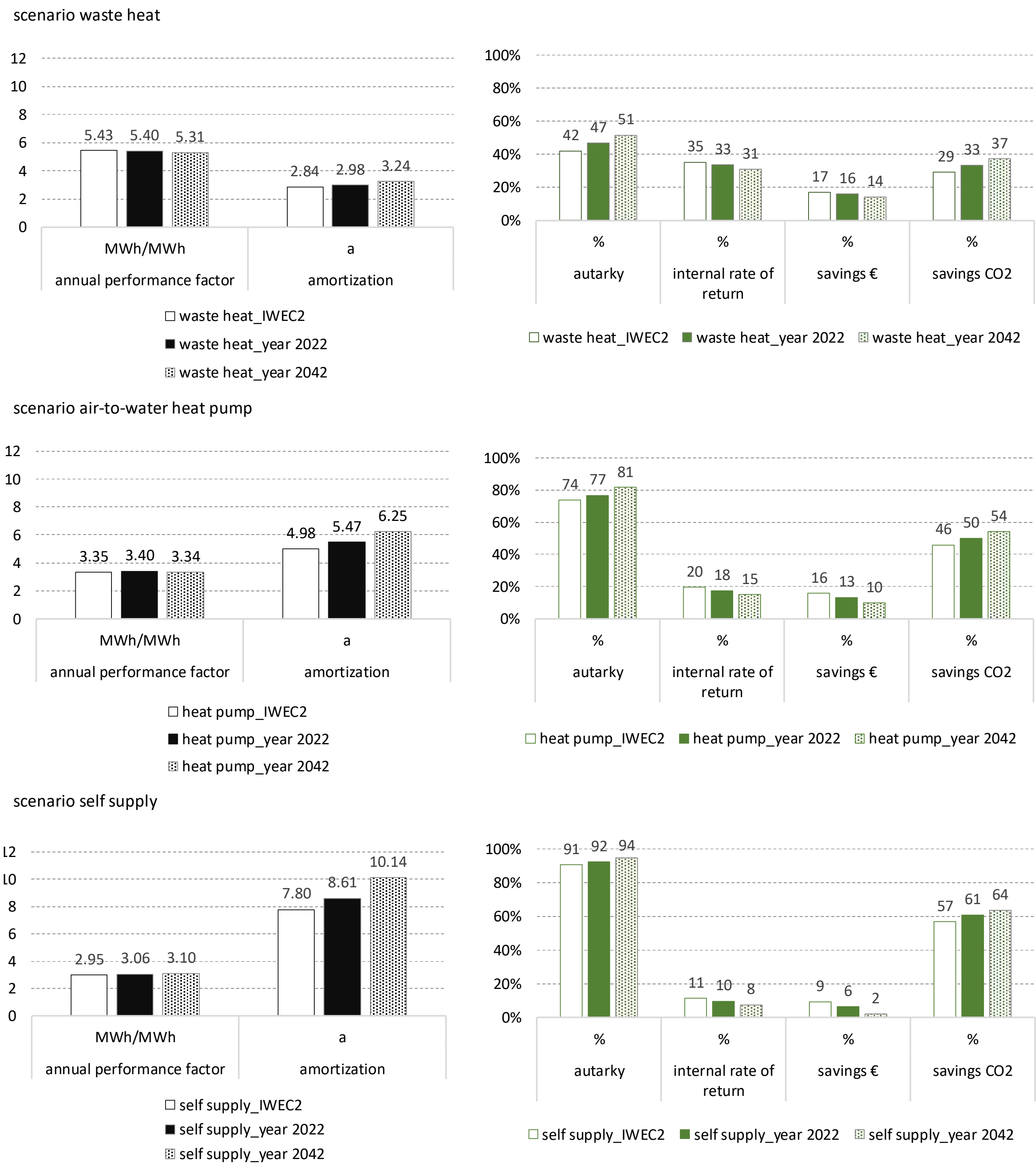

Figure 47: simulation based KPIs for the scenarios waste-heat, air-to-water heat pump and self-supply

The results show that the implementation of a first expansion stage (scenario waste-heat) of a heat pump with a thermal output of 670 kW on the condensation side appears to make sense in terms of energy, economy and ecology. This would allow the existing waste heat to be utilised in the future and to cover 42-51 % of the buildings currently supplied with district heating. SPF of around 5.4 are achieved, with an amortisation period of about 3 years.

A useful extension of the first expansion stage would be to add an air-to-water heat pump to the system, which can increase the heat potential (scenario air-to-water heat pump). In this case, a water-to-water heat pump with 1680 kW thermal capacity and an air-to-water heat pump with 762 kW thermal capacity on the condensation side can achieve a supply share of 74-81 %. The SPF calculated for both heat pumps are around 3.4, with a much longer amortisation periods of around 5-6 years.

Based on expansion stage 2, an attempt is now being made to generate a maximum amount of waste heat in order to further increase the degree of self-sufficiency and reduce CO_2-emissions (self-supply scenario). The optimum configuration for this is a combination of a water-to-water heat pump with 2500 kW thermal capacity and an air-to-water heat pump with 1204 kW thermal capacity on the condensation side. In this way, the use of urban district heating can be reduced by up to 91-94 %. The possible annual coefficients of performance are reduced to around 3.0 as a result of the high proportion of air-to-water heat pumps, which increases the amortisation period to 8-10 years.

2.8 VISUALIZE

Urban energy supply systems generally develop into complex systems due to the large number of components and their numerous interactions. Digital energy services analyse and optimise the energy system at various points and at different hierarchical levels. Relevant data, key performance indicators and analysis results must be communicated to people as the higher-level decision-making authority. The corresponding numerical and graphical presentation of information must be designed in such a way that it can be perceived clearly, comprehensibly and as intuitively as possible by users. This results in the following objective for the digital energy service VISUALIZE.

The **target** of this service is to present the analyses and findings created in the other services regarding the energy and emissions-related performance of the energy subsystems and the district system as a whole in a way that is clear and comprehensible to humans.

The VISUALIZE service (39) receives data from the RATE, MODEL, CONTROL and STORE services (38), which can be displayed in dashboards in the open source software Grafana (Figure 48). The organisation of the information processing and the individual dashboards is based on the hierarchical structure of the energy system (see chapter 2.5.1).

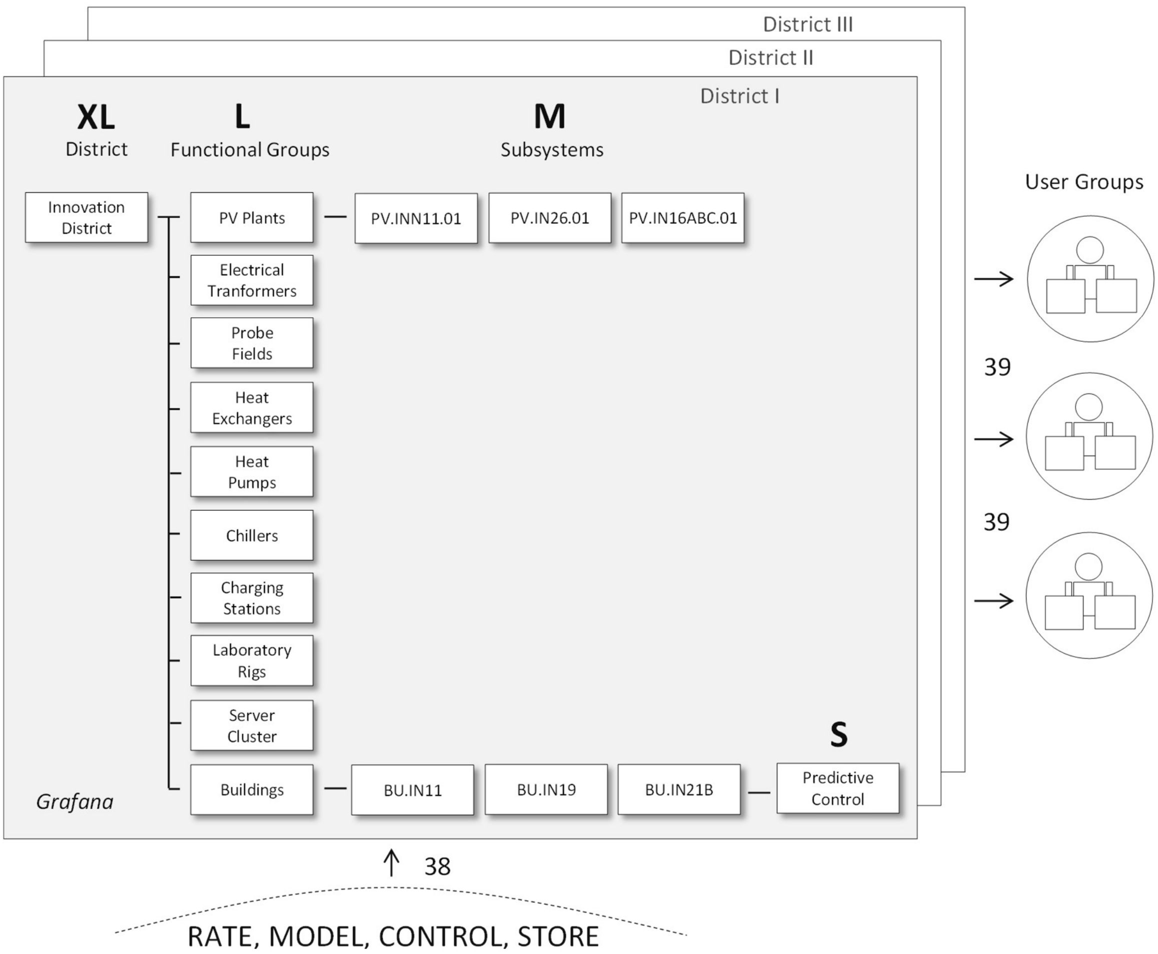

Figure 48: Functional scheme of digital energy service VISUALIZE

At district level XL, a dashboard shows the most important energy-related information for the entire Innovation District Inffeld. Level L contains a series of dashboards, each with information on one energy-related functional group (PV Plants, Electrical Transformers, etc.). In the detail level M below this, it is possible to create a separate dashboard for each subsystem. This is implemented for the three PV plants running since the beginning of 2022 (see chapter 2.1.6) and for some buildings. A dashboard is also created in level S for the Inffeldgasse 21b building. It supplements the information presented in Level M and provides insight into the comfort of individual indoor spaces, as well as into the parameters of the implemented predictive control (see chapter 2.6.3).

The structured modular design enables permanent internal development by further adapting, replacing or adding dashboards, as well as expansion to other districts. As part of the transition of the VISUALIZE service from a project to a permanent process, it will be necessary to decide which user groups will be granted access to which information (39).

2.8.1 Measured and predicted local climate data (Level XL)

Climatic parameters in various forms are of great importance as an essential framework condition for the fulfilment of service functionalities. PROGNOSE and CONTROL require both current and forecast climate data. RATE and MODEL, on the other hand, use historical time series of local outdoor air temperatures and solar radiation.

The current climate measurements are transmitted to ORGANIZE from the climate station installed on the roof of the Inffeldgasse 13 building as part of the project (chapter 2.2.2). The measured values are transmitted to ORGANIZE, stored in STORE and transferred to a dashboard in VISUALIZE (Figure 49). The outdoor air temperature, the global and diffuse solar radiation on the horizontal and the daily duration of sunshine are displayed in hourly values, each for the period of one week. The hourly values for relative and absolute humidity, dew point temperature and enthalpy are also visualised for one week. The latest updates of the outside air temperature and humidity (absolute and relative) are provided as individual numerical values as information for the current situation.

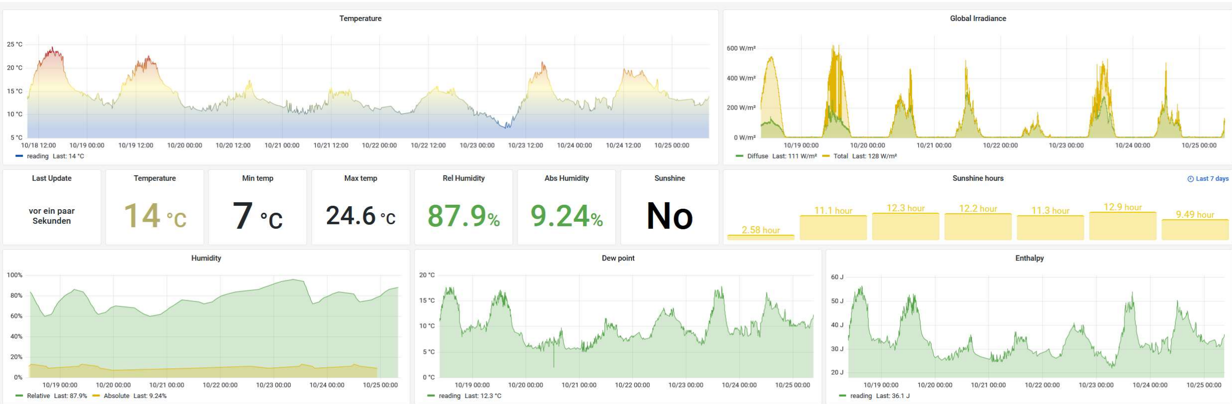

Figure 49: Dashboard for real-time visualisation of measured local climate data

2.8.2 Energy Consumption Building (Level M)

The energy consumption of individual buildings is calculated from the sensor values, as described in the RATE service. In the course of the project, it became apparent that the visualisation of a week with a time resolution of one hour is well suited for visual monitoring. Figure 50 shows a corresponding exemplary visualisation. The top part shows the climate data measured in the district (see 2.2.2). Outdoor temperature [°C] and global radiation [Wh/m²] are important framework conditions for energy consumption and are therefore helpful for the analysis. The second part contains the course of the consumption of electrical energy (Electricity Usage in kWh_e). Below this, the weekly progression of district heating consumption (District Heat Usage in kWh_t) is shown. The graph below shows that no cooling energy (kWh_t) was consumed in the week presented. The bottom part of the graph shows the cumulated GHG emissions (kg CO_{2e}), stemming from the distinct energy flows which caused them.

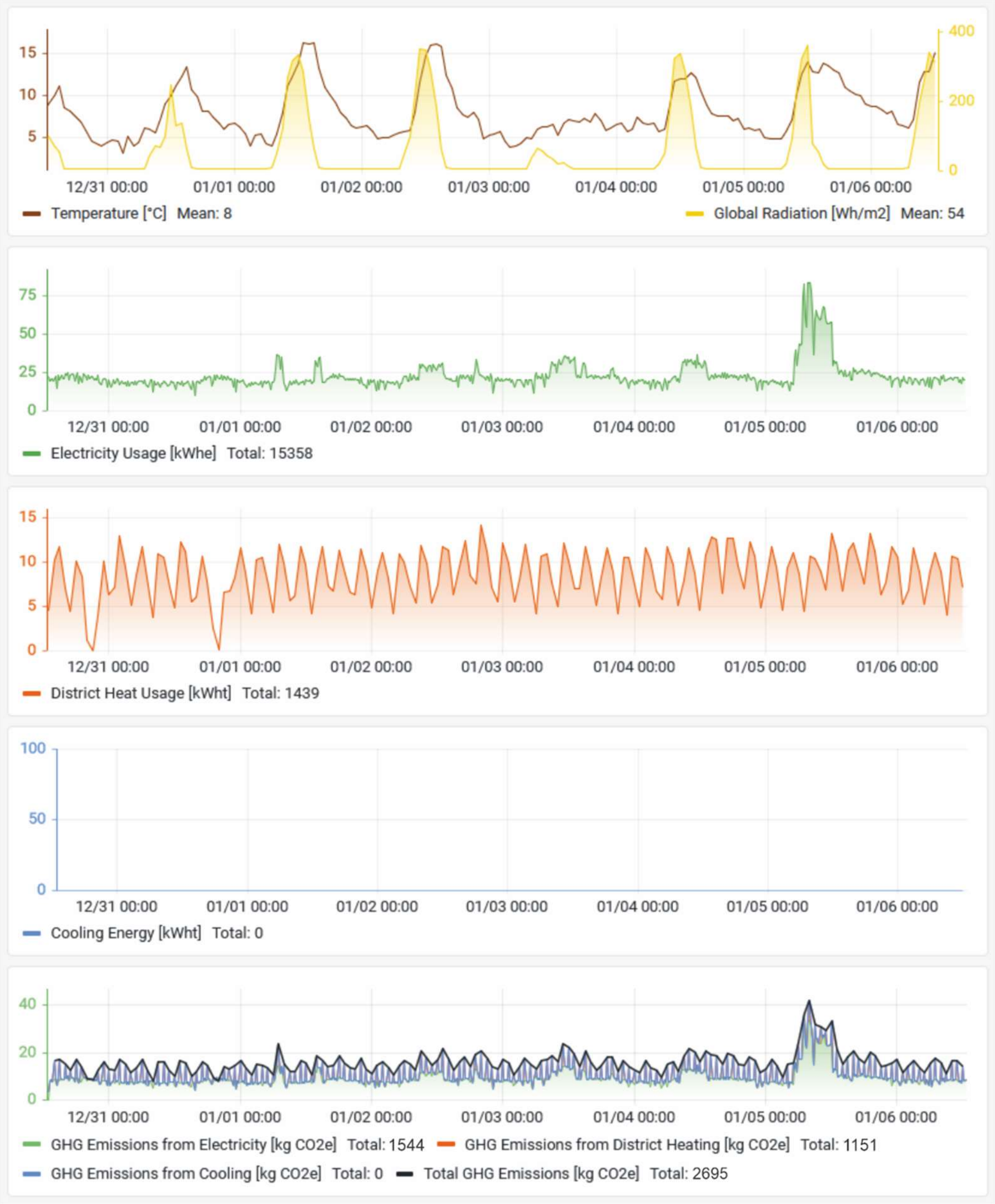

Figure 50: Real-time visualisation of building energy consumption in a dashboard

2.8.3 Prognostic Visualization (Level M)

In the PROGNOSE service (see chapter 2.4.1), the measured energy yield of three PV systems is compared with the results of data-based and physically defined forecasting methods in near real time. Figure 51 shows an example of a nine-day sequence with Figure data-based forecasts. As the basis of this forecast is the predicted solar irradiation, this is shown in the top part of the visualisation. Each of the three sub-graphs below shows the progression of the forecast values and the measured values for one PV system.

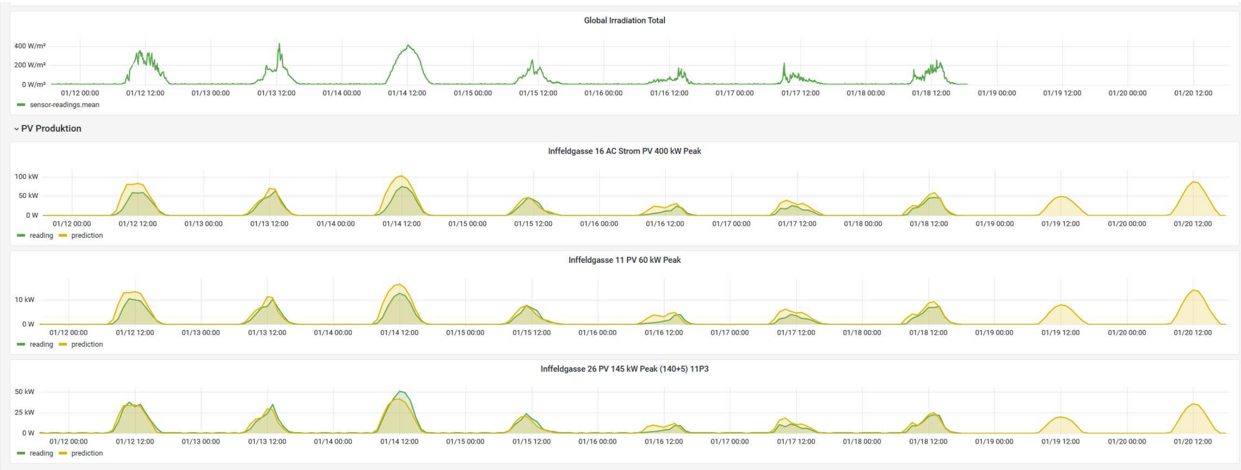

Figure 51: Real-time visualisation of prognosed and measured PV generated energy yield

2.8.4 Predictive Control Visualisation (Level S)

Figure 52 shows parts of the dashboard for visualizing the predictive control of the building Inffeldgasse 21B (see chapter 2.6.3). The solid lines are the measurements of the last 7 days and the dashed lines are the forecasts of the Energy Management System for the next 48 hours. The plots to the left show air temperatures of different rooms and the measured temperatures of the story ceilings. The plots to the right show valve positions and the mean temperature of one floor.

Figure 52: dashboard visualization of the predictive control in building Inffeldgasse 21B

3 Summary and Outlook

The UserGRIDs project comprised a wide variety of individual technological developments in the fields of information, simulation, energy and control technology. Combining these into a functional overall system proved to be a challenging task. In addition, the project team was able to gain a great deal of valuable experience during the realisation in an educational and research quarter, which could only be gained through direct confrontation with real conditions. Interdisciplinary and inter-institutional coordination processes, changing responsibilities, data protection issues.

3.1 Hard- and Software Concept

In terms of **hardware** the entire digital service structure is allocated on different servers and based on a couple of software packages (Figure 53 and Figure 54). The backbone of the system consists of the services STRUCTURE (12, 13, 14, 15), ORGANIZE (2) and STORE (3, 4, 5), which provide all other services information for their individual tasks. ORGANIZE and STORE that together can be called IoT-Platform, are hosted by servers of the central IT service of TU Graz (ZID). The services STRUCTURE and RATE (9, 10, 11) are located on a server of project partner IWT, while the service CONTROL runs on a server assigned to partner BEST.

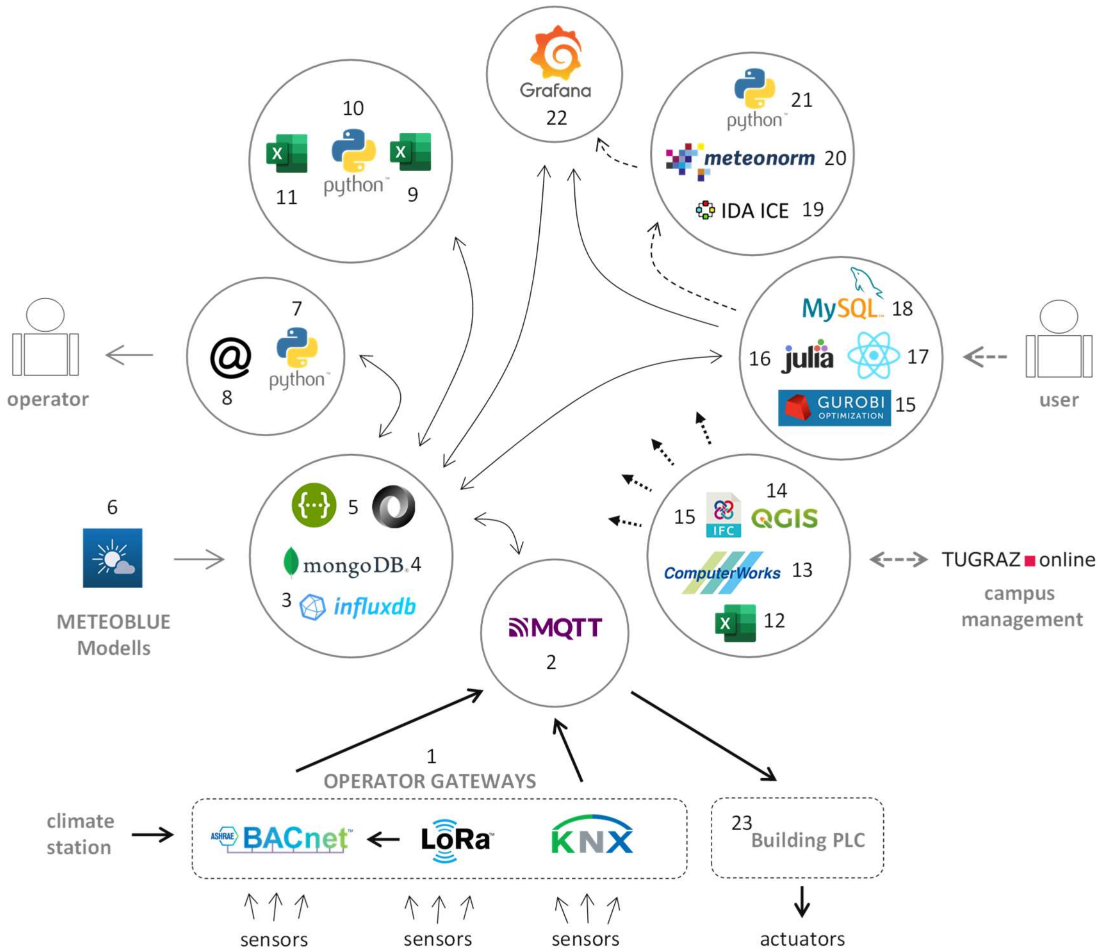

Figure 53: Information technology components and interfaces of the digital energy services

The different **software solutions** are either automated or partially automated linked together to achieve the desired functionality. Large amounts of data flow through the entire service structure, which are symbolised by arrows in the graphic. Monodirectional data flows are marked symbolised by an arrow. A bidirectional data exchange is represented by arrowheads in both directions. The type of arrow line provides information about the degree of automation. Solid arrow lines indicate that the data flow is fully automated – no intervention of humans is needed. Dashed arrow lines show that human intervention is required to transmit the corresponding data.

Nr.	Name of application	Function of application
1	BACnet, LoRa, KNX	Bus systems of the district's energy systems
2	MQTT	Bidirectional data transfer between district and digital energy services
3	InfluxDB	Storage of data series
4	MongoDB	Ontology database (attributes of sensor and calculation values)
5	API /Swagger	User interface for data exchange
6	Meteoblue	Climate data prediction
7	Python	Data forecasting Machine learning and modelling, error detection
8	email	Error detection warning
9	Excel	Automated conversion algorithm
10	Python	Conversion of sensor values to energy flows
11	Excel	Calculation of key performance indicators KPI
12	Excel	Area and infrastructure data evaluation
13	Vectorworks	CAD/BIM building infrastructure model
14	IFC	Transport of structural data to 18
15	GUROBI	Solver for solving the optimisation
16	Julia	Mapping of the predictive control of the EMS
17	react	App for mapping the comfort survey
18	MySQL	Database of the control variables
19	IDA ICE	Simulation of infrastructure and operating scenarios
20	Meteonorm	Calculation of synthetic climate data
21	Python	Analysis of the simulation results
22	Grafana	Visualisation of measurement and simulation data
23	PLC	Programmable logic controller (control unit of a building)

Figure 54: Listing of applications in the digital energy service structure

3.2 Stakeholder-innovation process

The development of digital energy services and, above all, their implementation on a university campus has a direct impact, or at least an indirect impact, on a whole range of institutions and the people working in them. Each of these stakeholders is affected by or involved in the implementation process in different ways and has specific tasks to fulfil in this context.

In the UserGRIDs project, it was assumed that a basis for successful implementation is to be able to name the affected stakeholders. It also was important to know their roles and interests and to take these into account appropriately when designing the implementation process. The project team was of the opinion that a lack of or inadequate integration of stakeholders leads to resistance, which can have a significant negative impact on speed, quality and acceptance.

In UserGRIDs, the involvement of stakeholders was developed in several steps: Stakeholders that were already included in the project planning and stakeholders that were recognised during the course of the project. At the beginning, the individual stakeholders and their roles had to be identified. On this basis, interviews were conducted with stakeholders and their views on different energy development options for the district were analysed. This allowed workshops to be organised in which the project team could discuss development goals and possible approaches with stakeholder representatives. Later on in the working process, based on the ongoing characterisation of the services, initial perspectives for utilisation, maintenance and further development could be determined.

Identification of stakeholder roles

Thirteen different stakeholder roles were identified based on the specific situation at the Innovation District Inffeld. Figure 55 shows the digital energy services developed in the UserGRIDs project in the centre. The stakeholder roles involved in the development and operation of the services are shown around the centre.

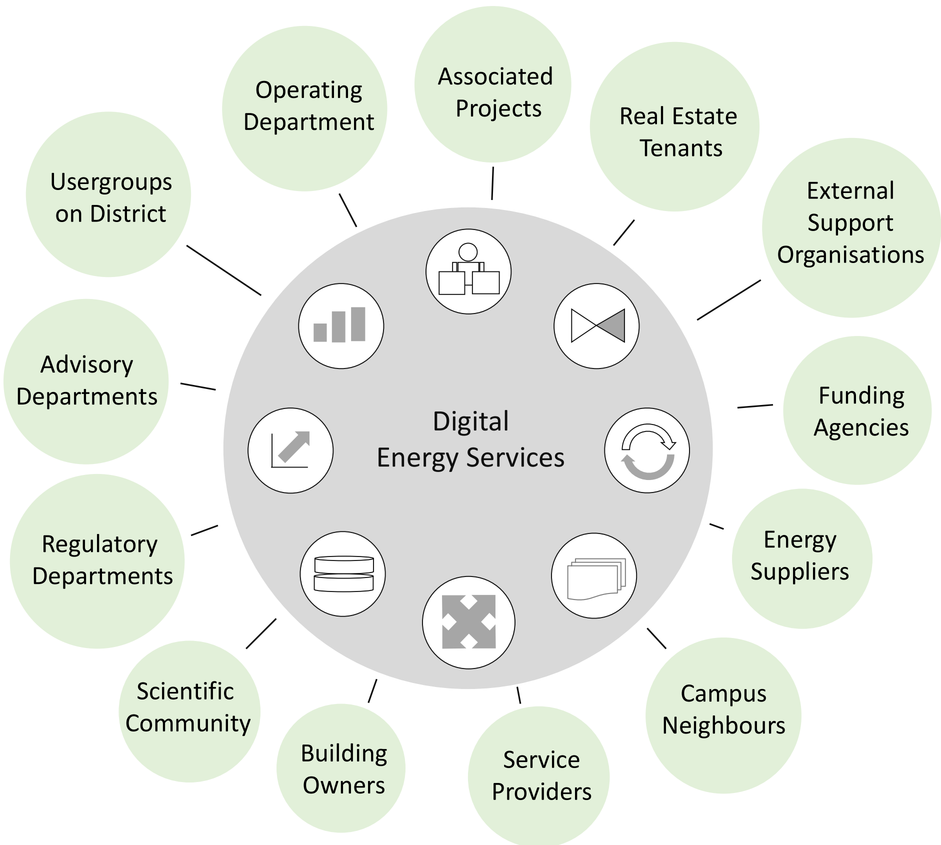

Figure 55: Digital energy services surrounded by stakeholder roles

Evaluation of stakeholder views and opinions

After identifying the stakeholders, it was important to get to know their opinions on the energy development of the Innovation District Inffeld. For this purpose, semi-structured interviews were conducted with representatives of the stakeholder roles in order to subsequently subject the results to a multicriteria analysis. In the interview, nine different options for action were given, which had to be evaluated in relation to their implementation in the Innovation District Inffeld.

1. Alternative fuels
2. Demand-side management
3. E-car charging stations
4. Energy communities
5. Renewable electricity generation
6. Seasonal thermal storage
7. Electricity storage
8. Purchase of UZ 46 Electricity
9. Carbon Capture Storage and Utilisation (CCSU)

The evaluations showed that the assessments of the effectiveness of the individual options for action were widely spread. This was particularly remarkable as the interviewees were all trained in energy technology and informed about the specific conditions in the Innovation District Inffeld. The identified reasons for the widely differing assessments were pointed out as …

- *First, assessments diverged because of the different but equally plausible estimations of future developments. This happened, for instance, when the decarbonization potential of electricity storage systems was rated differently based on the expected future availability of UZ 46 electricity*
- *Second, the mapping exercises left room for individual assumptions regarding precise delimitations of the infrastructural and technological scope. For example, the assessments about the decarbonization potential of demand-side management varied depending on whether synergies with other options had been considered or not.*
- *Third, divergent evaluations can be explained by the fact that the participants viewed the questions from their personal and professional perspectives.*
- *Finally, participants sometimes simply lacked relevant knowledge, such as when one participant did not consider the continuous investments in expanding renewable energy production that are associated with the UZ 46 electricity scheme.*

These four explanations, as well as, criteria mapping, and deeper explanations are published in the peer-reviewed inter- and transdisciplinary journal GAIA - Ecological Perspectives for Science and Society:

► *M. Kriechbaum, N. Katzer, G. Getzinger, S. Pabst, T. Mach, Transforming a university campus into a sustainable energy district: Multi-criteria mapping of implementation options, GAIA 32/2 (2023): 249 – 256, 2023*

Stakeholder ideas development

The first efforts to increase energy efficiency at TU Graz were launched long before the reference year 2022. Therefore, a number of currently ongoing measures were already in place at the beginning of the development period of the Innovation District Inffeld (Figure 56). The consistent expansion of the installation of photovoltaic systems and the gradual improvement of the insulation of building envelopes were well advanced in 2022. The decision to equip all new buildings with vertical ground source heat pumps has also been taken and is being implemented. In addition, the individual cooling systems are being connected step by step to form a cooling network, the mobility charging infrastructure is being expanded and preparations are being made for the purchase of certified renewable electricity. In addition, a bundle of further measures in various areas of sustainability development is being developed in the "Roadmap Climate-Neutral TU Graz 2030" [66]. However, the goal of a climate-neutral Graz University of Technology should also make use of the innovative power of a technical-scientific educational institution to contribute to the reduction of emissions in its own organisation. Stakeholder workshops (Figure 56) have proven to be a suitable instrument for initiating interdisciplinary idea development ①. Investigating and analysing ideas is a proven task for research projects and academic work ②. If this scientific work identifies potential, decision-makers must be informed of the outcomes in order to decide ③ whether implementation ④ should take place.

Such processes were initiated and used several times in the UserGRIDs project to bring ideas and the associated decision-making basis closer to those responsible and decision-makers and thus actively support the decarbonisation process.

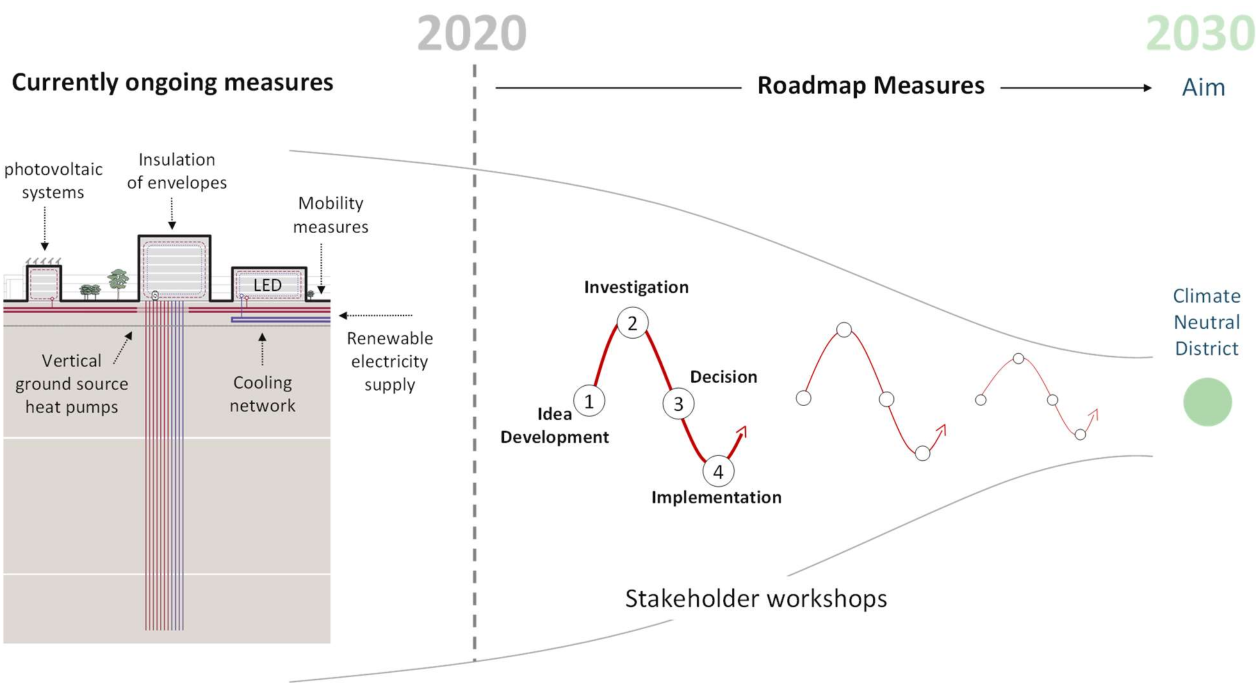

Figure 56: Presentation of the procedure for developing and reviewing emission-reducing measures

66 https://www.tugraz.at/tu-graz/universitaet/klimaneutrale-tu-graz/roadmap

3.3 What we have achieved

In March 2020, the UserGRIDs project consortium began its work on a three-year research, development and implementation programme. The following points of the comprehensive work programme were successfully implemented:

- The design of eight digital energy services for the largest campus of Graz University of Technology has been completed. The campus is to be developed into the Innovation District Inffeld by 2030. The basic development approach of the digital energy services follows the goal of utilising the constantly growing possibilities of digitalisation. Energy efficiency and the use of renewable energy sources in operations have been strengthened. The results will be incorporated into the future development of the site in order to reduce the induced greenhouse gas emissions.

- The functionality of the services is based on an urban structure model in which all relevant and available structural information on buildings and the thermal and electrical urban infrastructure has been implemented. This "single source of truth" serves as a consistent and common database for all other services.

- The developed and implemented IoT platform acts as an intermediary between the energy control systems running in the district. About 400 sensors are periodically queried and the measured values are stored in the database system developed for this purpose. Data series from the measurements can be automatically transferred to other services and external users via a developed interface.

- Based on the structural information and the sensor values, prediction models for the consumption and photovoltaic generation of electrical energy were developed, implemented and tested using machine learning and physical modelling. These models continuously compare current measured values with results from the models and can automatically detect and report operating errors on this basis.

- The sensor values are automated and continuously combined to create a picture of the energy flows in the district and used to analyse the performance of the energy system. Key performance indicators, which provide information on the current and past consumption of energy sources and the associated greenhouse gas emissions, have been implemented for some buildings.

- The energy management of an office building has been running via the CONTROL service of the IoT platform, since December 2022. Measurements and simulations have shown that the predictive control models used, which operate with the direct integration of user feedback, deliver excellent results. Thermal comfort was significantly increased and the energy requirements for heating and cooling were reduced considerably. In an accompanying study, the chosen approach to optimisation was compared with an optimisation approach from the field of machine learning or AI.

- For the analysis of future transformation options, new approaches have been developed for the semi-automated construction of energy-related district models. In addition, two master theses have successfully begun to create semi-automated transfers of building components (walls, ceilings, etc.) and energy technology components (radiators, etc.) from the structural model into simulation programmes.

- The district's energy model (building, heating network, cooling network) was used to analyse the scenario of implementing a large heat pump using waste heat produced in the district. The energy, environmental and financial benefits of such a solution were analysed. The model was also coupled with predictive control models via CO-simulation in order to design and virtually test the optimised operation of the heat pump system components involved (building, heat pump, deep probe field, PV systems).

3.4 What we have learned

The following observations are based on the experience gained by the project team over the course of the three-year UserGRIDs project during the design and implementation of digital energy services in the Innovation District Inffeld. These can be used to make the planning of similar future projects more targeted. Before generalising these statements, however, it is necessary to compare them with experiences from similar projects.

- **Close interdisciplinary and inter-institutional cooperation**
  The realisation of such comprehensive district-related approaches gives cause to a variety of challenges at different levels. At the technical development level, the combination of thermal, electrotechnical, structural, metrological and IT expertise is of crucial importance. ► Different ways of thinking, methods and specific technology related vocabulary must be continuously coordinated between the participating experts and integrated into the work processes.

- **Conflicting goals of operation and knowledge generation**
  A challenge known from the realisation of implementation-oriented research projects is the intervention in complex ongoing operational processes. The objectives of those responsible for operations (failure-free operation, financial feasibility, etc.) naturally differ significantly from the scientific objectives (development, experiment and knowledge gain). The different positions associated with this become particularly obvious in the course of agreements on procedures. ► A constant discussion on weighing up the interests of all partners involved was an indispensable basis for good cooperation.

- **Wide dispersion of stakeholder opinions**
  A surprising finding of the social science project monitoring was the disagreement regarding the evaluation of transformation measures. It has been shown that even within an experienced and well-qualified group of experts, the assessment of the usefulness of specific urban efficiency and transformation technologies varies widely. ► Stakeholder management based on active information and communication is an effective instrument for bringing divergent opinions closer together and strengthening consensus towards a harmonised approach.

- **Distributed knowledge and gaps in the database**
  Detailed knowledge of the structure of buildings and energy systems is essential as a basis for transformation planning. Access to this knowledge is widely dispersed in terms of personnel and institutions for an object of investigation of this size and complexity. The processing by a large number of different people and institutions over the course of several decades requires a large number of data holders and a wide variety of data formats. Some of the required information is not available in digital form, or the relevant data holders cannot be identified. When recording new data, the significance for the desired statements must always be weighed up against the costs incurred and the time required. ►Due to the inevitability of data gaps and different data qualities, it seems essential to always make statements taking into account the quality of the database.

- **Large heterogeneity in technical equipment**
  The Innovation District Inffeld analysed is, like supposedly most European urban districts, the result of decades of development. The building, energy and information technology structure to be found in the reference year 2022 is therefore a mixture of components from a wide range of technical development stages spanning five decades. ► The associated high degree of diversity in the technical equipment creates major challenges for the desire for automation in energy technology and its data processing.

- **Developing and analysing on the basis of constant change**
  A university campus is constantly being repaired, converted, modernised and extended. During the Corona pandemic, building use was extremely restricted, after which the measures to minimise potential energy losses and required energy-saving measures became effective. At the same time, two buildings were put into operation, various parts of the buildings were thermally refurbished and several PV systems were installed. ► The permanent change in the energy-relevant structure means that corresponding models must also be constantly revised. As the measurement data relates to constantly changing system configurations and framework conditions, valid comparisons are made considerably more difficult.

- **The complex functionality of the IOT platform requires constant maintenance**
  The functionality of the built IoT platform depends on a large number of individual components. External data deliveries (e.g. climatological forecast data) must arrive on time and in the correct formats. All sensors must transmit their data seamlessly and actuators must function both in terms of information technology and mechanics. Modifications to the hardware, but especially software updates, have proven to be an inherent source of malfunctions. ► In order to avoid long-term measurement failures or malfunctions, constant support is necessary. This must recognise any errors that occur as quickly as possible, identify their cause and take suitable measures to restore error-free operation.

3.5 What needs further development

The comprehensive project approach was intended to cover a range of approaches for increasing energy efficiency and the increased use of renewable energy sources. Under the given budgetary and time constraints, not every approach that was identified, could be fully developed, implemented and evaluated. The most important starting points and problems that require further investigation are described below.

- **Extension of the database describing the structure**
  During the three-year project period, a broad basis of structural data was collected and processed. Information that could no longer be obtained had to be determined by analyses carried out on site. In particular, these are the structural components of older buildings, for which the available documentation appears to be of limited significance or reliability.
  A measurement-based determination of the U-value could provide a solution here. The exact location and characterisation of energy pipes laid under the ground is also a problem area in this context. In particular, because verifiability can usually only be achieved with enormous effort. The expansion of the database should ultimately lead to an energy-related Urban Information Model (UIM) that contains all energy and emission-influencing information in a clear, comprehensible and consistent manner.

- **Addition of further data-recording sensors**
  A large number of sensor values were required to set up the digital energy services. In the first step, all existing sensors were linked to the IoT platform in collaboration with the relevant operators. The project funding also made it possible to implement additional essential sensors (e.g. heat meters). To complete the desired analysis picture, further sensors must be connected to the IoT platform or newly installed. This applies in particular to sensors for analysing the energy consumption of IT servers and electromobility charging stations.

- **Balancing grey energy**
  Because the focus was placed on other topics, the energy required for the construction and dismantling of buildings and energy infrastructure could not be taken into account in the UserGRIDs work programme. In order to achieve a complete environmental analysis of transformation measures, this level of consideration still needs to be supplemented. This would require the addition of a material model to the data. Particularly in the context of the planned expansion of the campus by several buildings, the assessment of grey energy must become an integral part of sustainable decision-making processes.

- **Quality assurance in measurement data analysis**
  The sensor data processed in digital energy services comes from a variety of different sensor types and is transmitted via different bus systems. Unintended measurement failures and planned changes in the measurement technology, as well as in the transmission technology, can lead to data gaps or the transmission of incorrect measured values. Measurement or transmission failures that are not detected in time often lead to gaps in analyses and misinterpretations. To avoid this, the project began to develop and implement the basic features of an automated quality assurance system. The complete structure and the corresponding test runs are to be considered in the further development.

- **Reliable robustness in functionality**
  The occurrence of errors (examples: failure of climate data transmission or server changes) is far more critical in systems that do not "only" work "ex post", but take over functions during operation. The reliability of the implemented systems (example: control systems) must be guaranteed. This requirement must be met in permanent operation and cannot be achieved by an R&D project, especially as this is by definition limited in time.

- **Simulation-suitable forecasts of future climatic conditions**
  The ongoing climate change is shifting the framework conditions for the design of energy technology systems to a significant extent. The majority of published climatological climate forecasts are based on high temporal aggregations. In most cases, monthly averages and, in a few exceptions, daily averages are published. Building and system modelling, on the other hand, is based on time steps of one hour or even finer temporal resolutions. For a number of tasks, e.g. performance or design determinations, climate data sets with a high temporal resolution developed by meteorologists would be very helpful.

- **Further development in automated simulation modelling**
  The creation of complex urban energy simulation models is time-consuming and error-prone due to the complexity and high number of sub-models. At least partially automated modelling based on structural data is a development goal. In the project, building geometries and component structures have already been transferred to models from the structural data in a partially automated process. In addition, a new method has been developed to transfer urban structural data (e.g. district heating pipes, heat exchangers, etc.) semi-automatically into a simulation model, and approaches have been developed to proceed in a similar way for technical building elements (e.g. radiators). The automation that has been started must be further developed at all the levels mentioned in order to be able to use and establish energy simulation as an integrated component of urban district planning in a targeted manner.

- **Avoidance of isolated data silos**
  In particular, care must be taken to share the prepared data with other data sources or their data holders in order to avoid data silos and establish consistency. The developed structural descriptions and measured values must be shared with other data holders in order to prevent parallel and inconsistent descriptions. For example, the determined spatial descriptions of the energy-related facilities must be transferred back to the TUGraz-online campus management system. This means that a master must be determined for each data or information group, whose data situation is seen as a "single source of truth" and who receives changes and corrections from all other data holders.

- **Transfer to a data-consistent continuous process**
  By definition, projects have a limited duration. In contrast, the pursuit of climate neutrality is a task that cannot be given an end date. Instead, it should be viewed as a permanent improvement or innovation process. The work begun in the UserGRIDs project to improve the energy and environmental technology of a university campus must therefore be embedded in structures that enable the activities to be continued in the long term.

- **Networking with external knowledge carriers**
  The development of measures to reduce greenhouse gases at district level is becoming established. Analysing university locations in particular is a suitable driver of this type of development. The networking of these activities at national and international level offers great opportunities to learn from each other and to exchange methods and experiences.

3.6 What has already been started

The need for further development in individual problem areas was recognised during the course of the project. This led directly to the definition of further project plans and subsequently to the start of the subsequent projects.

- The project **VRUrbanDev** - Virtual Reality as an innovative, digital tool for the integrative urban development of the future (FFG project number: FO999893555) is dedicated to the problem of analysing the energy performance of urban configurations. The large number of data series and evaluation levels required for this increases the complexity and reduces the clarity of analyses. VRUrbanDev investigates how the methods and possibilities of virtual reality can be used to support the clarity and comprehensibility of complex analyses.

https://nachhaltigwirtschaften.at/en/sdz/projects/virtual-reality-as-an-innovative-digital-tool-for-the-integrative-urban-development-of-the-future.php

- The project **COOL-KIT** - Modular solutions for integration of cooling in buildings of the founders' period (project number: FO999894603) is working on the integration of buildings of the founders' period in transformation processes. These buildings, which are often listed, have to be treated differently in terms of construction and building technology than buildings from the more recent past. The tasks focus on methods for the modular implementation of cooling and heating systems under the premise of reducing the induced greenhouse gases.

https://greenenergylab.at/projects/cool-kit/

4 Information sources

4.1 Contact details

Project Lead		
TU Graz	Institute of Thermal Engineering, TU Graz Contact Person: Thomas Mach	

Scientific Partners		
TU Graz	Institute of Software Technology, TU Graz Contact Person: Gerald Schweiger	
	Buildings and Technical Support, TU Graz Contact Person: Siegfried Pabst	
	STS - Science, Technology and Society Unit Institute of Interactive Systems and Data Science, TU Graz Contact Person: Günter Getzinger	STS
	Institute of Building Physics, Services, and Construction, TU Graz Contact Person: Michael Monsberger	ibpsc
	Institute of Automation and Control, TU Graz Contact Person: Valentin Kaisermayer	IRT
BEST Bioenergy and Sustainable Technologies	Area Automation and Control BEST Bioenergy and Sustainable Technologies GmbH Contact Person: Markus Gölles	

Business Partners	
BIG	Bundesimmobiliengesellschaft m.b.H. Contact Person: Florian Frühwirth
EQUA	EQUA Solutions AG Contact Person: Peter Nageler
eam	EAM Systems GmbH Contact Person: Michael Herzlieb
Fronius	Fronius International GmbH Contact Person: Kefer Kathrin-Maria
E	Energie Steiermark AG Contact Person: Mathias Schaffer

Associated Partners	
green energy lab.at	Green Energy Lab Contact Person: François Laurent

4.2 Translation

Large parts of the translation of the German-language raw report were carried out using the free online version of the translation tool DeepL and subsequently revised.

4.3 Academic works

Michael Mörth (master thesis)
Thermisch-elektrische Modellierung und Validierung eines Quartier-Energiesystems am Beispiel des Innovation District Inffeld (in co-operation with COOL-QUARTER-PLUS)
Supervision: Heimrath R. & Mach T. / Assessment: Hochenauer C.
completed: April 2022

Manuel Pöschl (master thesis)
Analyse und Transformation von Quartiers-Energiesystemen am Beispiel Innovation District Inffeld
Supervision: Heimrath R. & Mach T. / Assessment: Hochenauer C.
completed: Juni 2022

Milos Babic (bachelor's thesis)
Data collection services for smart energy systems
Supervision and Assessment: Wotawa F. & Schweiger G.
completed: December 2022

Mario Oboril (master thesis)
Verfahren zur teilautomatisierten Übertragung von BIM-Daten in eine Gebäudesimulationssoftware
Supervision and Assessment: Monsberger M. & Fuchs M.
completed: September 2023

Lisa Marie Fochler (master thesis)
Recilient Habitat (in co-operation with COOL-QUARTER-PLUS)
Supervision and Assessment: Hirschberg U. & Edtmayer H.
completed: December 2023

Felix Profanter (master thesis)
Konzepte zur teilautomatisierten Adaption von BIM-Modellen für dynamische Gebäudesimulationen
Supervision and Assessment: Monsberger M. & Fuchs M.
completed: April 2024

Michael Mörth (dissertation)
Work title: Thermisch-elektrische Modellierung und Transformation von Quartier-Energiesysteme am Beispiel Innovation District Inffeld
Supervision: Hochenauer C.
expected date of completion: December 2024

4.4 Publications

In addition to a series of presentations and workshops, the following publications were realized:

- Thomas Mach, Hermann Edtmayer, Gerald Schweiger, Michael Monsberger, Lisa-Marie Fochler & Richard Heimrath, Energie System Analyse: Herausforderungen für digitale Werkzeuge zur Transformation urbaner Energiesysteme, ÖIAZ, Österreichische Ingenieur- und Architekten-Zeitschrift, 166, September 2021

- Andreas Moser, Valentin Kaisermayer, Daniel Muschick, Christopher Zemann, Markus Gölles, Anton Hofer, Daniel Brandl, Richard Heimrath, Thomas Mach, Carles Ribas Tugores, Thomas Ramschak, Automatic Thermal Model Identification and Distributed Optimisation for Load Shifting in City Quarters, conference proceedings, The International Sustainable Energy Conference - ISEC 2022, full paper in: International Journal of Sustainable Energy, 2022

- Qamar Alfalouji, Gerald Schweiger et al., IoT Middleware Platforms for Smart Energy Systems: An Empirical Expert Survey, Journal: MDPI Buildings, February 2022

- Thomas Schranz, Qamar Alflouji, Thomas Hirsch and Gerald Schweiger, An Open IoT Platform: Lessons Learned from a District Energy System, 2022 Second International Conference on Sustainable Mobility Applications, Renewables and Technology (SMART)

- Thomas Schranz, Thomas Mach, Gerald Schweiger, Das Internet der Dinge für die Energiewende, Zeitschrift Nachhaltige Technologien

- Michael Kriechbaum, Nicolas Katzer, Günter Getzinger, Siegfried Pabst, Thomas Mach, Transforming a university campus into a sustainable energy district: Multi-criteria mapping of implementation options, GAIA Ecological Perspectives For Science And Society, 32/2 (2023): 249 – 256

- Kathrin Kefer, Samuel Haijes, Michael Mörth, Richard Heimrath, Thomas Mach, Valentin Kaisermayer, Christopher Zemann, Daniel Muschick, Bogdan Burlacu, Stephan Winkler and Michael Affenzeller, Evaluating Machine Learning and Heuristic Optimization Based Surrogates as a Replacement for a Complex Building Simulation Model, 20th International Multidisciplinary Modeling & Simulation Multiconference, 2023

- Kaisermayer, V., Muschick, D., Gölles, M., Schweiger, G., Schwengler, T., Mörth, M., Heimrath, H., Mach, T., Herzlieb, M., Horn, M., Predictive Building Energy Management with User Feedback in the Loop, Smart Energy, 2024