PROJECT REPORT

DIGITAL TWIN FOR MODELLING FUTURE ENERGY NEEDS IN THE GOTHENBURG BUILDING STOCK:

A tool for increased stakeholder collaboration, efficiency, and coordination of energy issues

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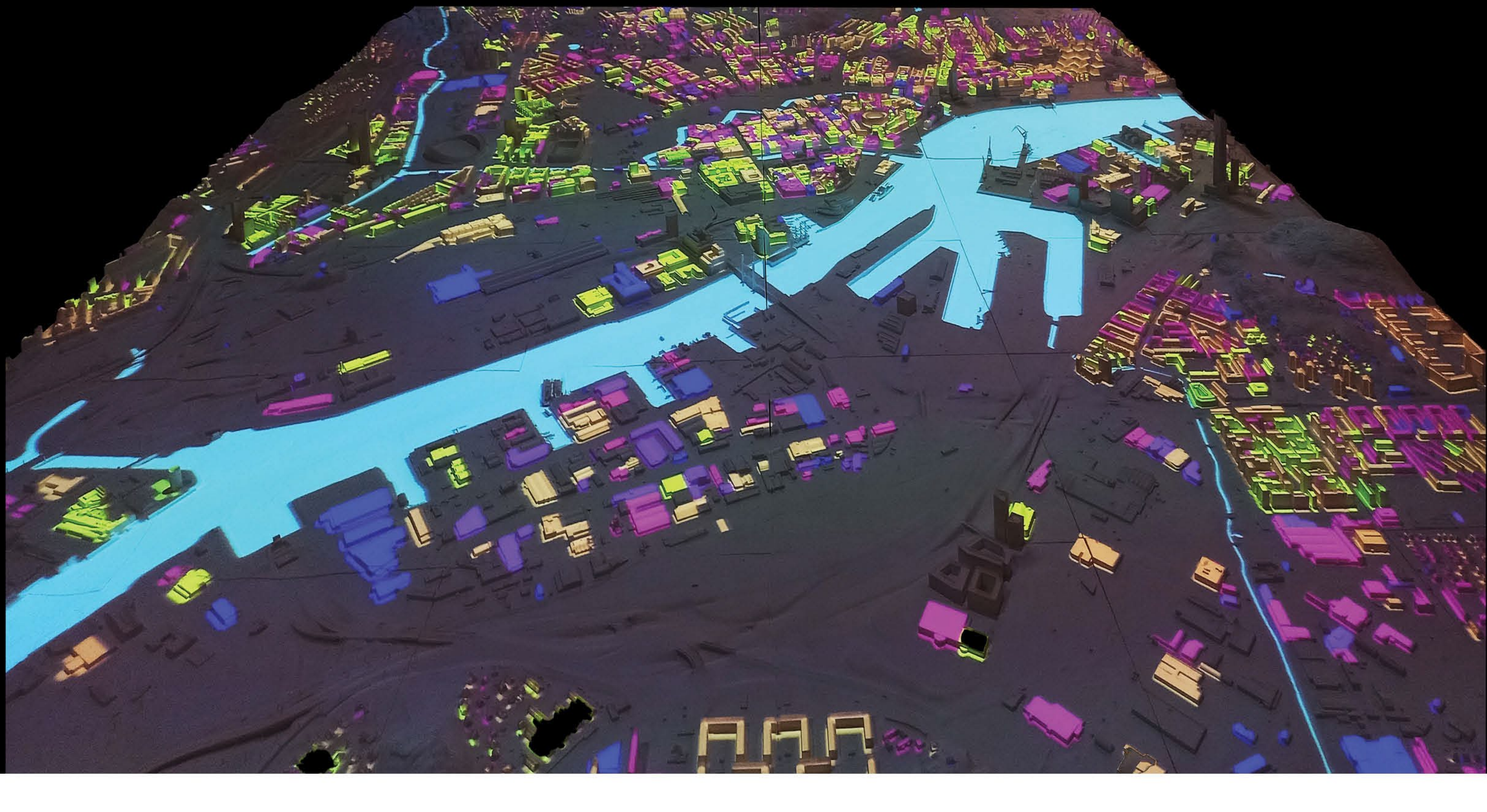

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Cover image: Projection of energy classes on a 3D model of Gothenburg. VisLab exhibition, Universeum, Gothenburg.

Photo: Daniela Maiullari

Abstract

The research project "*Digital twin for modelling future energy needs in the Gothenburg building stock: A tool for increased stakeholder collaboration, efficiency, and coordination of energy issues*" (DTE project) combines building stock modelling with digital twins to develop a visual communication platform to support stakeholders with responsibilities for urban energy transition and enables more efficient decision-making with focus on the city of Gothenburg. The project makes use of digital twin technology, to generate a virtual copy of the city including 3d models of buildings and related data such as building age, energy systems and functions.

The project was carried out during April 2021 and December 2023 and conduced in four phases:

1) Inventory of needs and alignment with Gothenburg Energy Plan (GEP)
2) Development of qualitative scenarios
3) Building stock modelling (BSM) and quantitative scenario development
4) Development and testing of visual communication platform, the Digital Twin Energy (DTE) Viewer.

Phase 1 focussed on identification of challenges and measures for prioritization in policy development (Chapter 4). Existing policies and especially the GEP were analyzed in a document study. Together with a stakeholder workshop and interviews conducted with experts from Gothenburg Energy (GE) and the Environmental department at the municipality of Gothenburg, key factors were set to address multi-actor needs. The analysis revealed that the GEP mainly addresses the risk of shortage. From the interviews and workshops additional challenges were identified: the alignment of urban development and energy plan, district heating and cooling, electrification of buildings and transport, and communication and tools.

In *phase 2*, relevant drivers of change and their consequences on the system as well as relevant actions for decarbonization and their impacts on the system were identified (Chapter 5). Based on a literature review, interviews, and participatory stakeholder workshops, qualitative scenarios were developed representing three strategic scenarios (Smart scenario, Building intensity scenario, and Green intensity scenario) and the three external scenarios (Extreme climate scenario, Electricity price scenario, and Electrified mobility scenario).

For the implementation of the scenarios in *phase 3*, we advanced our existing BSM with increasing temporal resolution, adding a cooling module, and model validation (Chapter 6). Selected qualitative scenarios were translated into quantitative scenarios and three sets of energy demand scenarios were modelled for the city of Gothenburg: Current and future city, Effect of climate warming on the energy demand of the current building stock, and Effect of renovation measures on building energy demand.

In *phase 4*, the viewer development and testing, we created a workflow to present energy demand in different scenarios (Chapter 7). Potential users were involved in the interface developments through workshops activities. Two assessments concluded the testing process and allowed reflections on possible implications in decision-making practice.

The viewer can be used to simulate among others the heating demand, cooling demand, and total energy demand of buildings for the city of today and the city of the future. Users can

also see how climate change and rising temperatures will influence the energy performance of buildings. This information can be used to visualize possible future scenarios and establish common ground for stakeholders to make strategic decisions on decarbonization plans. For example, decision makers can visualize renovation options and compare the effectiveness of different measures such increasing insulation of roofs and walls or install more efficient energy systems.

The contributions of DTE project are manifold. They range from supporting the energy planning in the city of Gothenburg, over initiation of a broader stakeholder discussion to tackle energy and climate challenges in the city, to demonstration of the importance of collaboration. The DTE project also puts the data sharing topic and its challenges on the agenda as well as it gives directions for future work. Not at least, the developed online DTE Viewer seem to have a large potential to support stakeholder dialogue regarding urban energy. This potential should be explored more and the viewer advanced. Further development should also investigate how the DTE viewer can be integrated into ongoing workflows in municipal organizations and companies involved in and responsible for the energy planning and energy transition of the city of Gothenburg. A particularly important question that needs further investigation is the ownership and management of the DTE Viewer over time to ensure knowledge spreading and taking care of DTE Viewer and results.

Future work with the DTE Viewer and stakeholder dialogue should have two directions. One is the continuation of the viewer development content-wise, for example, the implementation of additional scenarios such as solar energy potentials in the building stock, and functionality-wise the implementation of envisioned functions such as uploading and downloading of data and results. More general building related extensions of the viewer could consider smart buildings, real time and flexibility questions, building as energy providers connected to grid or electric vehicles. Other potential extensions are additional layers including grid development, bottlenecks for planning department, scenarios with a 2030 perspective and fulfillment of goals. The second direction of development is the testing of the viewer in a concrete case with an increased resolution of the studied building stocks, specific stakeholders.

Benefits for GE

The DTE project offers benefits for GE in several ways. GE impacted content of study and investigation of for GE relevant aspects through active participation, learned about DTs and the DT potentials but also challenges related to it such as data gathering and sharing, explored and discussed application examples and results, and contributed to the initiation of collaborations across departments and organisations. Results of the project, including the DTE Viewer, can be applied for development of future, own analyses and provide inspiration for new types of analyses carried out within GE. Results can also inspire transfer to other domains of GE such as production and operative planning. Scenarios can provide input for GEs future investments and development of business plans as knowledge can be gained based on detailed energy demand analyses on the building and neighbourhood level for different types of buildings, for existing buildings, renovation options, and future development areas.

Finally, results of the DTE project have been summarized in both scientific and popular science articles and two short films (Appendix 1 and 2). An important output of the project is the pushing boundaries and initiating a discussion among the city's energy stakeholders.

Sammanfattning

Forskningsprojektet *"Digital tvilling för modellering av framtida energibehov i Göteborgs byggnadsbestånd: Ett verktyg för ökad samverkan mellan intressenter, effektivitet och samordning av energifrågor"* (DTE-projektet) kombinerar modellering av byggnadsbestånd med digitala tvillingar för att utveckla en visuell kommunikationsplattform som kan stödja intressenter med ansvar för urban energiomställning och möjliggöra effektivare beslutsfattande. Projektet använder sig av digital tvillingteknik för att generera en virtuell kopia av staden, inklusive 3d-modeller av byggnader och relaterade data som byggnadens ålder, energisystem och funktioner.

Projektet fokuserade på Göteborg och genomfördes i fyra faser under perioden april 2021 till december 2023:

1) Behovsinventering och anpassning till Göteborgs Energiplan (GEP)
2) Utveckling av kvalitativa scenarier
3) Byggnadsbeståndsmodellering (BSM) och utveckling av kvantitativa scenarier
4) Utveckling och test av den visuella kommunikationsplattformen, Digital Twin Energy (DTE) Viewer.

Fas 1 fokuserade på att identifiera utmaningar och åtgärder att prioritera i policyutvecklingen (kapitel 4). Befintliga policys och speciellt GEP analyserades i en dokumentstudie. Tillsammans med en intressentworkshop och intervjuer med experter från Göteborg Energi (GE) och miljöförvaltningen på Göteborgs kommun identifierades nyckelfaktorer för att kunna möta flera aktörers behov. Analysen visade att GEP främst pekar på risk för olika typer av brister. Från intervjuerna och workshopparna identifierades ytterligare utmaningar: anpassning av stadsutveckling och energiplanering, fjärrvärme och fjärrkyla, elektrifiering av byggnader och transporter samt kommunikation och verktyg.

I *fas 2* identifierades relevanta drivkrafter för förändring och deras konsekvenser för energisystemet samt relevanta åtgärder för utfasning av fossila bränslen och deras inverkan på systemet (kapitel 5). Baserat på en litteraturgenomgång, intervjuer och workshops med intressenter utvecklade vi kvalitativa scenarier som representerar tre strategiska scenarier (Smart scenario, Scenario förtätning byggnader och Scenario förtätning grönområden) och de tre externa scenarierna (Extremklimat-scenario, Elektricitetspris-scenario och Elektrifiering-mobilitets-scenario).

För att kunna implementera scenarierna vidareutvecklade vi i *fas 3* vår befintliga BSM med en högre tidsupplösning, tillägg av en modul för kyla, och validering av modellen med uppmätta data (kapitel 6). Utvalda kvalitativa scenarier översattes till kvantitativa scenarier och tre energibehovsscenarier modellerades för Göteborg: Dagens och framtidens stad år 2050, Effekten av ett varmare klimat (temperaturhöjning upp till 2,2 °C) på energibehovet i det befintliga byggnadsbeståndet och Effekten av renoveringsåtgärder på byggnadens energibehov.

I *fas 4,* utveckling och test av Viewern, skapade vi ett arbetsflöde för att presentera och visualisera energibehovet för de olika scenarierna (kapitel 7). Potentiella användare involverades i gränssnittsutvecklingen genom ett antal workshops. Två utvärderingar avslutade testprocessen och möjliggjorde reflektioner kring användbarheten av Viewern.

DTE Viewern kan bland annat simulera byggnaders värmebehov, kylbehov och totala energibehov för dagens och framtidens stad. Användarna kan också se hur klimatförändringar och stigande temperaturer kommer att påverka byggnaders

energiprestanda. Denna information kan skapa en gemensam förståelse av olika intressenters problembild och stödja strategiskt beslutsfattande för implementering av planer för minskade koldioxidutsläpp. Beslutsfattare kan till exempel visualisera renoveringsalternativ och jämföra effektiviteten av olika åtgärder som att öka isoleringen av tak och väggar eller installera effektivare energisystem.

Bidragen från DTE-projektet är många. Det handlar om att stödja energiplaneringen i Göteborgs stad, att initiera en bredare intressentdiskussion för att kunna ta itu med energi- och klimatutmaningarna i staden och att visa på vikten av samverkan. DTE-projektet lyfter även frågan om datadelning och dess utmaningar och ger riktlinjer för det fortsatta arbetet. Inte minst verkar den utvecklade DTE Viewer ha en stor potential att stödja dialogen kring urbana energifrågor. Denna potential bör utforskas mera liksom hur Viewern kan integreras i pågående arbetsflöden i kommunala organisationer och företag som är involverade i och har ansvar för energiplanering och energiomställning i Göteborgs.

För det framtida arbete med DTE Viewern finns det två inriktningar. En är att fortsätta utvecklingen av själva Viewern innehållsmässigt, till exempel implementering av scenarier som solenergipotentialer i byggnadsbeståndet, samt vidareutveckling av användargränssnitt genom implementering av tänkta funktioner som uppladdning och nedladdning av data och resultat. Andra byggnadsrelaterade komplement i Viewern skulle kunna inkludera smarta byggnader, realtids- och flexibilitetsfrågor, byggnader som energileverantörer anslutna till elnätet eller elfordon. Andra potentiella utvecklingar är ytterligare lager inklusive elnätutveckling, scenarier med ett 2030-perspektiv och måluppfyllelse. Den andra utvecklingsriktningen är att testa Viewern i ett konkret fall med en högre upplösning av det studerade området och med specifika intressenter. En särskilt viktig fråga som behöver utredas ytterligare är ägandet och förvaltningen av DTE Viewer över tid för att säkerställa kunskapsspridning och omhändertagande av DTE Viewern och DTE projektets resultat.

Huvudresultat

- Utveckling och test av online Digital Twin Energy (DTE) Viewer med olika energibehovsscenarier
- Initiering av samtal mellan stadens energiintressenter och relaterade utmaningar
- Input till energiplanering i Göteborg

Nytta för Göteborg Energi (GE)

Nytta för GE har flera dimensioner. Genom aktivt deltagande i hela projektet har GE kunnat påverka innehållet och inriktning på för GE relevanta aspekter. GE kan lära sig om Digitala Tvillingar (DT) och DT:s potentialer men också utmaningar relaterade till det såsom datainsamling och delning. GE:s deltagande i olika workshops och möten kring utveckling av Viewern har bidragit till att initiera samarbeten mellan avdelningar och organisationer.

Projektets resultat, inklusive DTE Viewern, kan användas för utveckling av framtida, egna analyser och ge inspiration till nya typer av analyser inom GE. Resultaten kan också inspirera en omtolkning för att passa andra områden inom GE, till exempel produktions- och verksamhetsplanering. Scenarierna kan ge underlag för GE:s framtida investeringar och utveckling av affärsplaner eftersom kunskap kan erhållas baserat på detaljerade energibehovsanalyser på byggnads- och kvartersnivå för olika typer av byggnader, för befintliga byggnader, renoveringsalternativ och framtida utvecklingsområden.

Slutligen, så har resultaten från DTE-projektet sammanfattats i både vetenskapliga och populärvetenskapliga artiklar samt två kortfilmer (se Appendix 1 och 2).

Contents

Preface

The project "*Digital twin for modelling future energy needs in the Gothenburg building stock: A tool for increased stakeholder collaboration, efficiency, and coordination of energy issues*" (Diarienr 10-2020-1697), financed by Gothenburg Energy's foundation for Research and Development, was carried out during April 2021 and December 2023 by researchers from the Department of Architecture and Civil Engineering at Chalmers University of Technology, connected to the national competence center Digital Twin Cities Centre supported by Sweden's Innovation Agency Vinnova (Grant No. 2019-00041), and initially linked to the European ERA-Net-SES initiative research project Regional Energy Demand Analysis Portal REDAP (Swedish Energy Agency project number 47839-1). The project has been supported by the consulting company Sinom with expertise in building stock modelling and the consulting company Paramountric for the online-viewer development. To secure relevance the projects has also been conducted in close cooperation with representatives from Gothenburg Energy. Finally, a reference group with representatives from academia, municipality, sector organisations, and property managers was linked to the project to guide and ensure implementation potential. During the project, several interviews and workshops were conducted with the reference group, researchers at Chalmers, and stakeholders with interest in energy and climate questions in relation to building stock development. Thank you all for valuable input during the project. A special thanks goes to Martin Boje from the environmental administration of the city of Gothenburg and most of all Henrik Törnsjö and Mariliis Lehtveer. Without you, we would not have reached that far.

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Daniela Maiullari, Project coordinator
Gothenburg, 14 February 2024

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1. Introduction

Sweden has set ambitious climate targets with the goal of achieving carbon neutrality by 2045. The Integrated National Energy and Climate Plan (Ministry of Infrastructure, 2020) established as intermediate targets for 2030 a 63% reduction in greenhouse gas (GHG) emissions compared to 1990, a 65% share of renewable energy, and 50% more efficient energy use compared to 2005. Hereby, municipalities and regions play a crucial role in climate and energy transition processes and the fulfilments of the goals. They are engaged in developing comprehensive plans to define and implement effective energy strategies to reduce GHG emissions, increase energy production from renewable sources, and increase energy efficiency. The development of robust urban strategies requires analyses and instruments to support decision-making. Existing buildings and building stocks are one of the important urban structures to address in the urban energy transition as they have substantial energy saving potentials. Buildings are also changing their system boundaries, functioning as energy supplier and being intertwined with mobility structures.

There is a lot of expert knowledge about energy systems and their climate impact, however the knowledge is scattered among different companies and municipal administration, and sometimes there is limited knowledge exchange within organisations. Thus, the knowledge is not efficiently implemented. Alongside with the scattered knowledge, we also have competing business logics with different timelines for planning and transformation of energy system as well as sequential decision-making which is time consuming, cost-inefficient, and results in a limited understanding of each other's problems and challenges. Nevertheless, the transformation to sustainable and smart energy systems needs a system perspective and stakeholder collaboration across system boundaries.

Recent development in digitalization and Digital Twins is promising not only for the implementation of smart energy systems but also for synchronised collection, coordination, visualization, and communication of energy related data. This potential has not been largely explored yet. When it comes to building, during the last decades building stock modelling research has made substantial progress to describe and model buildings stocks based on individual buildings and to simulate future energy demand and climate impact. Through simulation of different future scenarios, the models can support a better understanding of the consequences of actions, for example the effects of large-scale renovation measures.

The research project "*Digital twin for modelling future energy needs in the Gothenburg building stock: A tool for increased stakeholder collaboration, efficiency, and coordination of energy issues*" (DTE project) takes its starting point in the above-mentioned challenges and potentials and combines building stock modelling with digital twins to develop a visual communication platform to support stakeholders with responsibilities for urban energy transition. The focus is on the city of Gothenburg and building stocks. Gothenburg has an ambitious Environmental and Climate Programme (City of Gothenburg 2021a), is a member of the Climate Neutral Cities 2030 initiative (City of Gothenburg 2021b) and has recently published the Gothenburg Energy Plan (GEP) (City of Gothenburg, 2022). As the GEP is an important document for the energy transition progress, the DTE project has special emphasis on this document, both in terms of today's content and future development.

2. Digital Twins

Simplified a Digital Twin (DT) is a digital representation of a physical system (Ketzler et al., 2020) and the connection between the two (Grieves, 2023). In the context of cities, DTs can be used to represent, model, and simulate urban systems (Lehtola et al, 2022). Existing literature extensively focuses on technological and framework development of DTs (level of accuracy of digital models, data structure and standards), while a growing number of studies highlight the potential of using DTs in urban planning and design processes (Ketzler et al, 2020). Applications in different domains have shown that DTs can offer strategic information when dealing with risk and environmental management, support planning, as well as boosting economic, social, and environmental practices (Shahat et al, 2021).

Decarbonization strategies connected to energy performance of building stocks are recurring applications in city DTs, see Figure 2.1. The focus of the applications differs and comprise, among others, studies on solar energy potentials, GHG emission reduction, smart energy grids, and strategy findings (e g., Ruohomäki et al., 2018; Schrotter and Hürzeler, 2020; Pierce et al., 2024; Park and Yang, 2020, Leopold et al., 2023); addressing multi-scales, from districts to cities (e.g., Francisco et al, 2020; Pierce et al, 2024). Few DT developments integrate building stocks on the city level including all types of buildings.

Many city DTs are developed with the purpose of visualizing or analysing data to support decision making processes in urban planning and the ambition to improve collaboration between stakeholders or citizen participation. So far, technical challenges have been given most attention in the development of DTs (Weil et al., 2023), but more recent studies increasingly deal with the socio-technical dimension. This means that the development of DTs is considered as a socio-technical process driven by a need for a more strategic and policy-outcome orientation. It also emphasizes the importance of interdisciplinary insights and participative processes in conceptualizing what DTs of cities could and should represent, and how (Nochta et al., 2021). Therefore, it is central to involve potential users in the development process, among other, city planners and managers and people living and working in the cities. This project specifically addressed the question of how DTs can guide short- and long-term urban transformation facilitating the decarbonization pathways of Gothenburg with focus on building stocks.

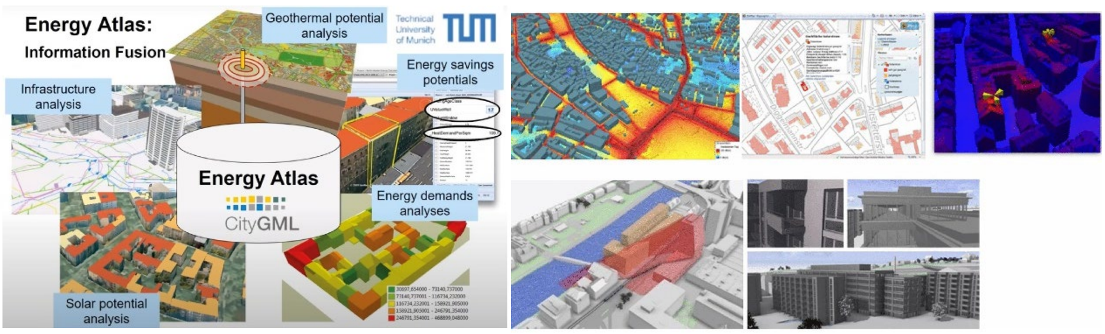


Figure 2.1 Examples of digital twins in the city domain. München (left), Zürich (right).

3. Project aim, target groups, and phases

The DTE project was carried out during April 2021 and December 2023.

3.1 Aim and scope

The aim of the DTE project was to explore the potentials of a digital twin to support dialogue and multi-stakeholder collaboration for streamlined decision-making processes regarding energy needs and development of the city of Gothenburg's energy plan with focus on buildings and building stocks. The objectives of the project were to:

- further develop an urban energy- and climate module for building stock modelling (BSM) for individual and all types of buildings;
- develop of scenario functions to enable projections of future energy demand and supply for heat, electricity, and cooling;
- develop, test, and evaluate a visual communication platform with an energy and climate module linked to BSM integrated into a digital twin.

While the project title indicates energy needs and the project will focus on the energy demand to make the project manageable within the given time frame.

3.2 Target group

The main target group of the project were decisions makers with impact on or responsibility for development and transformation of the energy systems in the city of Gothenburg, i.e. the energy supplier Göteborg Energi and municipal administrations such as the environmental and planning department. An additional target group were property managers.

The stakeholders have different responsibilities and needs as they act on different scales, all crucial for the fulfilment of energy and climate goals. Göteborg Energi is responsible for to secure the cities' energy supply over time, optimize systems, minimize GHG emissions, and adapt to changing demands. The city planning department is responsible for the long-term spatial development of the city and to provide master and detailed plans that enable good living and working environments. The planning department is also responsible for development and management of the municipal DT. The city environmental department is responsible for the implementation and monitoring of the Environmental and Climate Programme as well as the development and implementation of the GEP. Property owners are responsible for the management and development of building stocks. They decide on renovation measures for buildings in the property portfolio, what and when, and they must invest resources for the upgrading activities.

As we have identified several target groups for our project, we aspired to create a visual communication platform that is easy to use, facilitate multi-actor decision making processes, and provide relevant information for decarbonization process for the targeted stakeholders. The integration into a DT is fundamental to enable visualization, data coordination and exchange, and linking of models and simulations.

3.3 Phases

The project was and conducted in four phases (Fig 3.1) applying a variety of methods:

1) Inventory of needs and alignment with Gothenburg Energy Plan
2) Development of qualitative scenarios
3) Building stock modelling and quantitative scenario development
4) Development and testing of visual communication platform, the Digital Twin Energy Viewer.

The aim of *phase 1* was to align the project goals and outputs to the Gothenburg Energy Plan and to get an overview on the Status Quo regarding current research activities, people involved, and gaps. Thus, phase 1 focussed on identification of challenges and measures for prioritization in policies development. Existing policies, especially the Gothenburg Energy Plan, were analyzed in a document study and interviews were conducted with experts from Gothenburg Energy and the Environmental department at the municipality of Gothenburg (Maiullari et al, 2022a; Thuvander et al, 2022). Based on this, key factors were set to address multi-actor needs. Section 4 provides a detailed description of methods and results.

Phase 2 aimed at development of qualitative scenarios to describe possible futures by setting relevance and urgency. Drivers of change, their consequences on the system and relevant actions for decarbonization and their impacts on the system were identified in participatory stakeholder workshops (Maiullari et al, 2022b). Details are presented in section 5.

In *phase 3* the Building Stock Model was further developed and tested to enable scenario modelling. Here, selected qualitative scenarios were translated into quantitative scenarios, and the impacts of external drivers on energy demand and actions on the balance between demand and supply were estimated.

The aim of *phase 4*, the last phase, was to visualize the scenario results. A digital twin energy (DTE) was developed as a communication platform as an online viewer, and tested for scenarios, usability, and evaluation in decision-making processes (Maiullari et al, submitted). Based on the learnings from phase 1-3, mock-ups for the interface of the DTE viewer were developed, i.e., an illustration of how the outcome might look like. The mock-ups and the implemented viewer were evaluated in a series of stakeholder workshops.

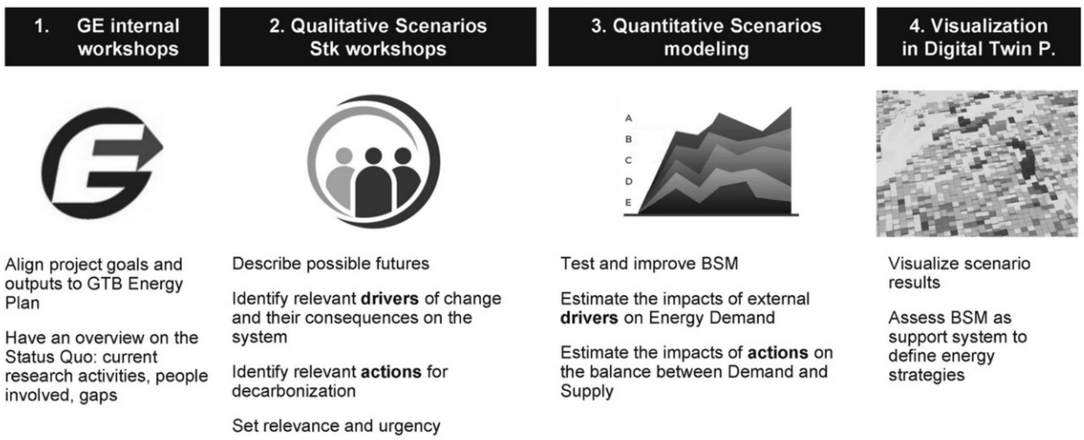


Figure 3.1 The four phases of the project.

The project process was set up to engage the targeted stakeholders from the beginning in the development of the DTE Viewer and all the preparation work including participatory workshops, interviews, and meetings. For continuity of content development and ensure relevance, the project team had regularly monthly meetings and reference group meetings twice a year, both online and onsite. Ongoing process and results have been disseminated through several channels, such as presentations at seminars and conference and publications in scientific and popular science articles, see Appendix 1 and 2 for details.

Chapter 4-7 are based on the following publications: *Pathways towards carbon neutrality: A participatory analysis of the Gothenburg's energy plan* (Maiullari et al, 2022a), *Matching energy targets, stakeholders' needs and modelling choices in developing urban energy scenarios* (Maiullari et al, 2022b) *Gothenburg Digital Twin. Modelling and communicating the effect of temperature change scenarios on building demand* (Maiullari et al, 2023), and *Digital Twin for supporting decision-making and stakeholder collaboration in urban decarbonization processes. A participatory development in Gothenburg* (Maiullari et al, 2024).

4. Inventory of needs and alignment with Energy Plan

The DTE project acknowledges that municipalities and regions play a crucial role in the process of climate and energy transition. Regarding the climate targets 2030 in the Environmental and Climate Programme (City of Gothenburg 2021a), Gothenburg needs to reduce territorial emissions by at least 7.6 % annually. Except the overarching climate goal, the city has four sub goals for the climate; reducing primary energy consumption in residential buildings and facilities by 30% (compared to 2010), reducing transport-related emissions by 90% (compared to 2010), converting fossil-based generation plants (district heating, cooling, electricity) to renewable sources as well as reducing emissions from purchases in a life cycle perspective.

The process of developing effective actions and implementation guidelines for the above goals is still undergoing. The recently published Gothenburg Energy Plan (GEP) (City of Gothenburg, 2022) identifies lines of action and related measures that should be implemented between 2022 and 2030. Additionally, it attempts to highlight drivers of change and challenges to address. However, often identified the factors partially overlook the potential challenges arising from the dynamic interconnection between innovative practices, set of rules in the local context and long-term exogenous trends, or in other words from the transition of the urban energy system intended as a socio-technical system (Geels & Schot, 2007).

4.1 Approach - Document study, interviews, workshop

In the first project phase, we analysed the state of the GEP and identified, through local stakeholders' engagements, the specific challenges and potential bottlenecks related to the social, technological, and spatial dimensions of the Gothenburg decarbonization transition. The research is based on a document study, in which the GEP (71 pages in total, 29 pages core text) has been analysed and discussed half-day with experts in the energy sector and city representatives. Twelve interviews and one workshop with 18 participants representing stakeholders from the energy utility company, municipality, researchers, and consultants were carried out between September and December 2021 to understand potential challenges in the implementation of GEP. Specifically, representatives of the energy utility company, the Premises Committee, the Parks and Landscape Committee, and the Environment and Climate Committee were involved (Figure 4.1) because the GEP has been assigned a set of key measures to these authorities. Other participating stakeholders are experts in the energy field but external to the GEP implementation process. The interviews were semi-structured, and questions aimed at identifying the progress on the measures and the related debate on how to implement them. The interview was divided into three sections focusing on i) the overall challenges for the energy system of the city, ii) the involvement in the GEP and actions undertaken, as well as iii) the potential bottlenecks in implementations of the GEP measures. The workshop was carried out online using collaboration platform Miro. First, the participants were asked to score the relevance of both decarbonization actions and drivers of change, and second, to discuss more in-depth challenges in the plan's implementation.

Figure 4.1 Municipal stakeholders with dedicated measures in the Gothenburg in Gothenburg Energy Plan, stakeholders 1-4 have key measures for implementation. Black: boards/committees. Grey: companies owned by the City of Gothenburg.

4.2 Challenges and uncertainties for the implementation of the GEP

The GEP describes the city's mission and represents the joint effort of city authorities to identify the spheres of intervention, offering a comprehensive summary of the paths for the transition of the urban systems. The plan defines eight areas of action, each containing a set of measures for the city to transform its energy system (Table 4.1). It also identifies five main challenges related to its energy system (Table 4.2).

Table 4.1 Gothenburg Energy Plan's action areas and (shortened) examples of measures.

Area of action	**Example measures**
1. Flexible and capacity-secure energy system	a) Introduce technologies/services to reduce peaks in heat and electricity demand; b) Develop a hydrogen strategy; c) Ensure saving in district heating; d) Stabilize electricity need; e) Create conditions to secure energy infrastructure and facilities.
2. Energy efficiency in the municipal sector	a) Investigate energy efficiency measures for owned building stock and street lighting; b) Perform a cost and energy efficiency analysis for existing buildings and new constructions; c) Provide information/incentives for tenants to reduce their energy consumption.
3. Energy efficiency in the private sector	a) Provide advice to private actors (district heating and cooling customers, companies, associations).
4. Renewable electricity	a) Establish a solar energy plan, contribute to small-scale production
5. Renewable and reused heat	a) Investigate combinations of district heating and heat pumps; b) Promote reused heat.
6. Renewable end reused cold	a) Favour district cooling if feasible, make it a competitive alternative
7. Energy efficient and fossil-free transports and machinery	a) Investigate adjustment congestion charge to reduce car use; b) Ensure charging stations for light/heavy electric vehicles; c) Use sustainable machinery; d) Deploy bicycle parking to meet the needs.
8. Carbon Capture and Storage (CCS)	a) Investigate conditions and benefits for CCS plants in Gothenburg

Table 4.2 The Gothenburg Energy Plan's five challenges.

Challenge	Description
1. Risk of power shortage	Electrification of transport, industry and service sector are expected to double peak power demand, while weather-dependent renewables make electricity production more irregular. Assessments show that the local electricity grid has sufficient capacity until 2030. However, long term solutions are required to increase grid capacity and establish a flexible market to allow producers and consumers to match needs to the grid capacity.
2. Climate change impacts and pressure of heat waves on district cooling and the electricity network	Energy supply needs to meet the increased energy demand for cooling, while heat mitigation measures should be implemented to decrease urban temperatures.
3. Population growth	Population growth of 60.000 inhabitants by 2030 suggests a further increase in energy consumption if no drastic behavioural change and efficiency of the systems occur.
4. The impacts of national and European policies and the unpredictability of their effects at the local scale	Waste incineration tax specifically affects a system that relies on cogeneration plants for district heating and electricity production. Higher taxation on waste incineration and higher incentives on recycling might affect the heat supply capacity.
5. Availability of resources to make decarbonization happen	Staff, knowledge, and money for investments are necessary. However, once available, resources must be used wisely, supported by solid business plans for investments and collaboration between municipality and companies.

The challenges summarized in Table 4.2 and actions described in the GEP mainly address the risk of shortage. From our interviews and the stakeholder workshop, several complementary challenges have emerged. These challenges regard the alignment of urban development and energy plan (4.1.1), district heating and cooling (4.1.2), electrification of buildings and transport (4.1.3), and communication and tools (4.1.4). For more details, see also Maiullari et al (2022a) and Thuvander et al (2022).

4.1.1 The challenge of aligning urban development and energy plan

Today, estimates of future power demand and investments in power production capacity are to a large extent based on the prognosis of population development and city growth. These scenarios do not have a high resolution in time and space and are challenged by the high level of uncertainty in urban planning processes. However, coordination between urban development and energy planning is crucial to ensure goals' alignment.

For the coming years, the development model for Gothenburg promotes an increase in density in the existing urban areas. The vision of a denser Gothenburg follows the sustainable compact city paradigm and aims to limit urban sprawl and individual transport in favour of transit-oriented development. While the benefits of this model are clear in terms of land-use and mobility-related energy consumption, the influence on the building stock and vulnerability of the energy systems require further investigations.

Local stakeholders pointed out four critical challenges for the urban energy system: urban heat island effects, flooding, competition of land use, and mismatch of planning processes. Higher density might influence the magnitude of urban warming phenomena (urban heat island effect, heat waves) and exponentially increase cooling demand during summer periods. Mitigation measures need further investigation to better understand, for example, the impact of vegetation and green roofs on local climate and thus on energy loads. The size and quality of green coverage are also considered crucial for its contribution to rainwater treatment, ecosystem service, and carbon sink functions. The level of infrastructure vulnerability would increase due to disruptive events such as rain and river flooding because of the concentration and high density of the supply network. A further challenge regards the availability of space and the competition for use. When urban density increases, public and private space available for energy production and infrastructures is reduced (to allocate solar panels, smart storage, and mobility infrastructure).

The urban development model through infill and densification processes also poses the challenge of upgrading the energy supplying infrastructure within consolidated areas in the city. The decisions on energy systems for new buildings are crucial. Connecting a building to district heating and cooling or full electrification (installing heat pumps) needs a re-dimensioning of production and distribution of energy either for district supply or for electricity. New production plants and related networks require a longer planning and construction period than developments of conventional buildings (housing, offices, etc.). Due to this timing difference, many decisions on the dimensioning of the energy infrastructures are taken before having design and system details about new buildings and their level of efficiency. Additionally, in the short-term, construction projects can be delayed while infrastructural planning and investments are already going on. The risk for increased infrastructural costs is, thus, remarkably high in both cases of underestimating or overestimating the demand.

The interviewees seemed to agree on the need for better coordination between the city administration, planning offices and energy providers for new urban developments and the exploitation of local waste heat. Representatives from GE pointed out that facilitating synergies in early planning phases for surplus heating and cooling requires new frameworks and integrated planning workflows to understand the hidden local potentials and possible symbiosis. City representatives stressed that energy providers should take a proactive role to indicate potential heat excess that can be recovered and to suggest clusters of functions that benefit from closeness, informing a more systemic planning approach to guide the developments towards areas with higher potential and needs for infrastructures.

4.1.2 Challenges for district heating and cooling

In the long term, district heating and cooling must deal with the uncertainties of phasing out fossil energy sources and the availability of waste for production plants, while the distribution is challenged by the risk of suboptimization and efficiency losses. The Environmental and Climate Programme (City of Gothenburg 2021a), for district heating and cooling, requires the replacement of existing energy production facilities with non-fossil-energy-based production plants. This implies planning a careful transition to ensure a secure and continuous energy supply. For example, the phasing out of one of the power plants by 2030 (centrally located) might pose problems for the supply of district heating and cooling in the central areas of Gothenburg and require new investments for production and distribution networks (increasing pipe sections). These measures are not allocated in the plan. Interviewees and workshop participants expressed concerns about the uncertainties regarding the future energy production from waste incineration and waste heat from refineries, one of the main sources today for district heating and cooling. A higher recycling rate is expected to progressively reduce waste for incineration while refineries are at the end of a cycle.

For heat recovery, mentioned challenges concern the management of the transition and the coordination of decision making between waste-heat providers and energy providers. Waste-heat providers oversee identifying sustainable sources and transforming their production. The transition towards CCS, hydrogen and electrification might result in a change in temperature levels and the total provision of annual waste heat. Energy providers are responsible for a reliable energy provision along with the transition of production systems and adaptation to the new level and characteristics of waste-heat supply.

While the above can be considered macro factors of change, experts from the energy sector pointed out challenges to the system's efficiency. Some interviewees commented on the lack of a comprehensive framework to facilitate symbiosis between decentralized and centralized systems and the risk of having multiple, efficient systems that work against each other. Specifically, increased installation of heat pumps in areas served by district cooling and heating networks might negatively affect the urban energy system's efficiency. This process could not only affect the return temperatures, but it is also environmentally costly from a life-cycle perspective and economically for customers and providers. Heat pumps would increase electricity demand, increasing the risk of power shortages. However, combined solutions of district heating and heat pumps lack a business and management model. Local production owned by others than the energy provider requires adaptation of legal agreements and new management models to share the responsibility of energy provision.

Meanwhile, supply infrastructures for cooling are challenged by factors that undermine their efficiency of production and the security of the service. Recent years, the City of Gothenburg has invested in the development of a district cooling system in the city center to double the production capacity and expand the network in the coming years. Sources for district cooling can be considered decarbonized (free cooling from the river, surplus heat, etc.). However, experts from the energy provider stressed that increasing the temperature difference between supply and return, and thus improving the efficiency of the district cooling system, requires interventions by buildings users. Another factor that requires investigation is the future distribution of the service. Today, the district cooling network supplies data centers, office buildings, hotels, hospitals, and commercial malls. Workshop participants highlighted that higher outdoor temperatures and heatwaves will likely increase cooling demand in residential buildings. This future demand would probably rely on electricity sources (small scale cooling systems) and exacerbate peak loads and risk of disruptions if no measures are taken to encourage connection to district systems. Although it is a benefit to connect multifamily houses to the district cooling network, this requires technical upgrade of building systems, new business models and economic incentives.

4.1.3 The challenge of electrification of transport and buildings

Reducing energy demand in all forms is a key goal for the city. However, the predominant discourse about the shift from fossil-based sources to electricity tends to hide the priority of decreasing energy use also in the form of electricity. Decarbonization translates almost directly to electrification for the transport and industry sector, which will result in an exponential increase in electricity demand, posing challenges of sufficient production and load of the grid. Major uncertainties, highlighted by the representatives of the energy provider, regard the extent of such demand increase. Questions arose on what to prioritize for electrification and how to ensure a balance between production and consumption, i.e., what measures should be implemented for saving electricity and what economic incentives should be created to guide the prioritization.

Electric vehicles (EVs) for private use are promoted in the GEP as a solution for reducing carbon emissions. Highlighted by all workshop participants, the level of penetration in the market and society will have consequences on the level of electricity demand rise. The questions are to what extent can the existing power grid sustain an electrified transport system, and what are the impacts of the increased demand on electricity production plants and supply networks? The city-owned energy provider is aware that for the EV transition it is their responsibility to prepare the grid to handle the load for charging and to grant access to chargers which need coordination with sub-companies. Representatives of the city's energy company pointed to the high level of uncertainty in planning investments and that the extensive use of EV do not fulfil alone the decarbonization goals for the transport sector, since the energy provider is responsible to guarantee clean electricity sources. A high EV share would thus require substantial investments and new business models. In the short term, decisions are needed on the granularity of charging services, i.e., whether they should be provided on the household level or as a common/shared neighbourhood facility.

Regarding building stocks, interviews with energy experts focused on whether supply by district cooling and heating based on waste-heat recovery should be prioritized over electrified solutions (heat pumps, decentralized cooling systems). Unfortunately, regulatory frameworks and energy performance assessments do not indicate a clear selection path for building owners. Thus, in consolidated urban areas where the infrastructure already exists, there is a risk that the diffusion of heat pump installations might force the provider to suspend or interrupt the district cooling or heating service. Similarly, in new urban developments, if heat and cooling demands were predominantly met by electric systems, it will not be appropriate for the energy provider to serve the area with district systems. Interviewees pointed out that the risks of a comprehensive transition to electric heating and cooling are the further increase of peak demand during extreme winter and summer periods, and consequently the raised vulnerability of the city system. Thus, a fast transition of building heating and cooling to electric sources seems to be a potential bottleneck for decarbonization (energy security). In terms of investments, this would result in costs for the improvement of the electricity grid and the phasing out of the existing power plants and the dismantling of the network.

Additionally, among the GEPs measures, workshop participants jointly highlighted the relevance of installing smart meters to reduce electricity consumption in apartments and buildings. Smart meters can help to manage loads more efficiently and to reduce peak demand, and at the same time provide data to better understand user behaviours and develop more accurate predictions which could be used in developing policies to reduce the energy use. However, it was also pointed out technological and organizational challenges regarding their deployment. From a technological perspective, critical decisions regard the type of equipment, software and components, data management platforms, and cybersecurity. From a governance perspective, responsibilities need to be defined to allow a fast implementation. Especially for a new complex system which involves different institutions and private actors, it is essential to develop clear roles in management and implementation. Decisions might be further influenced by decisions on other scales and models of decentralization. This implies that future new models to produce and consume energy locally at the neighbourhood level should be promoted. Consequently, also the use of smart meters should be explored at the neighbourhood scale rather than at the single buildings/household scale.

4.1.4 Communication and tools

Fragmentation in expertise and task division between municipality and energy companies results in discontinuity of knowledge and can delay decision-making processes. This lack of knowledge integration is also a potential bottleneck internally in companies where expertise is divided into different departments. Improving communication and increasing the level of understanding among departments is vital to facilitating agile decision processes. Furthermore, cooperation between the private and the public sector seems to be one of the major challenges in implementing decarbonization strategies and measures. New business models and guiding instruments are needed to align private and public investments toward coherent and integrated energy strategies. From the energy provider perspective, communication with building owners is essential to avoid suboptimization and facilitate systemic thinking to benefit the community rather than single owners. The development of coherent planning strategies also relies on knowledge and data sharing among experts, authorities, and owners. Visualization of results of energy computational models with spatial representations could support the communication and coordination between different stakeholders and authorities (road, water company, public transport) to discuss existing energy systems (production capacity, local waste flows) and their effects on it when development plans or energy measures are discussed. From a management perspective, more efficient planning on underground infrastructures would require further information on the subsoil and tools to coordinate interventions to minimize secondary effects on road traffic and disruptions of the service.

5. Qualitative scenarios development

To support the development of exploratory instruments that can better inform decisions in the energy transition context, the DTE project developed a method to support the energy transition in practice in the City of Gothenburg with focus on building stocks.

Taking decisions about the energy future of cities means dealing with overly complex systems, a high level of uncertainty and a variety of actors that bring their perspective and expertise which makes it difficult to identify common/shared pathways to follow. Thus, despite setting common visions is fundamental to align the implementation of measures and to prioritize interventions, it is a challenging task for municipalities.

In the context of energy and urban planning, scenarios are widely applied as they allow to explore and evaluate the possible impacts of long-term decisions. Scenarios can be defined as descriptions of alternative images of the future, created from models that reflect different perspectives (van Notten & Rotmans, 2003) and can be classified into three major categories according to the objective of the investigation (Börjeson et al, 2005): Predictive scenarios address the probability of events, explorative scenarios explore the results of possible decisions or change in conditions, while normative scenarios analyse how a certain target can be reached (Figure 5.1).

Another classification divides scenarios based on their qualitative and quantitative approach. While quantitative scenarios approaches enhance the description of possible futures through numerical assessments and complex modelling methods (Varho &Tapio, 2013), qualitative ones, through participatory activities, allow to develop common visions and analyse multidomain processes that cannot be entirely quantified (van Notten & Rotmans, 2003). Additionally, a few attempts in integrating qualitative and quantitative approaches have shown that combined methods increase the robustness of scenarios and their value for informing decision-making (Fortes et al, 2015; Kowalski et al, 2009).

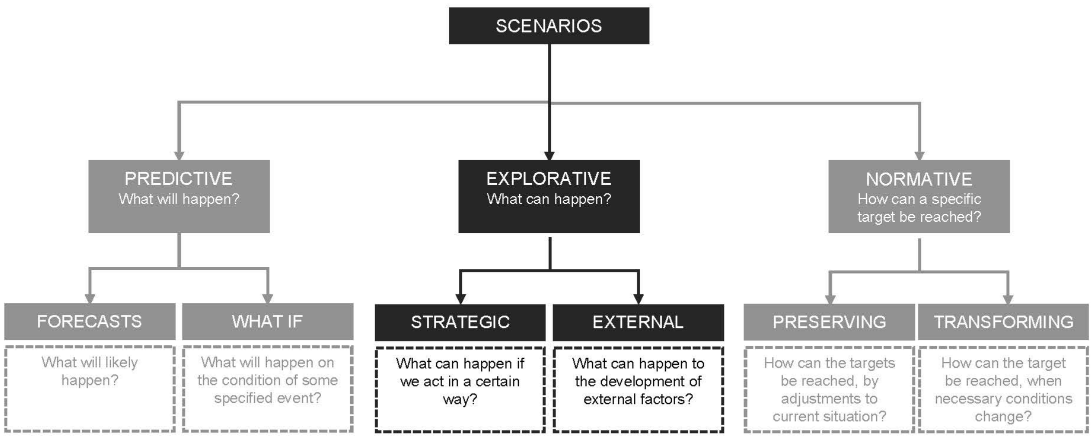


Figure 5.1 Categories of scenarios. Selected scenario type for the project in black.

5.1 Approach: scenario method, literature review, and participatory workshop

In this second project phase we developed the scenario method to identify key drivers of change and decarbonization actions and envision the possible impacts on energy supply and demand in the form of qualitative scenarios (QLs). Based on a literature review, the researchers listed potential actions and drivers for future development paths. In a next step, a half-day online workshop was carried out with invited local stakeholders to identify and prioritize key decarbonization actions and drivers of change which later have been translated into strategic and external QLs (Figure 5.2 and 5.3). For more details, see also Maiullari et al (2022b).

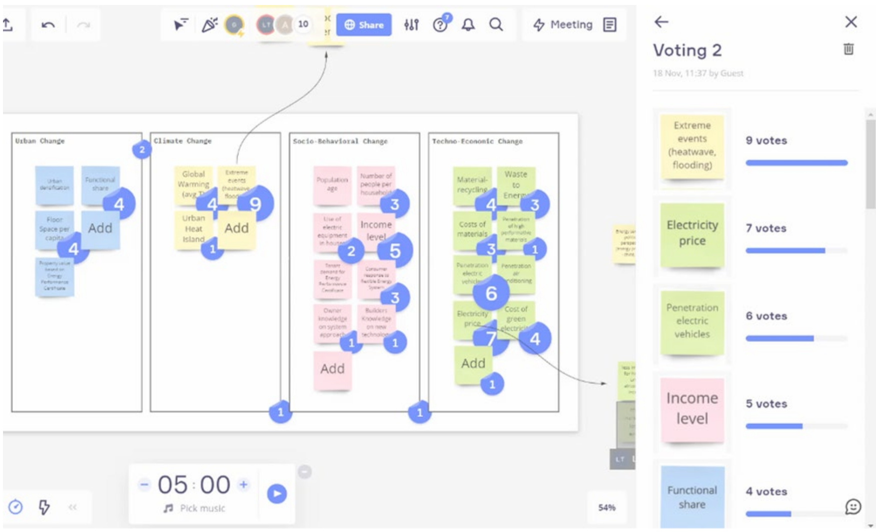


Figure 5.2 Voting of scenarios during the participatory workshop using the online collaboration board Miro.

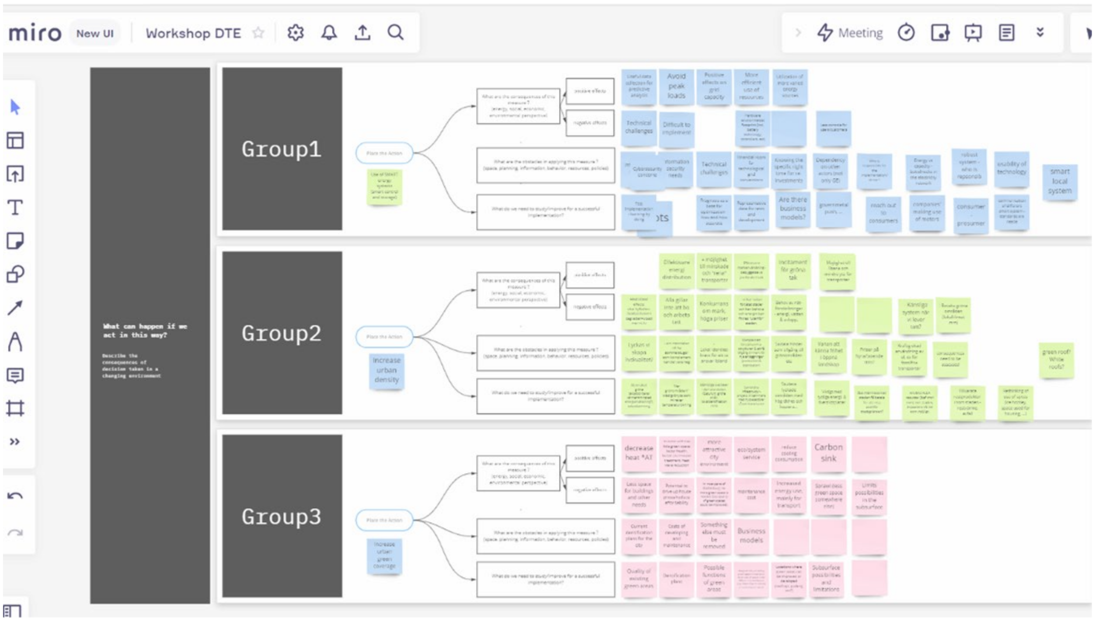


Figure 5.3 Scenario development in groups using the online collaboration tool Miro.

5.2 Key actions and drivers

The first step had the goal of identifying key decarbonization actions and drivers of change and to select the categories of scenarios to be applied. Based on a review of scientific literature and the GEP (City of Gothenburg, 2020, 2022), a list of potential actions and drivers for future development paths was compiled by the researchers. The actions identify energy measures that can be implemented in the future to reduce energy related GHG emissions, while the drivers are independent external factors that can modify the speed of the energy transition and are not directly controllable by local actors, but rather depend on global and national processes. For the QLs, explorative scenarios were selected as they allow to explore results of possible decisions or change in conditions following the distinction between external and strategic scenarios.

In our analysis, we identified actions and drivers related to reducing energy consumption and transitioning to sustainable energy systems. We categorized the identified actions into three primary areas: *building*, *transport*, and *city-oriented measures*. Regarding buildings, we proposed actions such as improving design, installing efficient energy systems, and promoting behavioural changes. In the transport sector, our suggested actions involved supporting biking and walking, enhancing public transport efficiency, and increasing access to electric vehicle chargers. City-oriented actions focused on reducing the need for cooling through increased vegetation and supporting clean energy supply.

The list of drivers influencing the energy transition is categorized into climate, economic, and social-technical factors. Climate drivers include the urban heat island effect, global warming, and extreme events. Economic drivers encompass changes in property values, electricity prices, and the cost of green electricity and materials. Social-technical factors involve the adoption of technological solutions like electric vehicles, smart energy systems, and efficient appliances. Social drivers include changes in income level, household composition, population age, and education levels that impact energy demand and investment capacity.

5.3 Prioritization

The second step aimed at prioritizing the listed decarbonization actions and drivers of change. For the purpose, a half-day online workshop was carried out with invited local stakeholders representing energy supplier(s), municipal administrations (city planners, environmental department), and researchers, in total 18 participants. The participants were asked to score the relevance of both decarbonization actions and drivers of change individually. Thereafter the 3 highest ranked actions were discussed in more depth in groups and documented using the online collaboration platform Miro. By scoring the relevance of actions, the workshop participants identified the introduction of smart energy systems, the increase in built density and green coverage in the city as incredibly important. For the drivers of change three key factors were identified: extreme climate events, electricity price and EVs penetration, see Table 5.1.

*Table 5.1. Importance of decarbonization actions and drivers of change rated by local actors in workshop. *Rated relevance. 1=high relevance.*

R*	Actions	Drivers
1	- Smart energy systems (smart control/storage)	- Extreme climate events (heatwave, flooding)
2	- Increase of urban density	- Electricity price
3	- Increase of urban green coverage - Incentives for builders to push efficient but costly options in construction	- Penetration electric vehicles
4	- Plan areas to reduce energy-intensive transport - Solar electricity production	- Income level
5	- Implement urban heat mitigation measures - Reuse of waste heat/cold at neighbourhood scale - Electrification of private transport-increase access to charges points	- Material recycling rate - Global warming (average temp. increase) - Cost of green electricity - Floor space per capita
6	- Apply passive energy measures - Heat pumps installation - Incentives to promote response to flexible market - Lower indoor temperature	- Waste to energy - Costs of materials - Consumer response to flexible energy system - Number of people per household
7	- Control indoor temperature in office - Increase solar shading - Individual metering in multi-family houses	- Use of electric equipment in houses
8	- Implement district cooling network - Increase building compactness	- Urban Heat Island - Penetration of high performative materials - Owner knowledge on system approach - Builders knowledge on new technology
9		- Property value based on EPC - Population age - Tenant demand for EPC - Penetration of air conditioning

5.4 Strategic and external scenarios

The third step investigated the possible consequences of systemic changes on the energy transition of the building sector by using QLs. External and strategic scenarios were developed, and the workshop participants were asked to describe two sets of possible visions based on the three actions and drivers identified as highly important. External scenarios explored the consequences of urban and national drivers that can hardly be influenced by local actors but modify the context in which energy strategies must be implemented and thus should be addressed to build robust strategies. These scenarios answered the question "how the drivers can influence the system?". Strategic scenarios explored the consequences of decisions answering to the question "what can happen if we act in this way?". The three elaborated strategic scenarios (Smart scenario, Building intensity scenario, and Green intensity scenario), Figure 5.3, and the three external scenarios (Extreme climate scenario, Electricity price scenario, and Electrified mobility scenario), Figure 5.4, are described in the following sections.

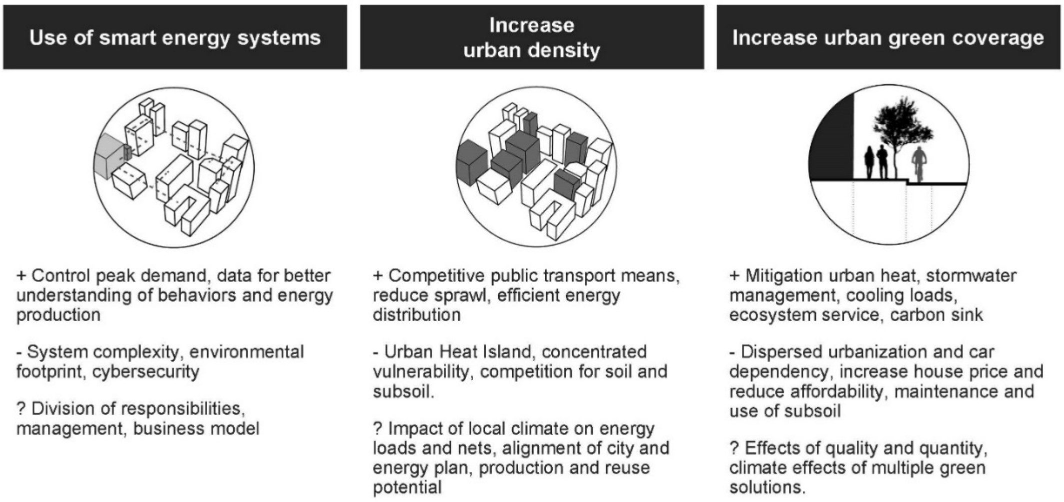


Figure 5.3 Selected external scenarios.

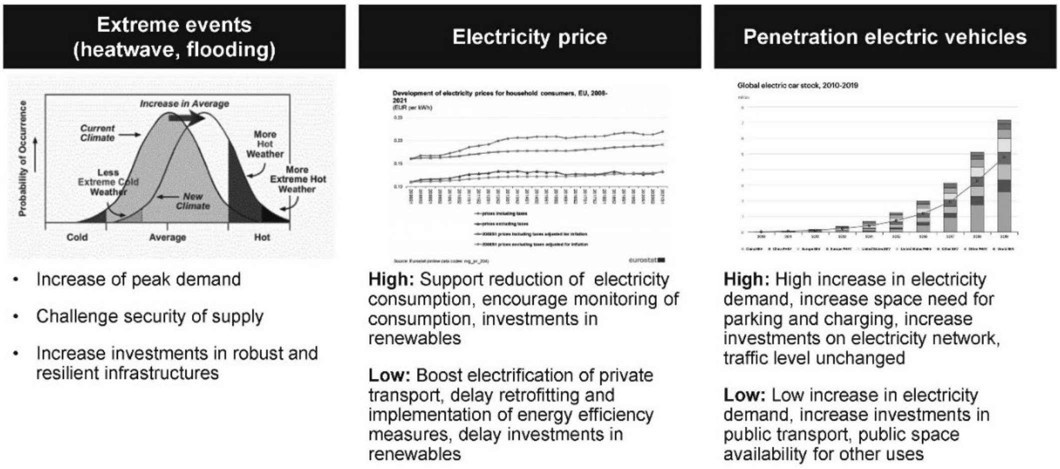


Figure 5.4 Selected strategic scenarios.

5.4.1 External - Smart scenario

Using smart energy systems in buildings is one of the stakeholders' highly ranked decarbonization actions. This first scenario depicts a future based on the widespread diffusion of smart meters and energy storages. Peak demand in buildings is reduced because users are more aware of their demand and are better informed when their appliances are activated. Data from smart meters are shared with energy providers and researchers supporting more accurate predictive analysis of energy consumption and user behaviours. Further, the gathering of real-time data allows providers to manage the supply to the electricity grid, district cooling, and heating network in a smart way and, by that, to reduce the risk of supply disruption. However, the massive introduction of this technology has a considerable environmental footprint in terms of new raw materials and CO_2 emissions for production of components, assembly, and distribution. From the user perspective, people with low-tech interests or limited education are left behind and the increase of cyberattacks requires further improvement in security to protect classified information.

5.4.2 External - Building intensity scenario

This scenario is based on the sustainable compact development model for the city, which implies the increase of built density as alternative to a horizontal expansion. The application of this measure in a long-term perspective contributes to reducing carbon emissions by providing more efficient land use, avoiding car-dependent diffused urbanization (sprawl), and saving space for food production and natural environment. GHG emissions are exponentially reduced because in a high density and compact urban environment, public transport means deliver a good service in terms of frequency and coverage, becoming a strong competitor to private cars. The high density of services and activities as well as the high level of accessibility also encourage 'slow' mobility (biking, walking). Additionally, the energy distribution of district heating and cooling is more effective because of the low-temperature losses of pipes. The closeness of different building functions creates more opportunities for creating synergies among them, exploiting, and reusing waste heat and cold. On the other side, less open space is available to accommodate energy transition measures (i.e., production through renewables, infrastructure for EVs), stormwater management solutions, ecosystem services, enhancing the competition for the use of soil and sub-soil. From a climate perspective, higher density causes an increase in the magnitude of the urban heat island (UHI) effect. Urban warming combined with higher global temperatures raises energy consumption for the space cooling of buildings. Energy production facilities and networks being more densely concentrated become also more vulnerable to extreme events caused by climate change, such as heavy rainfall and river-flooding.

5.4.3 External - Green intensity scenario

The scenario embraces the action of increasing vegetation coverage as a possible decarbonization solution. In this scenario, green areas in the city reduce the negative impacts of heat waves on people's well-being and reduce the magnitude of UHI effect. A highly green urban space provides (high level of) thermal comfort to perform outdoor activities, accommodate nature-based solutions for stormwater treatment and ecosystem service. An elevated level of vegetation coverage contributes to lower energy consumption for cooling buildings during summer and extreme hot events. Additionally, trees function as a natural carbon sink due to photosynthesis processes. However, dedicating more space to parks and green areas within cities has a result on the urban development model, supporting the horizontal expansion and diffuse forms of urbanization (sprawl), which in turn increases car mobility and the cost for energy infrastructures that must cover larger areas.

5.4.4 Strategic - Extreme climate Scenario

This first scenario builds on the changes induced by a climate driver. Climate change and increased average temperatures reduce heating days and increase cooling days per year in the Nordic climate zone. However, the higher frequency of extreme events challenges the security of provision, requiring big investments to increase robustness and the resilience of the supply infrastructure, to reduce potential disruptions of the service. More frequent heavy rainfalls translate into more frequent flood events posing at risk the distribution of energy and the integrity of infrastructures in the subsoil. Cold and heat waves result in high peak demand for cooling and heating of buildings. The management of district cooling and heating infrastructures presents an optimization problem. On the one hand, the average daily demand for cooling and heating decreases due to overall climate warming and the increased efficiency of buildings. On the other hand, the production is dimensioned upon peak demand calculated for extreme and winter temperatures, resulting in substantial economic investments for construction and maintenance of the infrastructure.

5.4.5 Strategic - Electricity price scenario

This scenario builds on the uncertainty in electricity prices identified by stakeholders as the second important driver. The scenario conveys the close interconnection between the economic dimension and the speed of the decarbonization process. Specifically, the increase or decrease of electricity price was described as a major factor influencing both demand and supply. If district heating and cooling remain stable systems, electricity is used for appliances, private and public transport, and industry. High electricity price encourages reducing electricity consumption and pushing consumers to monitor their demand and their appliances use, as well as companies to provide more details about products and their efficiency. Producing green electricity becomes more profitable also at the small scale, motivating private investments for PV systems installation and EVs. At the opposite, low electricity price results in electricity consumption increase and reduces investments in renewable production.

A critical point highlighted is also the fluctuation in the short and long term since investments decisions are based on long term forecasts. Specifically for energy-intensive industry, the prognosis of future electricity price is a driver for the transition towards more efficient energy systems and equipment. Investments however happen only if electricity price is expected to be high in a long-time span.

5.4.6 Strategic - Electrified mobility scenario

This third scenario is driven by the uncertainty that accompanies the penetration of EVs in the Gothenburg context. Electric private vehicles are promoted in the GEP as a solution for reducing carbon emissions. However, the level of penetration in market and society can drive significant variations in urban electricity consumption and it is governable to a certain degree. The energy providers are responsible for preparing the grid for handling charging loads and guaranteeing access to charges. A high level of penetration results in exponential rise in electricity demand and peak loads, requiring significant investments to raise the power supply and redesign public spaces and facilities to accommodate parking and chargers. Car traffic remains a major problem. A lower level of penetration results in a moderate increase in electricity demand and investments can be equally distributed for improving public transport efficiency and accessibility.

6. Building Stock Modelling

For the implementation of the scenarios, the temporal resolution of the BSM has been increased, a cooling module has been added, and the model has been validated. In total, three sets of energy demand scenarios were modelled for the city of Gothenburg.

6.1 BSM description and development

The Building Stock Model (BSM) (Österbring et al, 2019; Nägeli et al, 2018, 2019) uses a bottom-up engineering-based approach to model the energy demand of each individual building in the generated dataset. The energy calculation is based on a hierarchical structure, calculating the energy demand according to different system boundaries (useful energy, final energy, delivered final energy, primary energy and greenhouse gas (GHG) emissions) and differentiates the calculated energy demand and GHG emissions for different energy services (i.e. space heating, hot water, ventilation, appliances, lighting and auxiliary building services (e.g. pumps, etc.).

Input to the BSM is a digital twin of Gothenburg that is generated based on public datasets. Figure 6.1 gives an overview of the different datasets and data processing steps to generate the complete building stock datasets.

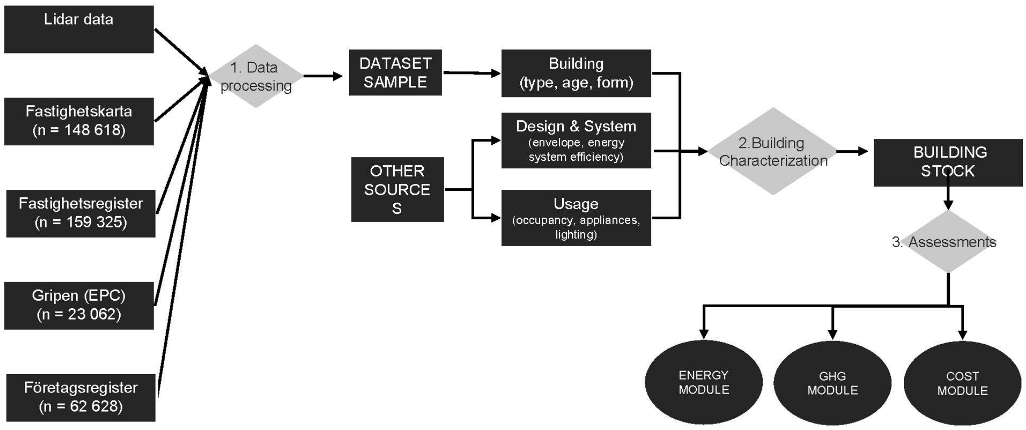


Figure 6.1 Workflow Building Stock Model – BSM.

Different datasets were cleaned and matched to generate a Gothenburg building stock dataset with the necessary inputs for the energy assessment. Data from different publicly available sources were collected and specific information derived from those was tied to individual buildings through a matching based on building ID or geographical position. The datasets include the property registry (Lantmäteriet, Fastighetsuttag, 2020), property map (Lantmäteriet, Fastighetskartan, 2020), LiDar data (Lantmäteriet, Laserdata NH, 2020), company registry (SCB, Företagsregistret, 2020), and building energy performance certificates (EPC) (Boverket, Energideklaration, 2020).

Important building characteristics such as building footprint, construction year, renovation year building function and floor area were extracted for the property registry and property map. As the height of buildings could not be derived directly from existing sources it was estimated based on LiDar data using the tool 3dfier (TU Delft, 2020). Additional relevant input data for the energy demand assessment of buildings was derived from the EPC database: type of HVAC (Heating, Ventilation, and Air Conditioning) system, number of floors, heated floor area, and energy carrier. In the EPC the coverage of residential buildings is comprehensive. When an EPC was not available for a non-residential building, heated floor area was calculated based on the number of employees and usage category stored in the company registry, while missing information about the ventilation and heating system was assigned based on the most common system used in the 50 closest buildings. In case no matching was possible with the company registry the energy demand could not be estimated. For the entire building stock, façade surface area and window area were generated based on building geometrical characteristics and window-to-wall ratio for each building type. The finally generated building geometry and related characteristics were stored in CityJSON format.

6.2 Increasing resolution and addition of cooling module

The BSM was further developed in order to increase the time resolution of the energy calculations from monthly to hourly as well as enable the calculation and assessment of cooling demand in buildings. For this purpose, the energy demand calculation was expanded with an hourly calculation module for the useful energy demand for space heating as well as space cooling based on the simple hourly method according to the norm ISO EN 52016-1 (ISO, 2017). This methodology is used in other similar models such as City Energy Analyst (CEA, 2024) and offers a good balance between accuracy, level of detail and computational demand as more detailed calculations often prove to computationally heavy to deploy at a city scale without the use of high-performance computers. Through the implementation of the simple hourly method also a module for the assessment of the space cooling demand of buildings was integrated in the model alongside adjustments to the space heating calculation. This also involved an extension of the modelled technologies in the BSM to include different technological solutions for space cooling such as district cooling.

6.3 Validation including data collection and sharing

The BSM was validated using measurement data provided from Göteborg energi. This data pertains to a selection of building owners, encompassing a range of properties managed by Gårdstensbostäder, Familjebostäder, Poseidon, Higab, Stena Fastigheter, and Castellum Väst (see Figure 6.2 for distribution of the building types in the dataset). The scope of the provided data consists of the measured hourly energy demand for district heating, district cooling, electricity consumption, and electricity production for the years 2018 and 2019, ensuring a robust dataset for analysis. The total number of records stands at 3,279, representing the number of measurement points. This extensive dataset is instrumental in validating our modelling results, providing a real-world basis for comparison and analysis.

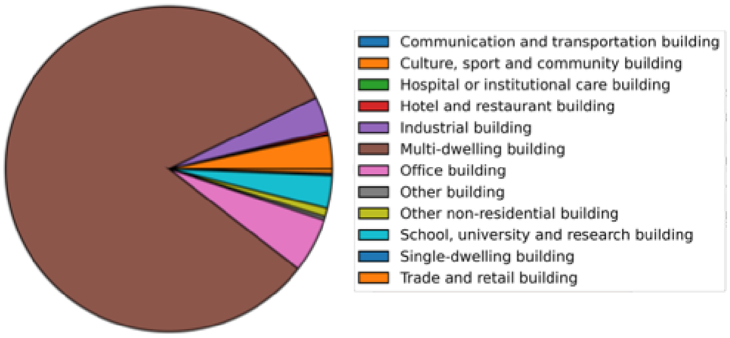


Figure 6.2 Distribution of building types in the matched building data used for validation.

The validation process is described in Figure 6.3, broken down into the following steps:

1. Data Matching:
   The measured data provided by Göteborg energi was linked with BSM results based on the address of the measurement point. If this did not yield a match, then the address was linked in a second step based on a cleaned address string where additions to the address were removed (e.g., house number 2A was turned into 2). This resulted in a matching of measurement data to 1986 buildings.
2. Aggregation:
   In order to ensure that the system boundary of the measured data and the calculated results match. This is necessary as the measurement point for district heating often covers multiple buildings. The data was aggregated in two steps: First both measurement data and modeling results data were aggregated to the property level, resulting in a dataset of 1176 properties. Analysis of these results shows that a considerable number of buildings had large deviations of the measured and calculated energy demand, stemming from the fact that measurement points often span across property boundaries. Therefore, as a second step, results were further aggregated to property clusters, where all properties of real estate owners in the same area were aggregated. This resulted in a dataset of 147 property clusters.
3. Outlier removal:
   At each step, the data was analysed for outliers and inconsistencies. This includes removing outliers where data was incomplete, e.g., where the measurement data does not cover the full time period presumably because the building changed owner during that time period.
4. Validation:
   Based on the generated dataset, the BSM was validated at different resolutions: Yearly, month as well as daily resolution for the district heating and electricity demand. Unfortunately, the dataset was too small to enable an assessment of the district cooling and electricity generation results of the BSM, as the data set only included a handful of records.

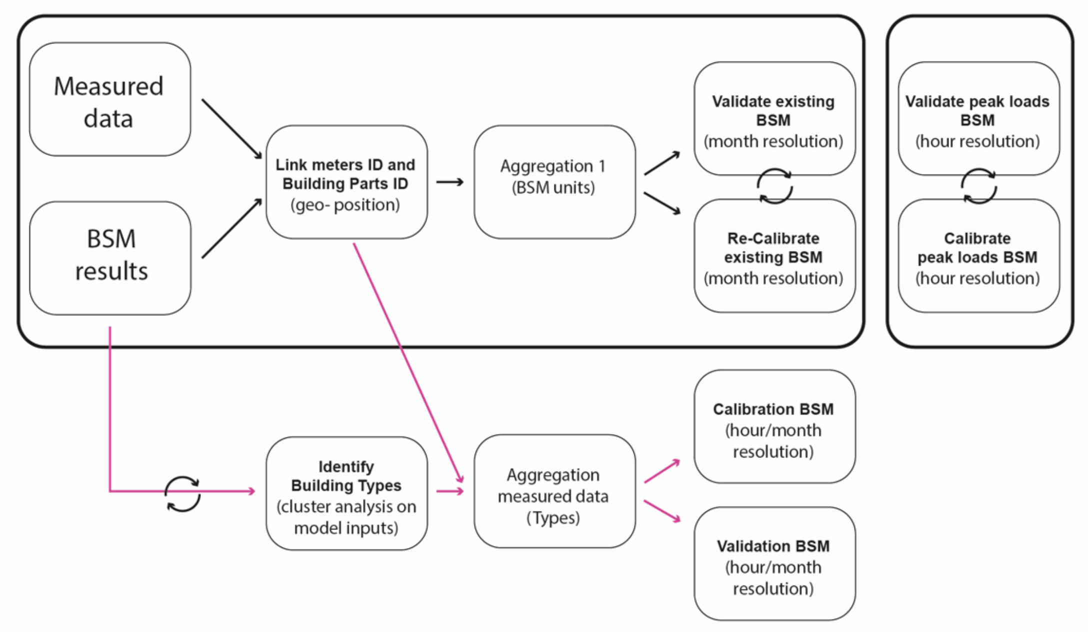


Figure 6.3 Validation workflow.

On an overarching level the results show that the model overestimates the demand, this could however be resolved by removing outliers from the dataset as described above. The validation results on an individual record level shows that the BSM on average can predict the building space heating demand accurately (Figure 6.4). However, there is a deviation due to the assumption going into the modelling (see section 6.1 above).

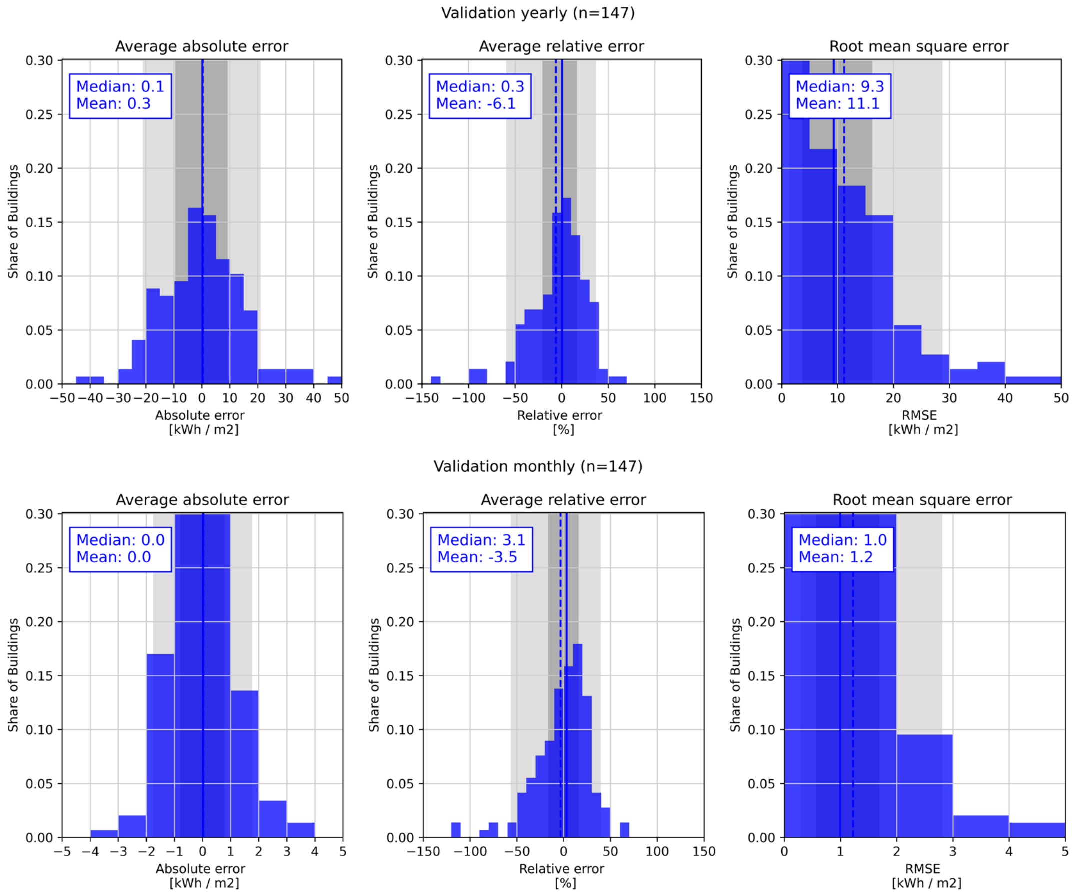


Figure 6.4 Validation results for district heating.

On an overarching level the results show that the model underestimates the electricity demand by about 20%, with a deficit especially during the winter months. This is also shown in the validation results on an individual record level (Figure 6.5), which show a deviation of the mean demand of 6.1% and an average root-mean-square deviation of 9.3%. This is primarily due to an inconsistency in the system boundary of the results as the modeling results only include building related electricity demand (HVAC and building services), while measurement results could also include electricity demand for lighting in shared areas and shared services in the building (e.g., laundry, etc.). That said, larger deviations also due to an uncertainty in the building use and the related electricity demand adds to the larger deviations in the modeling results from the measured demand compared to district heating.

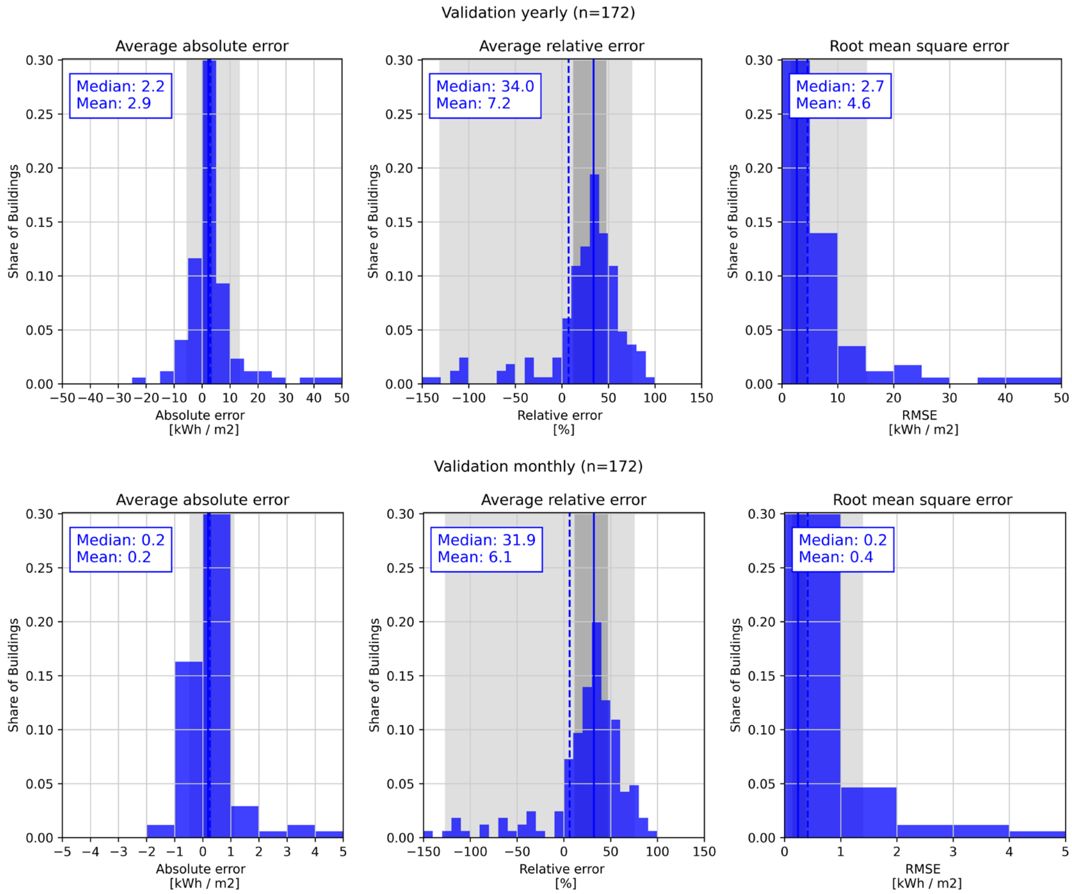


Figure 6.5 Validation results for electricity.

6.4 Scenario modelling

After the changes in the BSM described above, three sets of energy demand scenarios were modelled for the city of Gothenburg:

- Current and future city
- Climate warming impact on current and future city (2018-2050)
- Energy impact of renovation measures

The scenarios were modelled with the Building Stock Model (BSM) based on the assumptions summarized in Table 6.1.

Table 6.1 Assumption for the scenario modelling.

Scenario	Description	Assumptions
1. City development scenarios		
1.1 Current city	This scenario represents the city as it was built in 2020.	Building characteristics are retrieved from multiple sources (see below).
1.2 Future city	This scenario describes the city development as reported in the Gothenburg comprehensive plan (source).	Building usage of new buildings is assigned based on size: • 1000 m² floor area and less than 5 stories: Retail building • Larger than 60m hight: office building • Otherwise, residential building
2. Climate scenarios		
2.1 Current climate	Climate of year 2018	
2.2 1°C warming	Scenario representing the future climate based on the RCP* 2.6 from the IPCC (Intergovernmental Panel on Climate Change)** report.	
2.3 1.5°C warming	Scenario representing the future climate based on the RCP* 4.5 from the IPCC** report.	
2.4 2°C warming	Scenario representing the future climate based on the RCP* 8.5 from the IPCC** report.	
3. Renovation scenarios		
3.1 Reference	Reference scenario describing the current state of the building stock.	
3.2 Climate shell (Façade & Roof)	Focus on envelope components: roof, wall and windows aimed at reducing heating demand	All buildings built before 2010 are renovated: - Walls: +200mm insulation- Roof: + 300mm insulation- Windows: U-value 0.8 W/m² K
3.3 Building installations	Focus on building installations such as heating, ventilation, cooling, and solar cells	All buildings systems replaced: • Heating: switch to heat pumps if direct electric or fossil heating system • Ventilation: add heat recovery if possible • Add solar cells
3.4 Deep renovation	Combines climate shell and building installation scenario, See above	

6.4.1 Energy demand scenario: Current and future city

The first set of scenarios provides a comparison between the energy demand of the existing building stock and the future buildings stock as proposed in the comprehensive plan 2050 using the TMY 2020. The plan is based on a sustainable compact development model for the city and implies the increase of built density as an alternative to a horizontal expansion. The computation of final energy demand for the buildings in Gothenburg was carried out through the BSM on an hourly base.

In the DTE final energy demand, heating and cooling demand are calculated for each building based on the method described in section 3. Results show that on the city level, the annual final energy demand increases from 4201 GWh to 4768 GWh revealing that the city plan for 2050 will contribute to higher energy demand by 13,5%. Figure 6.6 shows that this variation is largely influenced by the increase in heating demand (including hot water) estimated at around 10,5% while the cooling demand is similar, about 69 GWh per year in both scenarios.

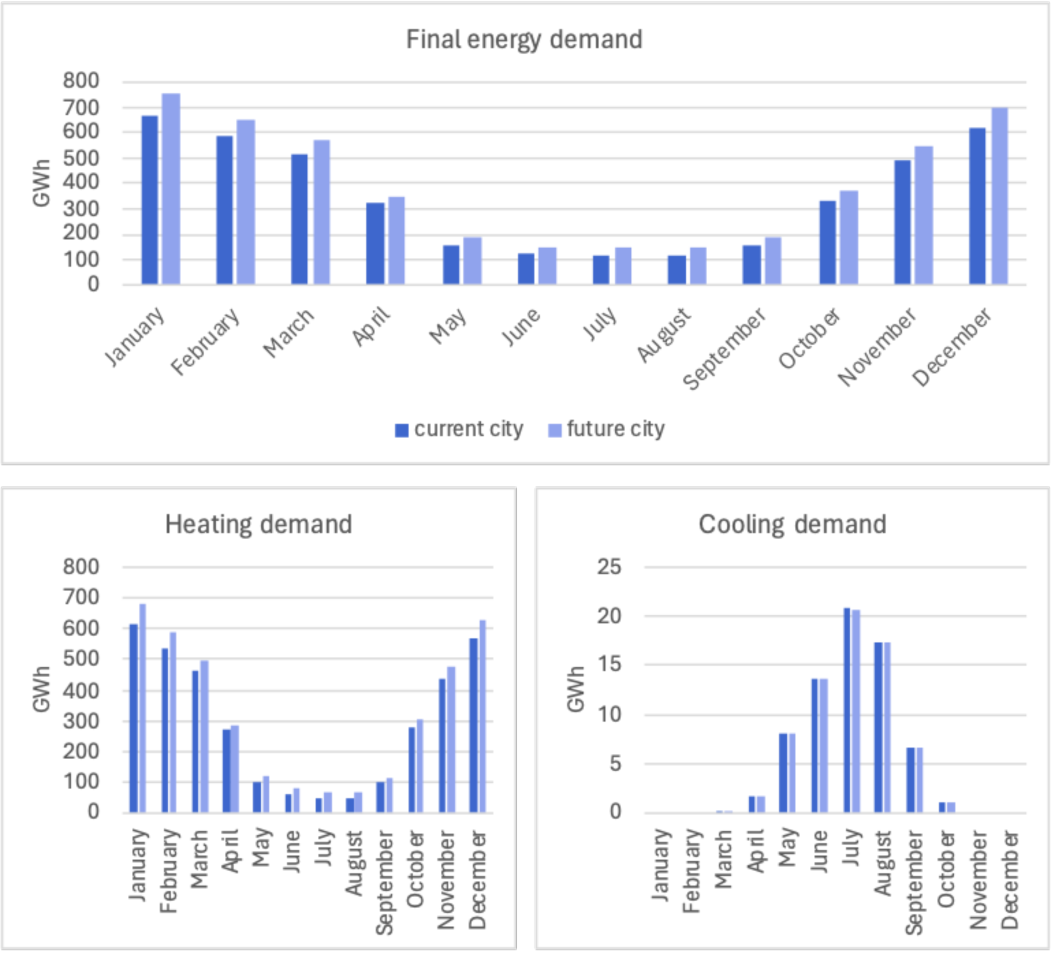


Figure 6.6 Monthly energy demand at the city scale for the current city and future city scenarios.

6.4.2 Energy demand scenario: Effect of climate warming on the energy demand of the current building stock

In order to assess energy demand in different future climate scenarios, Representative Concentration Pathways (RCP) are traditionally used (Lee et al, 2021). Energy models require weather files with hourly resolution that can be generated from regional or global climate models through dynamical and statistical downscaling. In this study, a statistical downscaling method was used to generate climate files for future scenarios by linking local weather files and future weather datasets derived from global climate models though the Meteonorm Weather Generator (Meteonorm, n.D.). This stochastic weather generator allowed to use Coupled Model Intercomparison Project Phase 6 (CMIP6) data to predict climate variables and create a Typical Meteorological Year (TMY) weather file with hourly temporal resolution. In our study, TMYs of 2050 are generated for Gothenburg following the RCPs 2.6, 4.5 and 8.5.

The RCPs trajectories, established in the IPCC report (Lee et al, 2021), are based on the probability of changes in radiative forcing as a direct measure of increased energy input and, thus, the atmospheric greenhouse gas concentration. Translated into temperature changes RCP 2.6 Wm-2 refers to a likely mean temperature rise below 2 °C by 2100. RCP 4.5 Wm-2 likely implies a temperature increase of around 3 °C, while RCP 8.5 will result in a warming of at least 4 °C by 2100.

The BSM model was modified to enable the use of the climate boundary conditions described in the previous step. Simulations were carried out using the four generated climate datasets for TMY 2018 (baseline scenario), and 2050 RCP 2.6, 4.5 and 8.5.

The first set of results regards the stochastic weather generation for the city of Gothenburg obtained through Meteonorm modelling. In Figure 6.7 results for the year 2050 RCPs 2.6, 4.5, 8.5 are compared against the baseline TMY 2018. The reported average monthly values indicate that, when considering the RCP 8.5, air temperature increases up to 2.2 °C compared to the 2018. Following the pathway RCP 4.5 air temperature increases between 1 °C and 1.6 °C, while the RCP 2.6 results in warmer climate up to 1.6 °C. Overall, the time distribution along the year indicates that in the latest scenario larger variations are observed during spring and summer months.

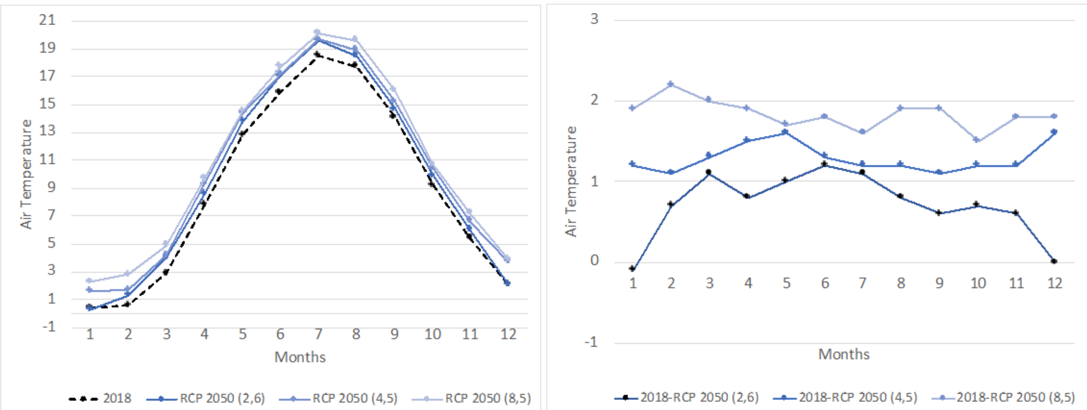


Figure 6.7 Monthly mean air temperature values in the four scenarios (left); variation in air temperature between TMY 2018 and the three RCP scenarios (right).

The average level of temperature increase in Gothenburg seems to be lower compared to the average temperature increase estimated in the IPCC report. This can be explained by the statistical downscaling of a global model to the temperate oceanic climate zone of Gothenburg. Additionally, the statistical method for producing TMYs does not predict extreme weather conditions and thus the possible contribution of heat waves on average temperatures.

The computation of final energy demand for the buildings in Gothenburg was carried out through the BSM on an hourly base. Modelling results of both scenarios are visualized in the DTE supplemented by comparative data plotting. In Figures 6.8 and 6.9 overall results for the current and future city are shown, by comparing energy demand calculated for the year 2050 RCPs 2.6, 4.5, 8.5 against the baseline TMY 2018. Regarding the current city scenario, the total annual demand is estimated to be 4201 GWh in TMY 2018. Lower yearly demand is observed for the RCP 2.6, 4.5 and 8.5 pathways, which led to a final energy demand of 4025 GWh, 3862 GWh, and 3695 GWh, respectively. A similar decrease in final energy demand can be observed for the future city plan, for which demand decreases from 4768 GWh in TMY to 4576 GWh, 4403 GWh and 4221 GWh in RCP 2.6, 4.5 and 8.5 respectively.

For both the current city and the future city, the analysis of the monthly variation between TMY 2018 and the RCP scenarios confirms that, in future warmer scenarios, the final energy demand and the heating demand generally decrease, while cooling demand increases. Especially during the winter and spring months, the largest reduction of final energy demand and heating demand is observed due to the milder climate conditions. Specifically, the pathway RCP 8.5 shows the highest reduction compared to the baseline case. Cooling demand increases for both the current and future city and results show similar annual percentile rise: 14% for RCP2.6, 20% for RCP 4.5, and 25.5% for RCP 8.5. Also, in this case the pathway RCP 8.5 is the one inducing the highest increase in demand for building space cooling compared to the baseline case TMY. As for the previous set of scenarios, the DTE shows the results of energy simulations at the building level.

Despite the description of a general pattern at the city level, the energy demand obviously varies according to the building characteristics such as use, envelope, and energy systems installed. For example, although at the city scale cooling demand is observed to increase up to 25.5% compared to the baseline scenario, simulations show that daily cooling demand during hot days can reach up to 300% increase.

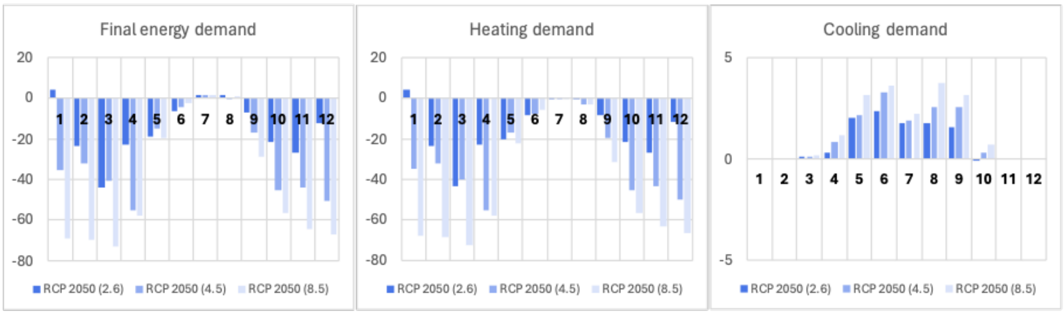


Figure 6.8 Climate warming impact on building energy demand in the city of today.

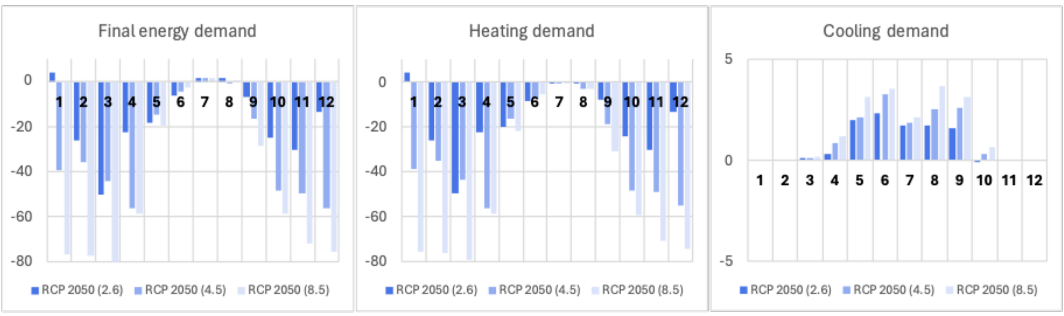


Figure 6.9 Climate warming impact on building energy demand in the city envisioned by the Comprehensive Plan 2050.

6.4.3 Energy demand scenario - The effect of renovation measures on building energy demand

The effect of renovation measures was assessed based on scenarios using different renovation approaches: one scenario with focus on improving the climate shell (e.g. insulating the walls, roofs and replacing windows) and one with focus on building installations (replacing HVAC systems and adding energy generation though solar cells where suitable) as well as a deep renovation scenario which combines the two approaches (see section 6.5. for a detailed description of the scenarios and the underlying assumptions). The results of the scenarios are applied to the current building stock, which also serves as the reference to compare the results against.

Figure 6.10 shows the difference in the distribution of the yearly building energy demand comparing the distribution of the different scenarios (in red) with the demand of the current building stock (in blue, as reference). The vertical line indicates the median energy demand in the building stock. In the Climate Shell scenario, the average energy demand results in a reduction of about 20kWh/m² and year, suggesting that interventions such as enhanced insulation, efficient windows, and roof upgrades can reduce heating requirements. The Building Installations scenario shows an even more significant decrease in the median demand of almost 30 kWh/m² and year, highlighting the large potential in energy demand through more efficient installations as well as through adding energy generation through solar cells. The Deep Renovation scenario shows the potential for energy reduction by combining both scenarios, which shows a decrease in the median energy demand of buildings by almost 50% down to 50 kWh/m² and year. These results underscore the potential energy savings in the building stock, which are hypothetically achievable by applying these renovation strategies. As the renovation scenarios are applied to all buildings without considering constraints such as cultural heritage value or economic feasibility, these results can be considered the technical potential for energy reduction in the Gothenburg building stock.

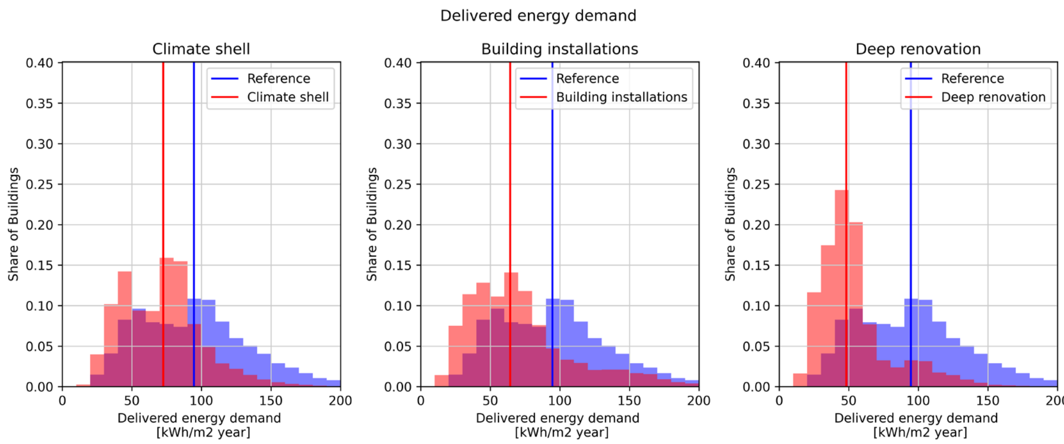


Figure 6.10 Distribution in the yearly delivered energy demand of the different renovation scenarios (red) and the current building stock in (blue).

Figure 6.11 shows the change in the distribution of the peak heating demand based on the different renovation scenarios. The climate shell scenario leads to an overall decrease in peak demand by about 20kW on average, the reduction in heating demand stemming from a more efficient building envelope. While the building installations scenario shows a slight increase in the distribution of the buildings with a much lower peak demand (e.g., buildings that shift from direct electric heating to a heat pump), the median peak demand shows no significant shift. This has several reasons, first of all, technologies like solar cells are effective in reducing the overall energy demand, but show little to no effect on peak heating demand as these demands typically occur during the coldest days in winter, in the morning or evening hours when production of solar cells is low or 0. Moreover, most buildings with high peak demand are large buildings, most of which are connected to district heating, where efficiency gains are less significant than if switching from direct electric heating to a heat pump. However, the results do not account for the potential to reduce peak demand through smart controls of the different building installations as this is beyond the scope of the BSM, such technologies have been proved to lead to significant reductions in peak demand e.g., by shifting heating loads. The deep renovation scenario highlights the combined effect of the two scenarios, where a secondary peak is shown, these are primarily single-family buildings where the combined effect of replacing the existing direct electric heating system with a heat pump and a more efficient building envelope leads to a significant reduction in peak demand.

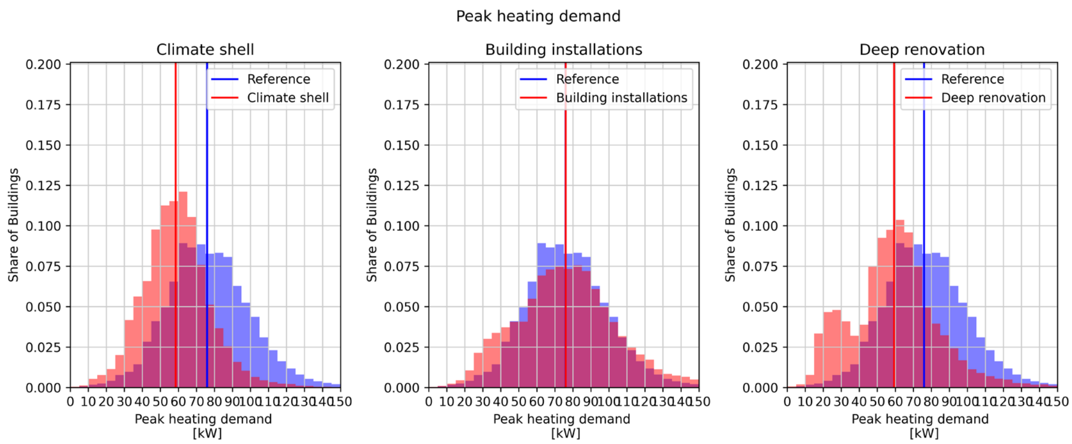


Figure 1.11. Distribution in the peak heating demand of the different renovation scenarios (red) and the current building stock in (blue).

7. Viewer Development and Testing

Finally, the fourth phase of the project aimed at developing a Digital Twin Energy (DTE) online viewer to interactively use the results of the quantitative scenarios.

In order to address the question of how the DTE can guide short- and long-term urban transformation and facilitate the decarbonization process of Gothenburg, we developed a workflow that presents energy demand in different scenarios. In this process potential users were involved in the development of the viewer interface through workshops activities. Two assessments concluded the testing process and allowed reflections on possible implications in decision-making practice.

A first set of workshops (workshops 1-2) had the primary goal of identifying the possible characteristics of the UI through co-creation settings. Workshop 1 was driven by three open questions regarding user needs, basemap content and time dimensions and was run internally with local researchers involved in DTs development. Workshop 2 aimed to assess the relevance of different options proposed for the basemap content, UI functions and data visualisation by engaging a reference group of external experts asked to select the three most relevant features.

The second set of workshops (workshops 3-5) had a focus on gathering input on clarity, content, and functionality in relation to the developed features. They were carried out by targeting the main groups of decision-makers expected to be the principal users of the CDTE: property owners, municipal urban planning and environmental department, and the city's energy company. The structure of the workshops was identical for each target group, based on a set of questions organised around a mock-up of the viewer and a first visualisation of the UI. The mock-up introduced 5 main features of the interface to:

- LEARN about the viewer,
- SET-UP energy scenarios,
- CUSTOMISE the view,
- USE the results, and
- COLLABORATE with own data.

Finally, the latest iteration of the viewer was assessed through user tests combined with an evaluation survey. For the survey, a questionnaire was prepared based on the Gemini framework (Bolton et al. 2018) and its nine principles developed to enable DT's better use, operation and maintenance. The questionnaire collected background information about the users and their familiarity with digital twins or other digital tools, their evaluation of the usability and usefulness of the DT and general reflections on the characteristics and the maintenance of the platform. Details about the workshops and assessment can be found in Appendix 4 and 5.

7.1 DTE Viewer description

Based on the city model generated by using the datasets described in Chapter 6 and additional cadastral data, the visualizations with the online DTE Viewer were prepared. A base map was generated by using street, water and trees features that are visualized in 2D for the full extent of the city. Building footprints and attributes of height, extracted from the

LiDar data were used to generate a 3D city model with buildings represented in Level of Detail 1 (LOD1). In LOD1, each building is represented as a simple block with a flat roof without considering its actual roof shape. Simulation data derived from the BSM are then appended to the building objects. To manage the large amount of data and reduce the visualization time, a vector tiling system was used. Tiling systems allow to break a physical space into smaller portions facilitating the storage and the analysis in a more granular level. On the DTE viewer the web client calls the loading of tiles when zooming in and out within the interface, trigging the query of x,y georeferenced values and being able to load between 1 and 16 tiles at the time. For the visualization of energy demand classes, data were encoded into colour scale images using a customized style. The pre-calculation of values and ranges for each energy indicator allow to reduce the rendering and visualization time.

An example of the results for single buildings are visualized in the DTE viewer through classification of the final energy demand in kWh/m² per year (Figure 7.1). Users can customize their visualization by selecting the future climate scenarios with different rises of temperature and related energy demand results.

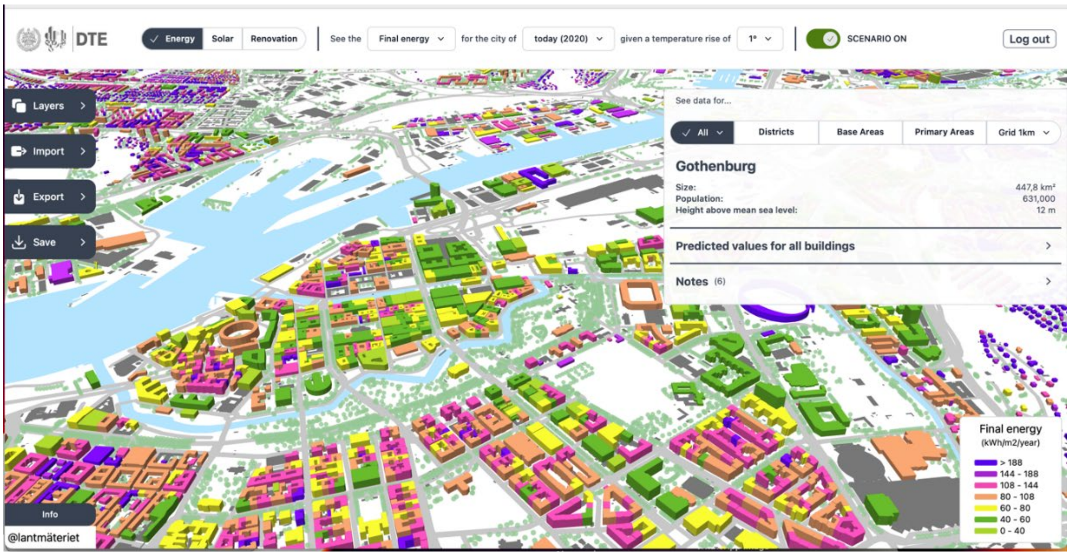


Figure 7.1 Screenshot of the visualization of the online Digital Twin Energy Viewer interface.

Pre-calculating the indicator data into the tiles is an optimized approach to handle the large amounts of scenario data required to derive the scenario insights. One technical challenge lies in managing over 100.000 buildings on the map, each with multiple indicators in a monthly time series resolution for selected scenario years, when doing custom scenario insights dynamically. The combination of scenario parameters results in exponential data growth. The filtering functionality allows to select buildings by predefined boundaries such as administrative boundary or grid, but also by using keywords for the filter based on the attributes of the features. This requires further calculation of the indicator values depending on the current user selection which means that thousands of buildings need to be searched through to produce the new insight. These dynamic insights are expected from a CDT but inflicts a challenge in the client/server system architecture and requires thoughtful consideration when looking into data management.

The tiling system used is based on vector tiles as specified in the MVT (Mapbox Vector Tile Specification) format. This is a suitable format for generating LOD1 features as the client can dynamically render 3D meshes from extruded footprint data representing volumes sufficient in energy simulation scenarios. A CDT with over 100.000 buildings could benefit from a layer of this resolution, achieved with MVT or other open vector-based formats, to quickly host colour indications of the BSM since this overview could help the user to indicate where to zoom in for more details using a more granular LOD. A traditional raster-based tile system would not support this dynamic behaviour.

Using the tiles directly as data source has the advantage of having the data nearby in the viewer, especially with optimised usage of WebGL, however at some point the viewer is expected to reach a limitation of responsiveness depending on the device hardware due to the scenario interaction. At this stage, a Geographic Information System database backend could be considered to concentrate the user scenario selection around a new request to the server, which would trigger a reload of the tiles with new indicator data. The viewer is open source (MIT) and built using the Digital Twin City Viewer project.

github.com/mapbox/vector-tile-spec/

github.com/paramountric/digitaltwincityviewer/tree/main/projects/dte-digital-twin-energy

7.2 User Interface Development

As mentioned in Section 3.2, to be able to address the diverse identified target groups, the requirements for development of the visual communication platform, the viewer, were i) easy to use, ii) facilitate multi-actor decision making processes, and iii) provide relevant information for decarbonization process for the targeted stakeholders enabled through well-designed visualizations, data coordination and exchange, and linking of BSM to scenario simulations.

In total 5 development workshops were carried out with the different target groups. The workshops resulted in several iterations of the viewer UI. The versions of the mock-ups were prepared and documented on a Miro board.

Figure 7.2 Viewer development workshop. Discussion of printed mockups of the interface with one of the target groups.

The main aims of the UI design were for users to first get an idea of what they could use the viewer for by constructing a 'scenario' (Figure 7.3), and subsequently narrow the data to the most relevant for them to see in their professional role, through filter functions.

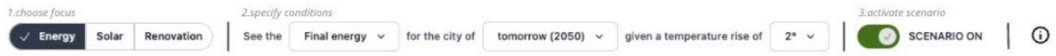
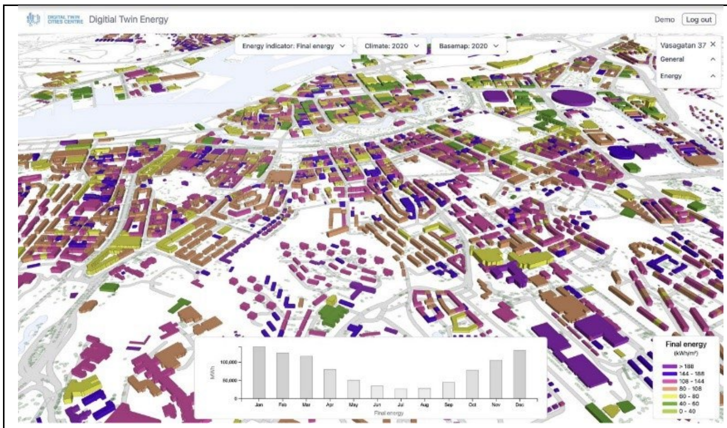


Figure 7.3 'Create a Scenario' feature of the Viewer. The user starts with choosing a focus (left), followed by selecting specification of the conditions (middle), and finally, activates the scenario (right).

A summary of the iterative development of the viewer is illustrated in Figure 7.4. The design guides the user towards what they can use the viewer for in practice, features that are recommended to be even further developed and adjusted once a backend has been introduced that improves functionality and speed. See Appendix 3 for details of the workshop settings.

	**a** – *Initial design of the UI*
	**b** – *First mockup* *Synthesised feedback from the first two workshops and identified three main areas in the UI, focused on three main actions: i) construct the scenario you wish to see ii) customize the data you want to see ii) Compare current and scenario data.*

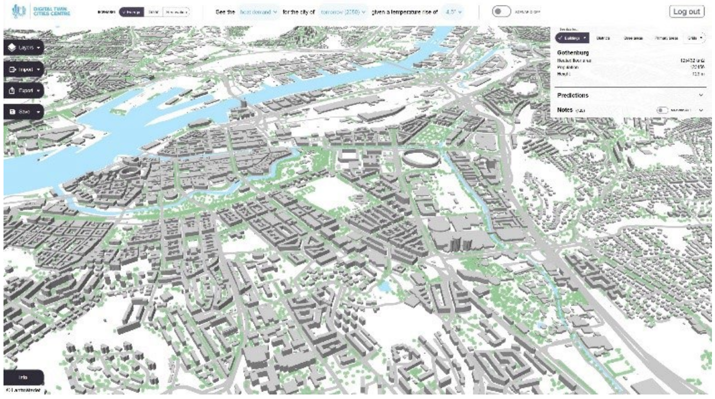
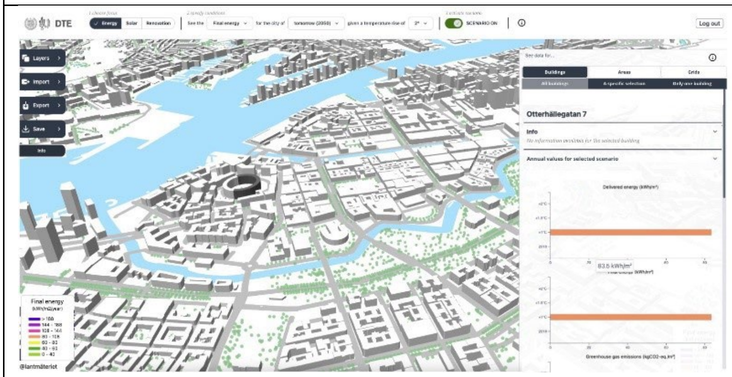
	**c** – *Second mockup* *Integrated current and scenario data into 'predictions' and added the filters atop the right-hand section to provide clearer connectivity between the filters and seen data.*
	**d** – *Final mockup* *The final design focused on guiding how to use the scenario feature, making the filtering more intuitive and adding features such as legends and info buttons to clarify the meaning and origin of the data.*

Figure 7.4 Mockup iterations of the different development stages of the DTE Viewer interface (UI).

As the focus has been on the scenarios, filters and layers of the platform, further attention is in the future needed on how to present the final data – such as data origin, accuracy, and visual representation.

7.3 Viewer testing

The user tests were also structured in workshop settings. After a short introduction, participants worked in parallel group sessions driven by the assignment of exploring the viewer and defining robust decarbonization strategies in different areas of Gothenburg using the DTE viewer. At the end of the assignment, each participant completed the survey and evaluated their experience of the viewer for decision-making.

In the project we conducted two assessment workshops were conducted: First, a workshop with 22 stakeholders representing the city energy provider, the planning and environmental department of the municipality, property companies both municipal and private, and researchers; and second, a workshop with 70 master students with a background in architecture and urban planning as part of a course on sustainable development and stakeholder engagement.

In the assessment of the DTE with stakeholders, participants were divided into four heterogeneous groups and a city area was assigned to each group. For each area, they had to negotiate decarbonization measures to implement by using the DTE to retrieve data about the current status and future scenarios and finally at the end complete the evaluation survey. The assessment of the DTE with students was conducted in two steps. Firstly, the students explored the DTE and their first-hand experiences were evaluated through an initial survey, before any introduction or clarification of the DTE and its functionality. Secondly, the purpose and functionality of the DTE were clarified in a presentation and a workshop was organised in which the DTE was used to explore, discuss, and negotiate renovation measures for three selected area in Gothenburg. During this assignment, the students negotiated renovation measures in groups from the perspective of individual roles that they were assigned (e.g. architects, politicians, developers, business owners, and citizens). Both surveys were conducted through the software Questback after which the survey responses were extracted and further analysed in Microsoft Excel. The first survey resulted in 24 responses, while the second survey gathered 38 responses.

Detailed assessment results are shown in Appendix 5 where the answers of the two survey groups are compared. The difference in expertise and background of participant groups is particularly evident in the answers given to the background questions (1-3) where the results indicate that 50% of the first group had already previous experience with DT, while only 8% of the students have some familiarity with a DT. Despite this, similar answers were given to question 5 about the possible applications of the DTE. Around half of the respondents consider the DTE relevant for communicating with other decision-makers and around one quarter could see relevance in analysing a building before making decisions on interventions. The last quarter acknowledged the potential relevance in the DTE for sharing information within companies.

The survey results from both the stakeholders and students indicated that the DTE was generally considered easy to use, especially, accessing the platform, visualizing scenario results, and visualizing building details or graphs (questions 6,7,8). However, the stakeholders found it more challenging to visualize scenario results and build details and graphs (around one-third reported that this was not easy).

Most of the respondents acknowledged the potential of the DTE to be useful to the public and enable performance improvements. Most respondents found visualizing energy scenarios the most useful function of the DTE, followed in terms of preferences by the data plotting function (question 9). Further, the DTE was evaluated to be useful for understanding the energy performance of single buildings (question 10). However, a few differences can be seen in the answers, were the student group fully agreed on the usefulness of the building performance analysis while among the decision-makers 14% considered the DTE not useful for the purpose.

Similarly, a discrepancy between the two groups is found regarding the usefulness of the DTE to define decarbonization strategies. About 94% of the students and only 36% of the stakeholders considered the DTE useful for identifying strategies able to reduce energy-related greenhouse gas emissions (question 11). However, these results seem to contradict the general agreement about the potential of the DTE in enabling (energy) performance improvements (question 14). Finally, most of the respondents responded positively regarding the potential of DTE viewer to be useful for the public (question 13).

The stakeholders were not sure about the reliability and quality of the data (question 15-16), which they pointed out as negative characteristics and highlighting the difficulty in understanding how data is created. This could explain why relatively few found the DTE useful for defining decarbonization strategies as it might be difficult to make decisions based upon uncertain data. After the assessment with stakeholders, UI optimizations were made to promote data reliability. Info buttons were integrated into the interface to explain functions, scenarios, and calculation methods, linked to external sources and original datasets. Thus, this change might partially explain the different responses of students that for the majority considered the data contained in the DTE of appropriate quality and showed an increased trust in the platform.

During the development phase, the DTE was made available only to projects, workshop participants and assessment groups. However, having a data platform open to users is considered important of a DT. When asked to indicate preferences about the accessibility of the public (question 17), the majority of the respondents indicated that the viewer should be accessible to municipal decision-makers (stakeholders) and citizens (students). For both respondent groups, about a third indicate their preference for granting accessibility to private companies. Together with accessibility aspects, the general concern about maintenance had emerged during previous workshops. In an open question regarding the identification of a responsible organisation for the maintenance in the long term (question 23), stakeholders indicated a preference for having the city of the public entity as a primary responsibility, followed by independent companies.

In the final part of the evaluation survey, the respondents of the two groups could share their opinion on the positive and negative characteristics of the DTE and give suggestions about new functions to include. The results, despite showing in some cases contrasting opinions, highlighted positively the visualization of complex data at multiple scales and the platform as a good basis for initiating a constructive dialogue. Among the negative aspects, a part of the respondents expressed difficulty in understanding how data was created and in using the interface.

Finally, in an open question, the assessment groups gave suggestions about future functions that should be included to make the DTE viewer more useful (question 22). Answers highlighted the need for inclusion of richer datasets (for example electricity and water demand) and scenarios results with higher time resolutions (hourly demand) and for multiple years (for example 2030). Other respondents reconfirmed the need for clearer information about building characteristics, modelling and variables in the scenarios function. The search function was perceived to be a bit hidden in the interface and it should offer more search options.

8. Recommendations and takeaways

This chapter provides a summary of main results, recommendations, and takeaways for each of the phases of the DTE project as well as a short reflection on data collection and sharing.

8.1. Recommendations for the update of the Energy Plan

The Gothenburg Energy Plan (GEP) defines challenges that need to be addressed to achieve decarbonization goals for 2030 on a national and city level and it frames a set of actions and measures. In this project interviews and a workshop with local stakeholders have highlighted additional key challenges for achieving the goals and assuring successful implementation of the GEP. The identified challenges regard i) the coordination between energy and urban planning, ii) the future stability of district heating and cooling, iii) the balance in electrification of the buildings and transport, and iv) instruments and tools for decision-makers. The GEP should also promote additional measures to guarantee the development of instruments and deep analysis to face the identified challenges.

The project results suggests that new measures should be allocated to:

- investigate the influence of the densification development model on urban warming phenomena and future energy security during extreme climate events;
- develop frameworks and planning-workflows to align energy and urban planning decisions to efficiently manage scarce available space in high-density conditions and facilitate symbiosis among buildings for exploiting local potentials (such as local waste heat);
- start envisioning alternatives to ensure a reliable provision of district cooling and heating based on sources based on different paths for the refiery's and the local waste-to-heat-plant (Renova) towards climate neutrality;
- develop models and frameworks that can facilitate decisions of building owners on centralized or decentralized heating and cooling supply systems to avoid suboptimizations;
- understand how to meet the potential cooling demand of multifamily houses and what technical and economic measures should be advanced;
- support the increased electricity supply needed for the transition towards a fully decarbonized private mobility, models of service and investments to upgrade the supply infrastructure
- investigate management models for smart systems implementation
- encourage the development of decision-making instruments to facilitate communication between private and public actors and to support knowledge and data exchange.

8.2. Moving from qualitative and quantitative scenarios

The scenario methods developed in this project contributes to advance the development of knowledge and instruments required to support decision-making in achieving decarbonization goals. The participatory approach, built around the integration of qualitative and quantitative scenarios approaches, supports creation of a multidisciplinary common ground to explore potentials and risks of decarbonized actions and drivers of change. Although the research departs from well-established decarbonization actions, derived from both literature and the GEP, the approach supports the setting of priorities in the research agenda to meet the needs posed by their implementation in local contexts.

Strategic scenarios highlighted the urgency of addressing the consequences of introducing smart energy systems, increasing built and green density on building energy demand. External scenarios underlined the necessity of analysing how changes in climate, electricity prices and penetration of EVs might affect a secure energy supply. However, the translation from qualitative to quantitative scenarios highlights that the agenda for energy models' advancement should address i) assumptions' projection for modelling future urban developments (e.g. occupancy, retrofitting rate, penetration of efficient energy systems), ii) inclusion of UHI and climate change projections as climate boundary conditions, and iii) increasing the accuracy of long-wave and heat flux calculation.

8.3 Energy demand and the warmer future

The BSM analyses for Gothenburg provide a clear picture of the potential future energy demand at the building level, allowing a better understanding of the interrelation between the spatial, energy and climate change domains. The developed workflow demonstrates the capacity of integrating climate and energy models in a Digital Twin. However, the climate scenarios, due to the statistical method used for the downscaling, cannot predict extreme weather condition, and thus modelling of peak demand cannot be estimated based on this climate assumptions. Despite this limitation, the Digital Twin allows to observe a general trend of energy demand decreasing mainly related to the decrease of building heating demand due to milder temperatures: whereas warmer summers relate to the increase of cooling demand. These results might already provide a basis to reflect on the measures to prioritize to achieve carbon neutrality goals of 2030 and further. Specifically, new questions should arise about the traditional effort in Gothenburg, and other north European cities, in supporting the implementation of measures to reduce building heating demand without considering the future trend of increased need for space cooling. Additionally, the visualization of the scenarios results at the building level for the whole city can support private and public owners to understand the future energy performance and importance of action, and thus identify more robust investments for longer-term energy efficiency. From an urban planning perspective, questions also arise on how to align climate adaptive urban strategies to energy saving ones in the long-term.

8.4 Digital Twin Energy Viewer

The project has created a viewer which has been developed in a participatory approach with stakeholders responsible for the energy transition and implementation of the energy plan of the city of Gothenburg. The project has demonstrated that the viewer has an enormous potential to function as a tool for driving the process. It can be a tool used in municipal organisations including the energy supplier and housing managers to explore development scenarios of buildings stocks. The development process and the related discussions of what parameters to include, which scenarios to work with, and in what processes to apply the viewer has been proven as important as the viewer in its own. This confirmed our starting point that a DT and visualizations can be a powerful tool for stakeholder collaboration and decision-making support.

All the workshop sessions enriched the DTE development process and highlighted technical challenges that should be addressed in future DT development. One of the major challenges is the sharing of existing energy consumption data. Having a publicly accessible digital twin entails the open access of data as well as and offers of sharing geographical data in the energy domain, including consumption data measured at the building or household level along with scenario results.

The DTE highlights the potential of digital twins in providing scenarios of possible futures and envisioning potential long-term changes in energy demand when taking decisions on robust decarbonization measures. Along with the scenarios modelled in the DTE, local stakeholders pointed towards other relevant key data that should be integrated to offer a comprehensive overview of cities' energy transition and support the implementation of measures. Among those the most frequently mentioned were: the cost of delivered energy and renovation measures, peak consumption during extreme climate events (heatwave and coldwave) on daily and monthly periods, the potential of energy production through renewable sources, and supply capacity of powerplants and networks. Extensive discussions with the local stakeholders specifically addressed the definition of building energy demand and its evolution in the electrification transition of the mobility sector. Private electric vehicles are expected to be increasingly connected to private chargers. Here, questions arise by energy providers on the overall new load on the electricity network and the need to model the supply infrastructure and its configuration in the building stock. Additionally, time scales for the energy planning should be further discussed in the development of future digital twins in the energy domain. Local administrations committed to achieving energy targets usually identify subgoals to reach in a specific time horizon. In the case of Gothenburg, the GEP identifies decarbonization goals up to 2030, while property owners organize their strategies on a 5 to 10 years planning. Thus, scenarios should be able to offer multiple time scales to answer the needs of different groups of decision-makers.

While current results emphasise the technical potential of energy savings in the Gothenburg building stock, which are hypothetically achievable by applying the indicated renovation strategies, the renovation scenarios applied to all buildings do not consider constraints such as cultural heritage value or economic feasibility. To facilitate assessment of the feasibility of the measures, richer datasets should be included.

The testing and assessment of the DTE highlighted that reliability is a crucial factor for users. Presenting results of the scenarios alone is sufficient to gain trust in the tool. Complementary sources and documentation with details about the modelling methods and the assumptions behind the calculations are necessary to provide. How to promote data reliability in digital twins is a key topic to address in future developments.

9. Benefits for Gothenburg Energy

GE navigates in an energy transformation sector, with fast increasing electrification of transport and industry and with buildings being a more active part of the energy system. 'Energy' Gothenburg grows, gets densified and becomes at the same time more efficient. GEs volume and costs for investments are increasing and there is a need for reliable predictions regarding time, volume, and location of development. Total costs need to be minimized.

The DTE project offered benefits for GE in several ways; impacting content and study of relevant aspects through active participation, learning about DTs and the DT potentials but also challenges related to it, exploration and discussion of relevant application examples and results, and initiation of collaborations across departments and organisations.

GE employees have been involved during the whole project in several way, with experts participating in regular project meetings and preparation of workshops, participation of employees from different divisions in workshops on DTE Viewer development and testing, and participation in interviews. Through this involvement, GE has gained knowledge, created new networks, and discovered gaps and topics for future focus areas within the company. GE was also able to directly impact on the project content and to explore for the company appropriate development path, for example, secure that relevant parameters are included in the viewer and what scenarios to develop.

Results of the project, including the DTE Viewer, can be applied for development of future, own analyses and provide inspiration for new types of analyses carried out within GE. Results can also inspire transfer to other domains of GE such as production and operative planning. Scenarios can provide input for GEs future investments and development of business plans as knowledge can be gained based on detailed energy demand analyses on the building and neighbourhood level for different types of buildings, for existing buildings, renovation options, and future development areas.

The learnings about what a Digital Twin is and can be in general and in the domain of GE, a tool to simulate and visualize future developments, are profound benefits for GE as well. The DTE project not only demonstrates the potentials but also revealed many challenges to reach the potentials, not at least related to gathering and sharing of energy data. The knowledge of the data-bottlenecks, risks might also help to find new ways for data sharing (different levels of aggregations, special municipal data pipelines for specific projects, etc.) which is necessary for a successful energy transition.

With help of the DTE viewer, future development scenarios for energy systems can be shown and the consequences of various measures can be studied and discussed, for example the future effect and energy situation in relation to Gothenburg's entire building stock and a sustainable urban environment. The DTE project helps GE to communicate the perspective of the company in the further development and implementation of the Gothenburg energy plan, to the environmental and city planning department of Gothenburg but also municipal property managers. This leads us to the main and most important benefit of the DTE project, the process of the viewer development which illustrated what role a DT can play for collaboration and communication within GE, within the municipality, and across the organisations, for goal alignment, decision making and potentially for business strategies.

Finally, the results, report and the short films that summarize the project and the use and content of the DTE Viewer offer GE the possibility to communicate with politicians, customers, and the public.

10. General contributions and further work

The general contributions of the DTE project are manifold. They range from supporting the energy planning in the city of Gothenburg, initiation of a broader stakeholder discussion to tackle energy and climate challenges and demonstration of the importance of collaboration. The DTE project also puts the data sharing topic and related challenges on the agenda as well as it gives directions for future work. Not at least, the online DTE Viewer developed in the project seems to have a large potential to function as an intermediator for energy and climate related question and a decision-making support in the city of Gothenburg.

10.1 Towards more robust energy and climate strategies

The study of the GEP together with the development process of the viewer, the stakeholder workshops, and the discussions among researchers, energy supplier, and municipalities provided input for the development of more robust energy strategies for the city of Gothenburg. Proposals for supplementations regard, among others, the coordination between energy and urban planning with a more active broader stakeholder involvement, the future stability of district heating and cooling, the balance in electrification of the buildings and transport, and instruments and tools for decision-makers (see chapter 8 for details). In a wider perspective, the project contributes to fulfillment of climate goals on the urban, national, and European level.

10.2 Digital Twin - collaboration potential and process support

The DTE project highlighted the importance of collaboration within and across organisations in initial stages, not at least to unveil potential goal conflicts or missing stakeholders to be involved in the process. Since Gothenburg shares many characteristics and sustainability challenges with numerous cities around the world, the study of the GEP and the DTE Viewer development provides transferable lessons and offers valuable insights for researchers and practitioners interested in urban transitions outside Sweden. The common DTE Viewer development process and testing of the viewer have been an important vehicle for initiating stakeholder conversations and shown a way to start overcoming the disconnect between energy planning and city planning processes. The DT allows tangible visualizations of development scenarios on different aggregations, from buildings over districts to the whole city, instead of diagrams that are interpreted differently by different stakeholder organisations. Thus, the DTE Viewer has a large potential to function as an intermediator in the energy transition and support decision making.

10.3 The paradox of open data and data sharing

The success and usefulness of the DT and the viewer is depending on what data the scenarios and analyses are based on. For the DTE project, a crucial and time-consuming part was the data gathering process and the alignment of data from diverse sources. The project revealed a concrete example of the difficulties of data sharing even if there is a willingness to do so. What data can be shared in what way be whom for what and what data is relevant? The project developed an approach to get access to data via property owner agreements. This worked well, even if time consuming, for a limited number of buildings and the purpose of validation of the BSM. The project also sparked a discussion about data exchange within and between organisations. If data can be shared across organisation, more collaboration can be enabled, and results should be usable by several stakeholders and organisations. Working on aggregated levels or with synthetic data could be one approach to tackle da. Even if data is not perfect or as detailed as possible, available data can help to identify a trend or to start a dialogue.

10.4 Future work

As the DTE Viewer has shown potentials to support stakeholder dialogue regarding urban energy, this potential should be explored more and the viewer advanced. Further development should be closely connected to investigations on how the DTE viewer can be integrated into ongoing workflows in municipal organizations and companies involved in and responsible for the energy planning and transition of the city of Gothenburg. Not at least for the revision of the GEP, the DTE Viewer can play a key role. Thus, a process for collaboration needs to be established. From a technical point of view, the backend of the viewer needs more thorough development. This is also connected to the workflow the DTE viewer could be connected to and with what organisations data are planned to be shared.

Future work with the DTE Viewer and stakeholder dialogue should have two directions. The first one is the continuation of the viewer development content-wise, for example, the implementation of additional scenarios such as solar energy potentials in the building stock, and functionality-wise the implementation of envisioned functions such as uploading and downloading of data and results. More general building related extensions of the viewer could take into account smart buildings, real time and flexibility questions and that buildings functions are changing; building act as new energy providers connected to grid or EVs. Other extensions of interest are not only buildings but, for example, additional layers which address grid development, identification of limitations for establishment of new industries, bottlenecks for planning department, municipalities needs - scenarios with a 2030 perspective and if goals are actually reached.

The second direction of development is the testing of the viewer in a concrete case with an increased resolution of the studied building stocks, specific stakeholders. These questions are dealt with in the recently started project Digital Twins for Positive Energy Districts (chalmersindustriteknik.se/en/project/digital-twin-for-positive-energy-districts). In this project the DT and DTE Viewer is applied for the neigbourhood Jättesten in Gothenburg to explore energy and climate development paths but also to investigate how systems interact to become the most effective PED (Positive Energy Districts), and how we can use a DT to support stakeholders and contribute to quality assurance. A higher level of detail is aimed at.

Further, the DTE Viewer with its base data layer on buildings (type, use, construction period, etc.) has not only value for the energy transition of buildings but could also be extended with additional information layers, for example, built-in resources and assumptions of where what building materials can be found and when they might be released. First attempts to link the built-in material perspective to the DTE Viewer are done in the JPI Urban Europe research project CREATE (jpi-urbaneurope.eu/project/create/).

Finally, a particularly important question that needs further investigation is the ownership and management of the DTE Viewer over time and to ensure knowledge spreading and taking care of DTE Viewer and results.

11. Project output and outreach

The DTE project has produced several outputs in form of publications on both scientific and popular science channels, production of a film that summarizes the work of the project and a film with stakeholder witnessing the importance of the project, and presentations at several seminars and conferences. During course of the project, also data sets with climate zone data were generated and uploaded to an open access database which put Gothenburg on the international map. Another data set was projected on a physical 3D model of the City of Gothenburg in the VisLab exhibition at Universeum, the national science center, where the energy use of buildings is visualized (Figure 11.1). A list with detailed information about the of output and outreach activities can be found in Appendix 1 and 2. In sum, the following output and outreach activities have been carried out [quantity]:

- DTE Viewer
- Scientific publications, open access [4]
- Popular science publications [2]
- Short films [2]
- Conference Presentations [8]
- Presentation at seminars [3]
- Local Climate Zones dataset [1]
- Dataset for projections on physical model at Universeum, national science centre [2]
- Pushing boundaries, initiating discussion among city energy stakeholders

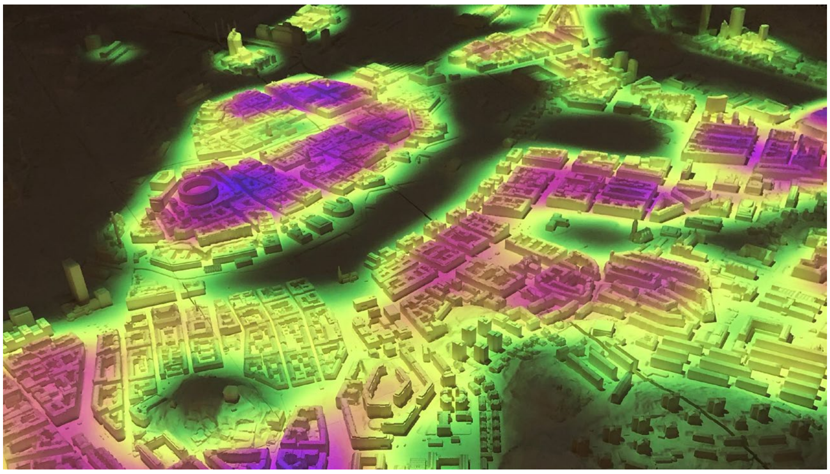


Figure 11.1 Visualization of the energy dataset. Energy density heat map projected on physical 3D model of the City of Gothenburg in the VisLab exhibition at the National Science Centre Universeum.

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Appendix 1 – Published project results

Publications

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Thuvander, Liane; Maiullari, Daniela; Nägeli, Claudio; Wallbaum, Holger; Rudenå, Andreas (2024). Digital Tvilling för Energi– Effekter av ett varmare klimat och renoveringar på byggnadsbestånd, *Bygg & Teknik,* Nr 2, pp 14-16

Links:

Video project summary:	Normal:	https://youtu.be/pO2XanyJ9qY
	4K:	https://youtu.be/URcKeteowx8

Video stakeholder testimonials: https://www.youtube.com/watch?v=ObU3hXgDW0c

Local Climate Zone data set: https://lcz-generator.rub.de/submissions

Appendix 2 – Presentations at conferences and seminars

Year 2024

- Göteborg Energi's Utvecklingsdag, 7 March 2024, Göteborg

Year 2023

- DTCC Digital Twin Cities Conference: Bridging the gap between vision and reality, 28 November 2023, Gothenburg
- International Symposium on Hybrid Energy Systems for Integrated Smart Buildings and Cities, 23-24 November 2023, Brest, France
- CISBAT conference The Built Environment in Transition, 13-15 September 2023, Lausanne, Switzerland
- Kartdagar, 18-20 April 2023, Helsingborg
- Presentation seminar City of Gothenburg, 24 March 2023, online

Year 2022

- 7th International Conference on Smart Data and Smart Cities (SDSC) 19–21 October 2022, Sydney, Australia (online presentation)
- sbe22 conference Innovations for the Urban Energy Transition, 11-13 October 2022, Delft, The Netherlands
- sbe22 conference Built Environment within Planetary Boundaries, 20-23 Berlin 2022, Germany
- Landvetter Södra, Mölnlycke, Webbinarium: Framtidens energi - Varifrån kommer den och vilket ansvar har brukaren, Presentation: Digital tvilling för samordning av energifrågor (23 May)
- ISPRS conference 2022, Nice, session: Digital twins (8 June)
- Göteborg Energi's Utvecklingsdag, 2 February 2022, Göteborg

Appendix 3 – List of workshops

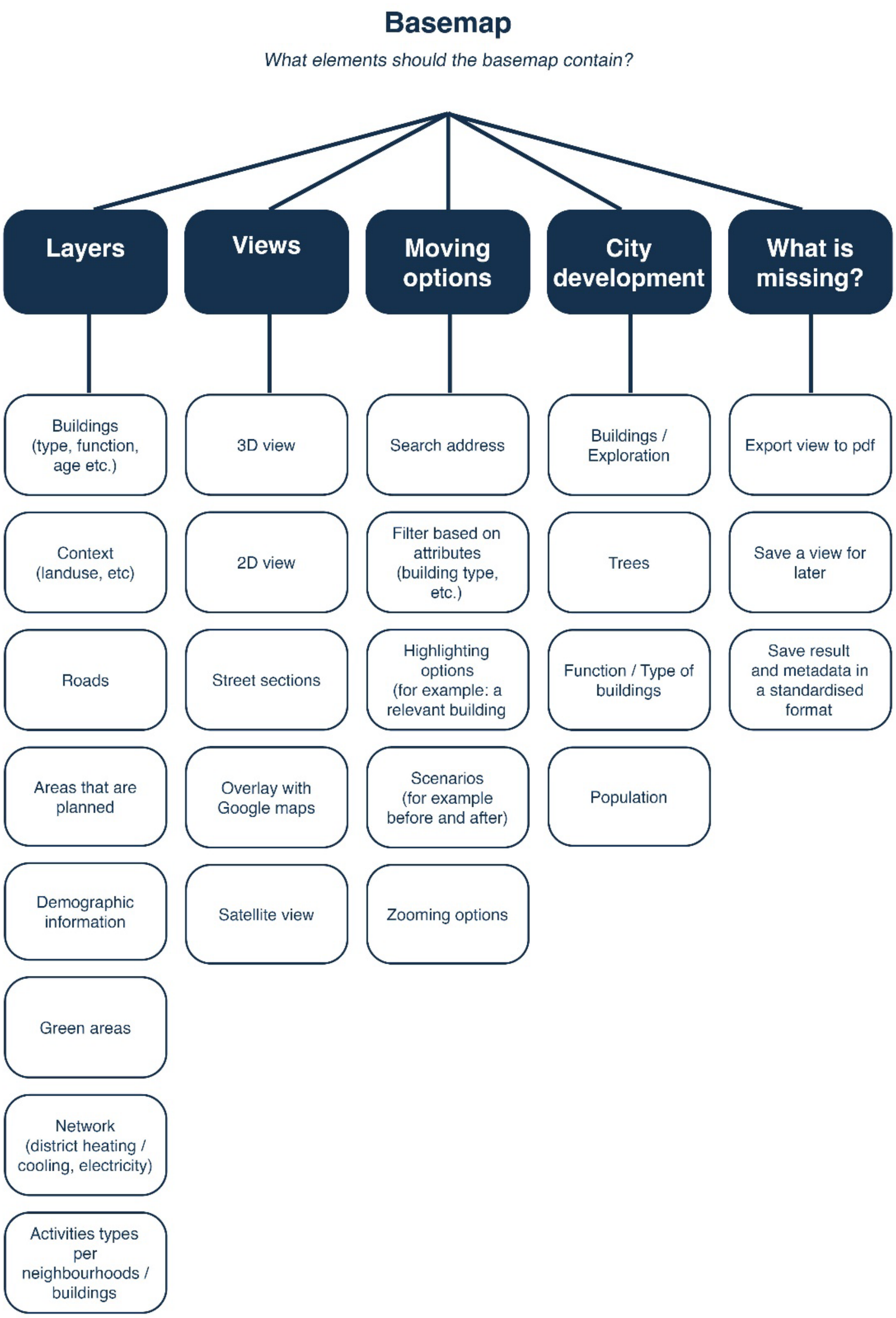
WS#	Date / location	Topic	Participants
1 S1	2021-11-18 Online via zoom Miro boards	Qualitative scenario development & GEP discussion	18 participants Local stakeholders from the energy utility company, municipality, consultancy, and researchers
2 VD1	Online via zoom Miro boards	Viewer development	Researchers
3 VD2	2022-09-16 Chalmers	Viewer development	Reference group
4 VD3	2023-02-03 Online via zoom	Viewer development	Workshop property owners (property owners also represented in reference group)
5 VD4	2023-03-17 Universeum	Viewer development	Energy Supplier
6 VD5	2023-05-05 Environmental administration Gothenburg	Viewer development	Municipal city planning administration and environmental administration
7 T1	2023-06-15 Visual Arena	Testing of DTE Viewer	22 participants Stakeholders
8 T2	2023-11-18/19 Chalmers	Testing of DTE Viewer	~70 master students Experts in architecture and urban planning

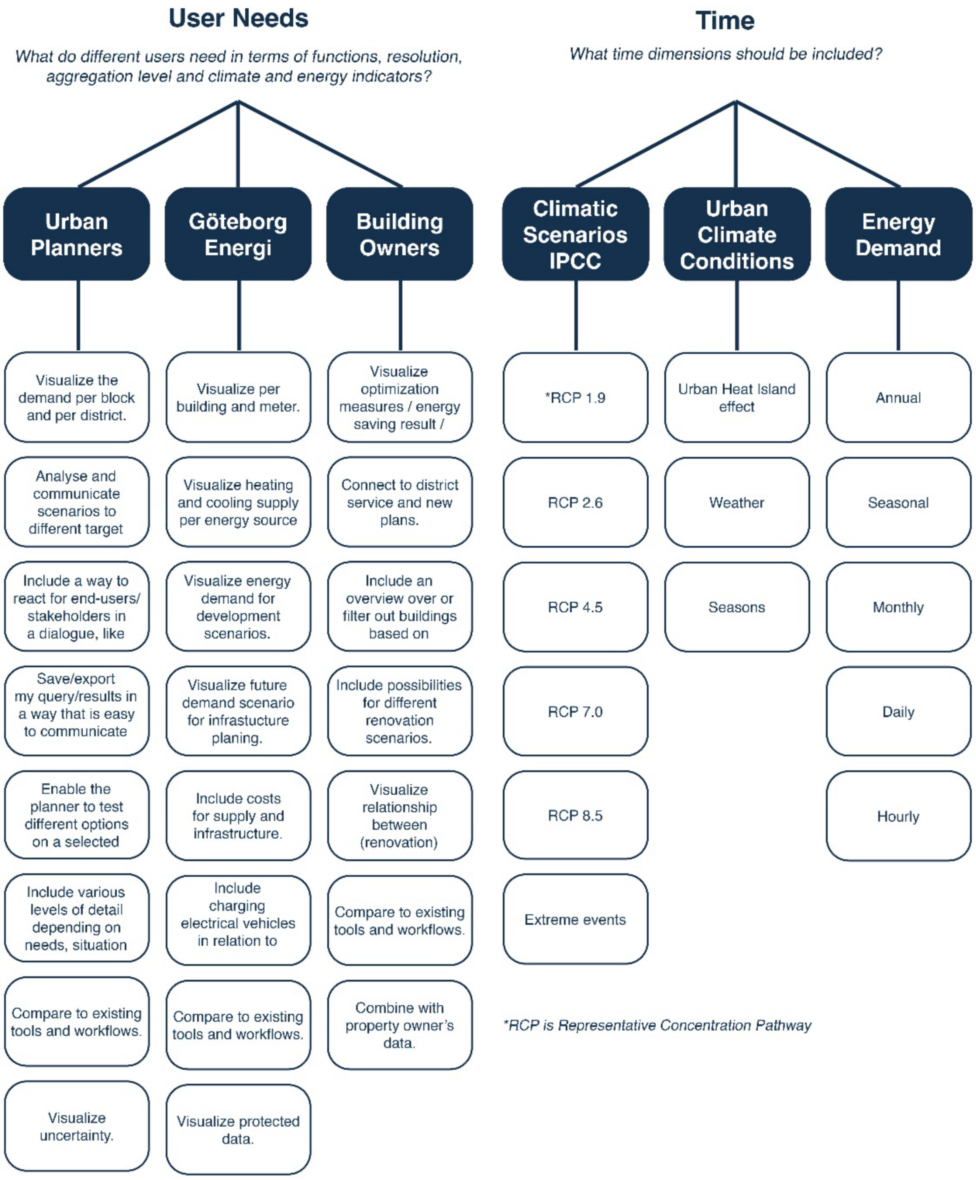
S = Scenario VD = Viewer Development, T = testing

The viewer development and testing workshops are described in chapter 7.

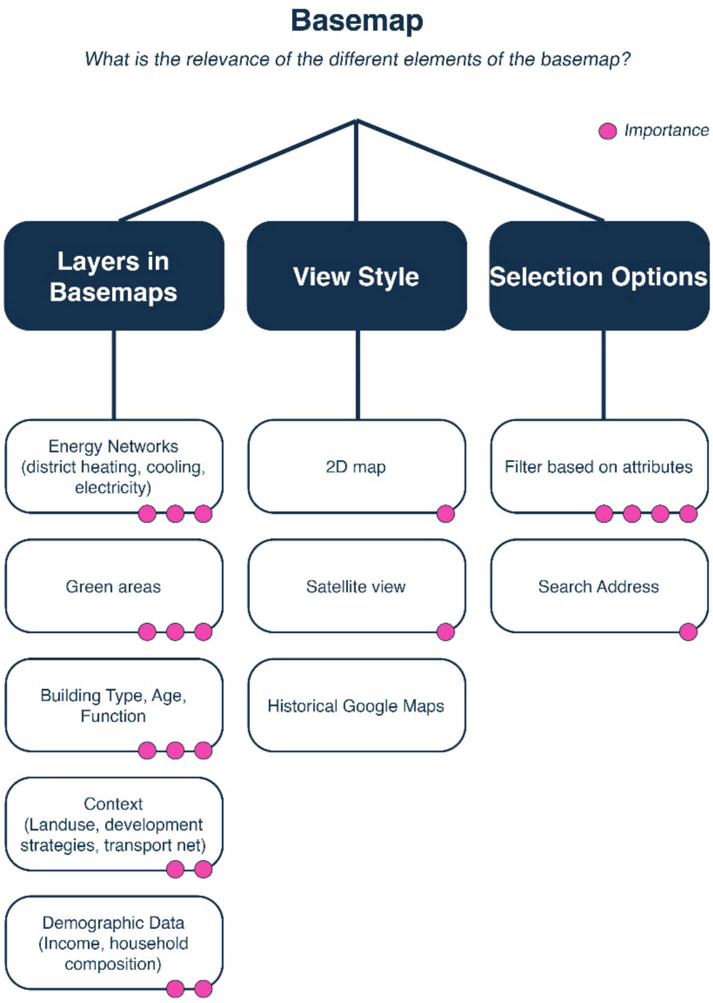
Appendix 4 – Viewer development (VD) workshops: Summary of Miro boards

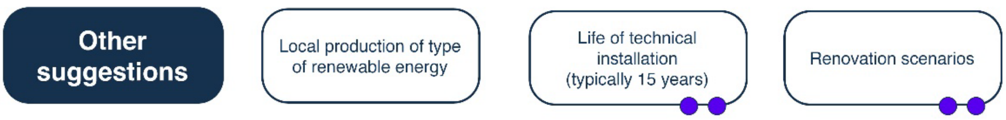
VD Workshop 1 with Researchers

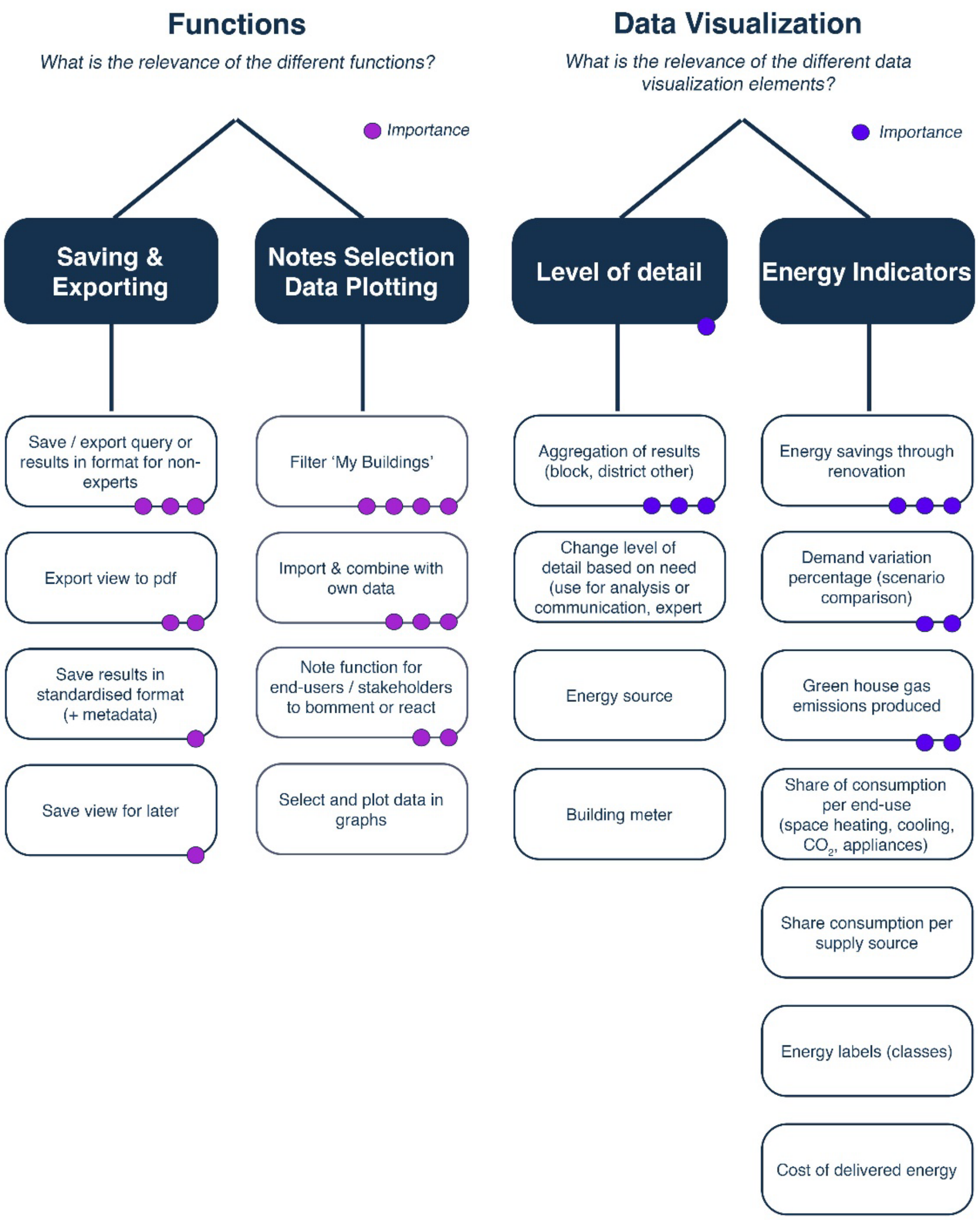



User Needs
What do different users need in terms of functions, resolution, aggregation level and climate and energy indicators?
Time
What time dimensions should be included?
Urban Planners
Göteborg Energi
Building Owners
Climatic Scenarios IPCC
Urban Climate Conditions
Energy Demand
Visualize the demand per block and per district.
Analyse and communicate scenarios to different target
Include a way to react for end-users/ stakeholders in a dialogue, like
Save/export my query/results in a way that is easy to communicate
Enable the planner to test different options on a selected
Include various levels of detail depending on needs, situation
Compare to existing tools and workflows.
Visualize uncertainty.
Visualize per building and meter.
Visualize heating and cooling supply per energy source
Visualize energy demand for development scenarios.
Visualize future demand scenario for infrastucture planing.
Include costs for supply and infrastructure.
Include charging electrical vehicles in relation to
Compare to existing tools and workflows.
Visualize protected data.
Visualize optimization measures / energy saving result /
Connect to district service and new plans.
Include an overview over or filter out buildings based on
Include possibilities for different renovation scenarios.
Visualize relationship between (renovation)
Compare to existing tools and workflows.
Combine with property owner's data.
*RCP 1.9
RCP 2.6
RCP 4.5
RCP 7.0
RCP 8.5
Extreme events
Urban Heat Island effect
Weather
Seasons
Annual
Seasonal
Monthly
Daily
Hourly
*RCP is Representative Concentration Pathway

VD Workshop 2 with Reference group

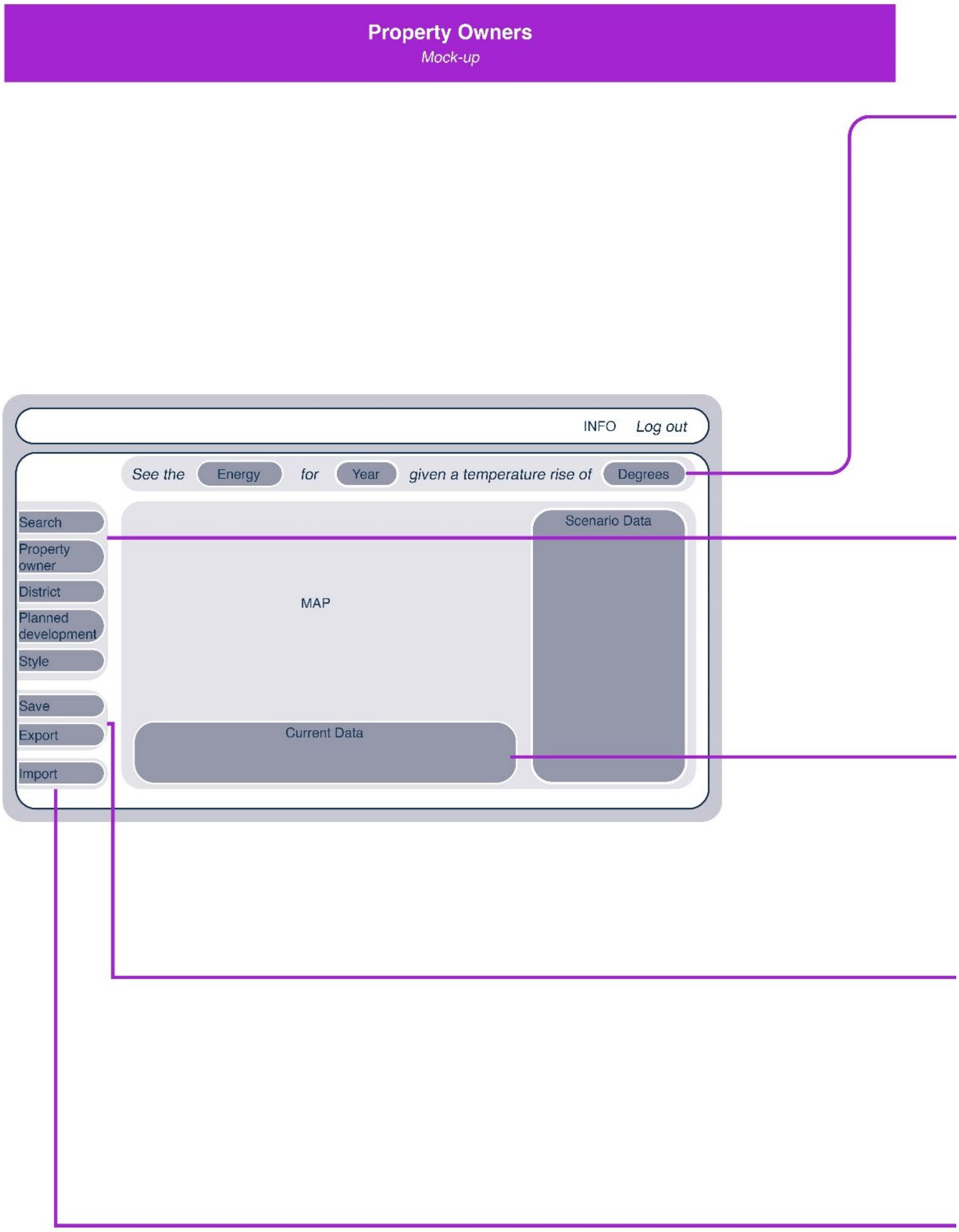






Functions
What is the relevance of the different functions?
Importance
Saving & Exporting
Notes Selection Data Plotting
Save / export query or results in format for non-experts
Export view to pdf
Save results in standardised format (+ metadata)
Save view for later
Filter 'My Buildings'
Import & combine with own data
Note function for end-users / stakeholders to bomment or react
Select and plot data in graphs
Data Visualization
What is the relevance of the different data visualization elements?
Importance
Level of detail
Energy Indicators
Aggregation of results (block, district other)
Change level of detail based on need (use for analysis or communication, expert
Energy source
Building meter
Energy savings through renovation
Demand variation percentage (scenario comparison)
Green house gas emissions produced
Share of consumption per end-use (space heating, cooling, CO_2, appliances)
Share consumption per supply source
Energy labels (classes)
Cost of delivered energy

VD Workshop 3 with Property owners



LEARN what you can do and how

About

What type of introduction would you need for the platform?

- Explain what kind of order you should set up the system in
- Explain what you can do with the platform

SET-UP your scenario

Scenarios

Which energy scenario options would be relevant for you? And are there other types of scenarios that could be useful to you?

- City demand according to green coverage
- Cooling demand
- Shading
- Risk and vulnerability level to climate change
- scenarios for 2030 (to align with GEP goals)
- Climate adaptation plan
- Solar radiation
- Solar panels
- Measures to implement for improving energy efficiency

CUSTOMIZE your view and seen data

View

Are the 4 limitation options (adress, owner, district, section) relevant, clear and useful for you?

- By heating source
- By building year
- By building type
- By energy performance
- By existing buildings with solar panels and potentials for application

Which timespans would be interesting for you to see under 'planned developments'?

- Include historical maps / visualize changes
- 10 year timespan

Are there any layers that you feel are missing?

- Transportation
- Heat sources
- Solar panels
- Colors on which ones are above and below threshold values

Data

What categories of data would you like to see aggregated? Which units would you want to see under each aggregation? How would you like the result to be visualized? 'text'or 'diagram'

- Add threshold values of performance: Defined ranges at the national level

USE the results

Saving & Exporting

Which saving and exporting formats would be useful to you?

- Save all your settings
- Save filtering options
- Excel format for exporting

COLLABORATE with your own data

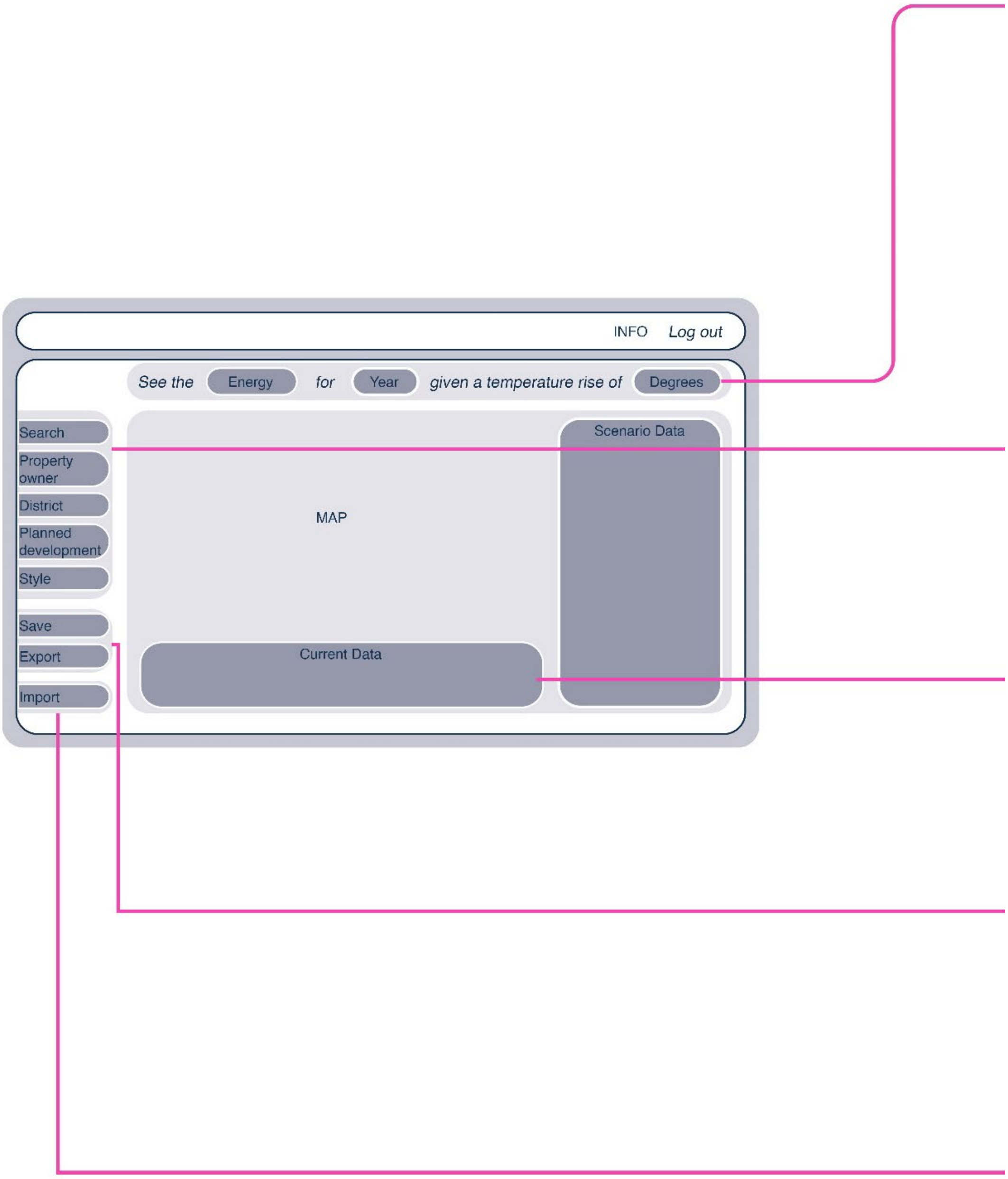
Importing

Would this be useful? What data formats and kind of data would you like to import?

- Most data is public - could potentially be used as a reporting tool / facilitate connection with public
- Upload data to correct errors or missing data
- Some data should only be seen if you are in the same company as the owners of the building
- Mark the data with the name of the contributor

VD Workshop 4 with Energy Supplier

Göteborg Energi
Mock-up



SET-UP your scenario

Scenarios

Which energy scenario options would be relevant for you? And are there other types of scenarios that could be useful to you?

- Development of district cooling
- Flexibility, location and potential of resources in the electricity net.
- Energy price compared to other things (like saleries)
- Development of charging
- Available flexibility kW/kWk per hour, for example
- Probability for different building projects (a lot, few, recession).
- Development of solar PV
- Buildings connected to district cooling and heating network
- Production through renewables on site
- Amount transformation office to appartment buildings
- Peak demand (kW) given the presumptions: then year winter, -x degrees, normal year, etc.
- City development projects
- Effectivise: percentage per type of buildings
- Per owner of the buildings
- All scenarios between the different stakeholders need to be synced (like: densification)

CUSTOMIZE your view and seen data

View

Are the 4 limitation options (adress, owner, district, section) relevant, clear and useful for you?

- Free drawing of a district / group
- Building type: single family, apartment block, tower, etc
- Building function

Which timespans would be interesting for you to see under 'planned developments'?

- 2030, 2045 More future time periods: 5, 10 years
- 2025, 2030, 2035, 2040, 2045, 2050
- Select parts of the day/ night. Only look for the 8 - 13 for example

Are there any layers that you feel are missing?

- Probability of being built by scenario year (2030, 2050)
- the planning process
- heating source
- Quality measurements Bios and Brom (?)

Data

What categories of data would you like to see aggregated?

- No other background map needed
- Own drawn district that allows to run scenarios. E.g. changes in energy demand in case of efficiency increase

How would you like the result to be visualized? 'text'or 'diagram'

- Aggregate building properties
- Electricity consumption profile in terms of volatility (lack of same storage) in a connection point
- Total needs for the area plus a profile
- Duration diagram
- Good export function is crucial

Which units would you want to see under each aggregation?

- Being able to extract data easily
- Background map: darkness conditions
- Temperature demands in a second page or possibility to extract data to use in other tool

USE the results

Saving & Exporting

Which saving and exporting formats would be useful to you?

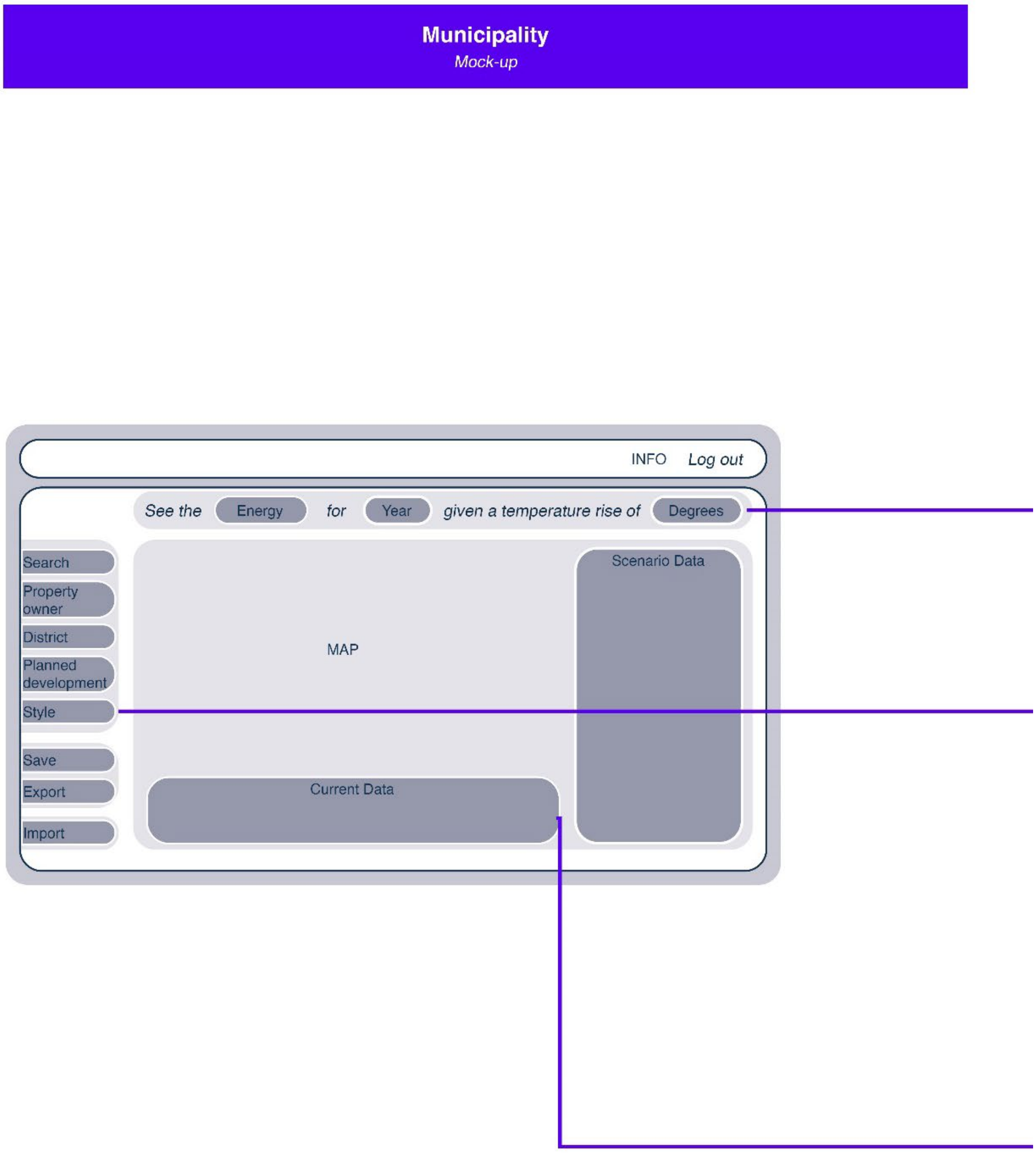
- Image file + data sheet + diagram
- Property level
- Export as transparant picture (georeferenced)
- Good to be able to export but better to own a Digital Twin fetching latest data by itself
- Import and export as csv (Excel)

COLLABORATE with your own data

Importing

Would this be useful? What data formats and kind of data would you like to import?

- The fundamental information object available in the solution
- Think about intellectual property
- Not a forecast
- Properties in the scenario (sources)
- Think about data ownership
- Type of data Comparable with own statistics
- Show the future to create interest


Municipality
Mock-up
INFO
Log out
See the
Energy
for
Year
given a temperature rise of
Degrees
Search
Property owner
District
Planned development
Style
Save
Export
Import
MAP
Scenario Data
Current Data

SET-UP your scenario

Scenarios

Which energy scenario options would be relevant for you? And are there other types of scenarios that could be useful to you?

- Levels of priority for renovation
- Energy plans measures by 2030 and levels of implementation
- Energy saving due to measures implementation on building types (public or residential buildings)

- Energy demand and carbon budget calculated per person
- Cost-efficiency and investment on renovation measures

- Tactic plan for future development including potential energy saving due to morphological, materials and color choises for new buildings

- Change of energy demand due to microclimate variations in the city (distribution and magnitude of Urban Heat Island effect and wind flows)

CUSTOMIZE your view and seen data

View

Are the 4 limitation options (adress, owner, district, section) relevant, clear and useful for you?

- Building type: residential / no residential
- Building type: public / private
- Building type: historical buildings
- Selection of owned building(s)
- Classes per building age
- EPC per buildings

Which timespans would be interesting for you to see under 'planned developments'?

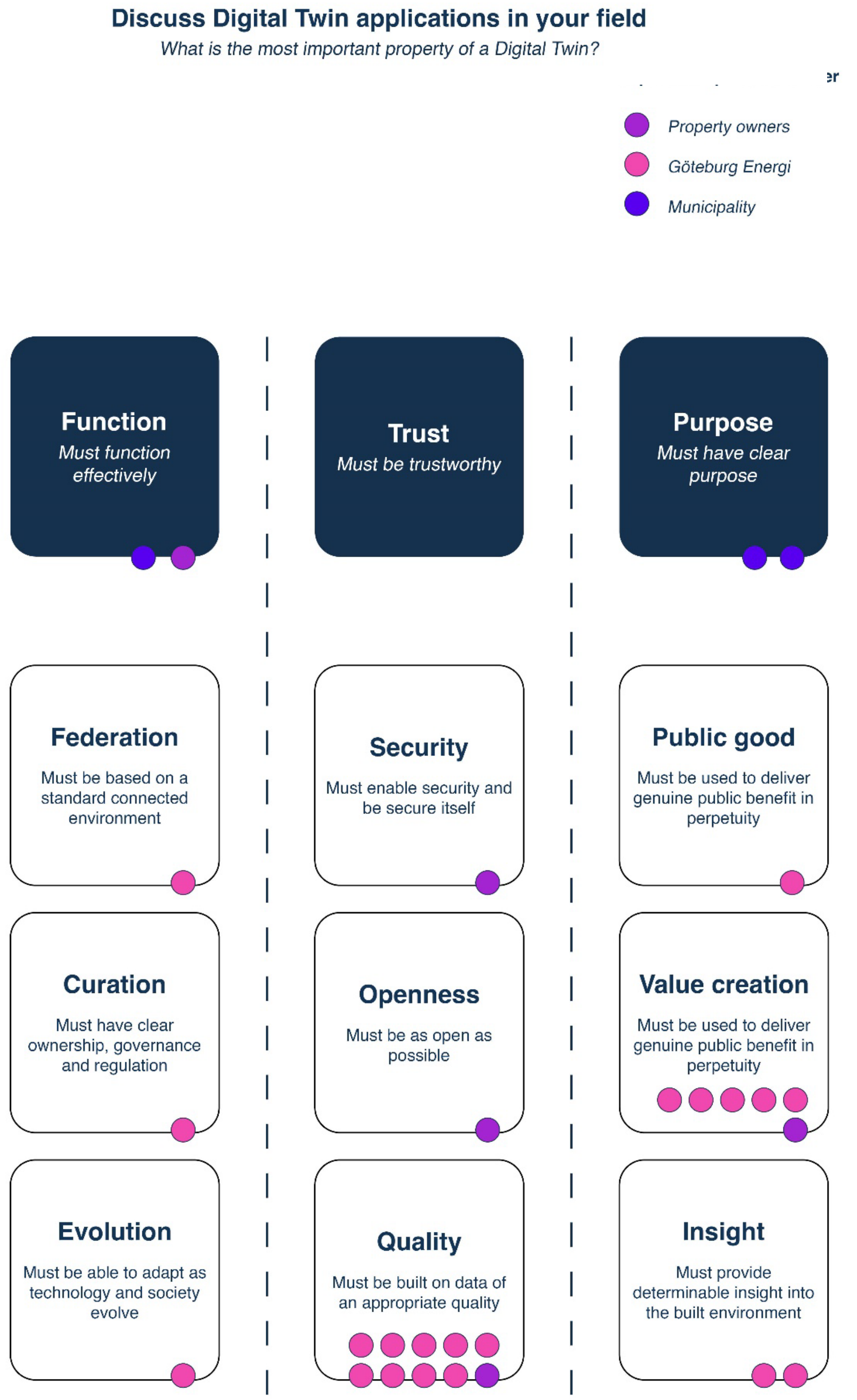
- 2030 / 2045
- every 5 years

Are there any layers that you feel are missing?

- population data
- orthophoto
- historical maps

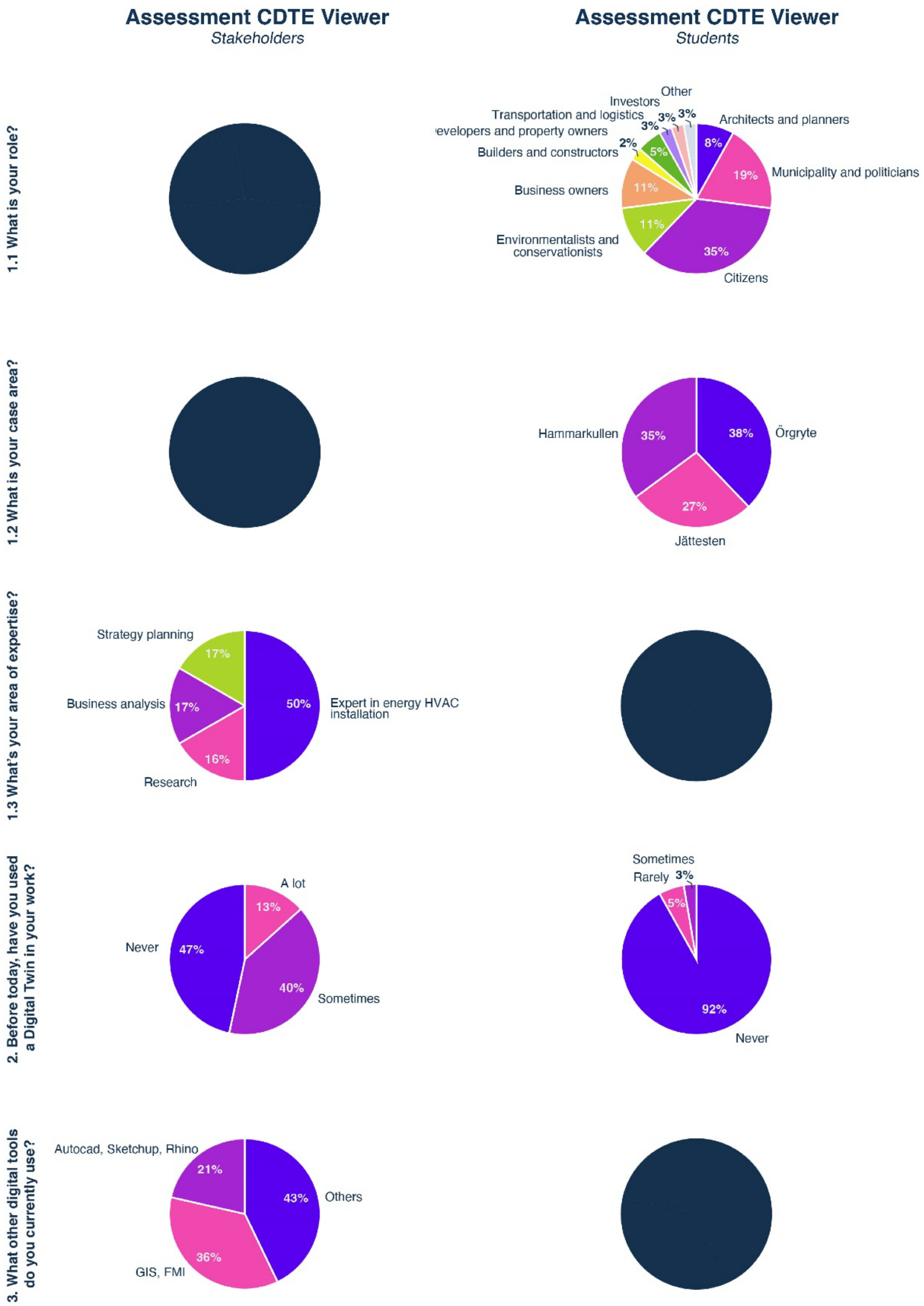
Data

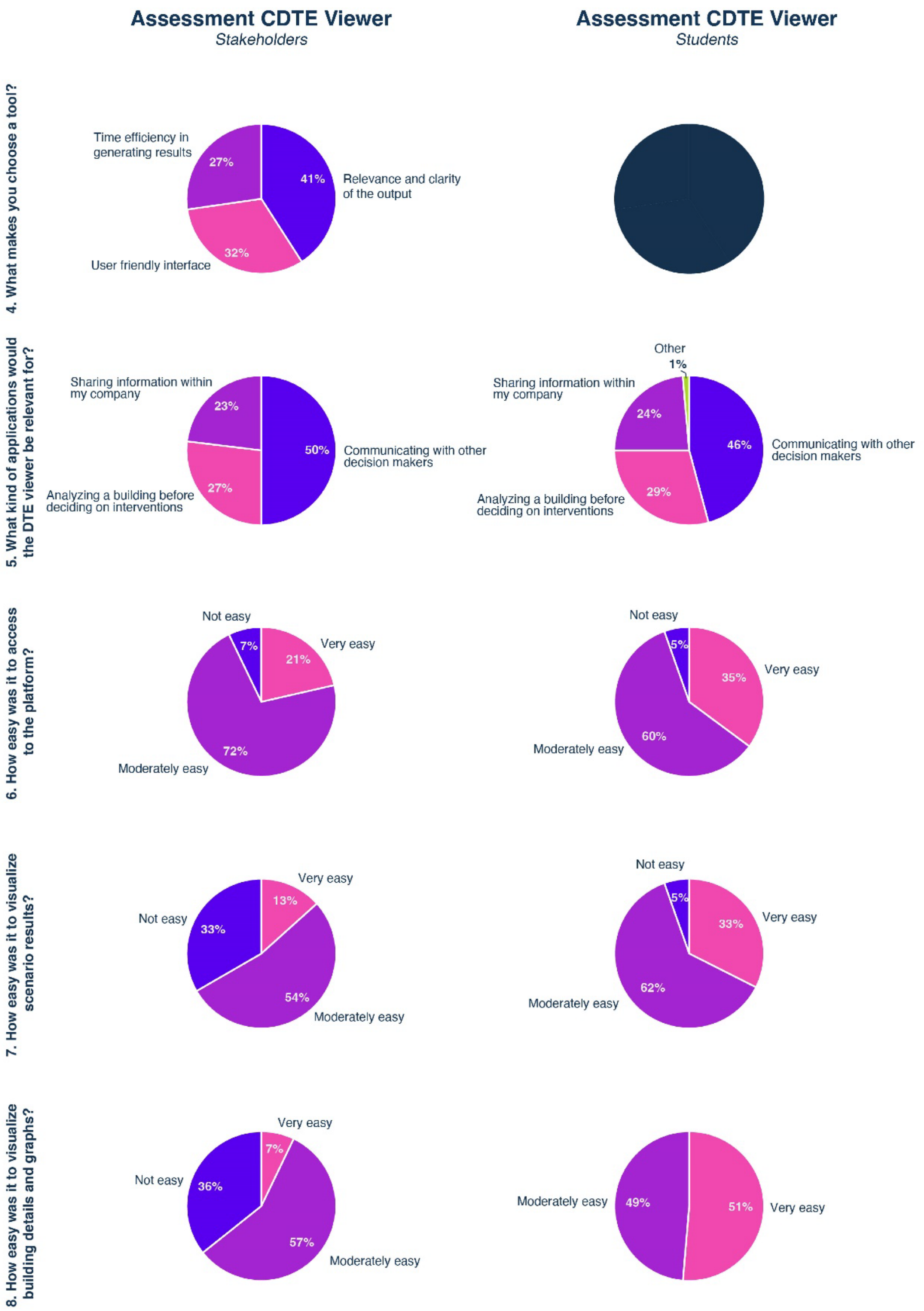
What categories of data would you like to see aggregated?
Which units would you want to see under each aggregation?
How would you like the result to be visualized? 'text'or 'diagram'



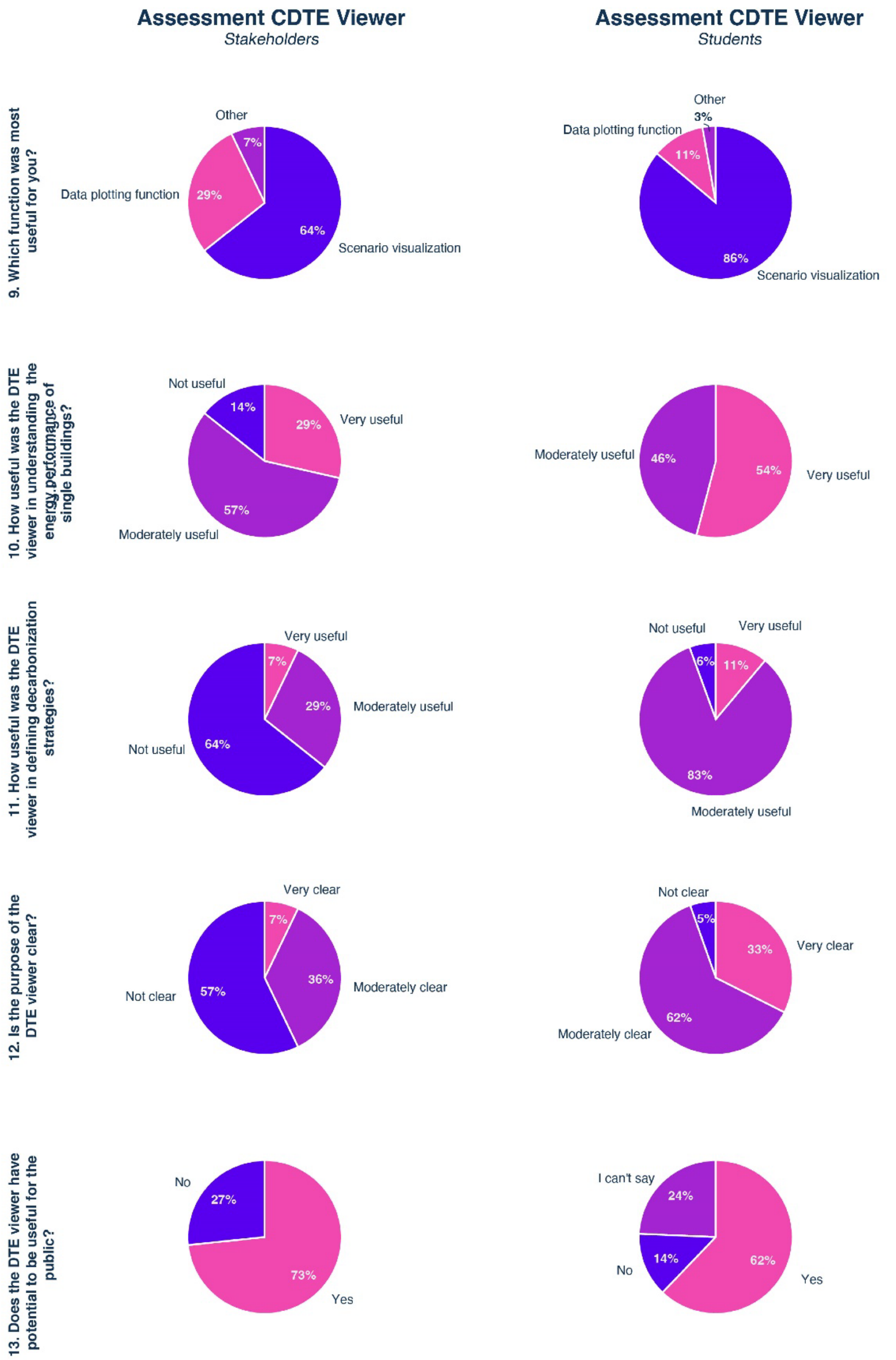
Matrix based on the Gemini framework (Bolton et al. 2018) and its nine principles developed to enable DT's better use, operation and maintenance.

Appendix 5 – Results from viewer assessment

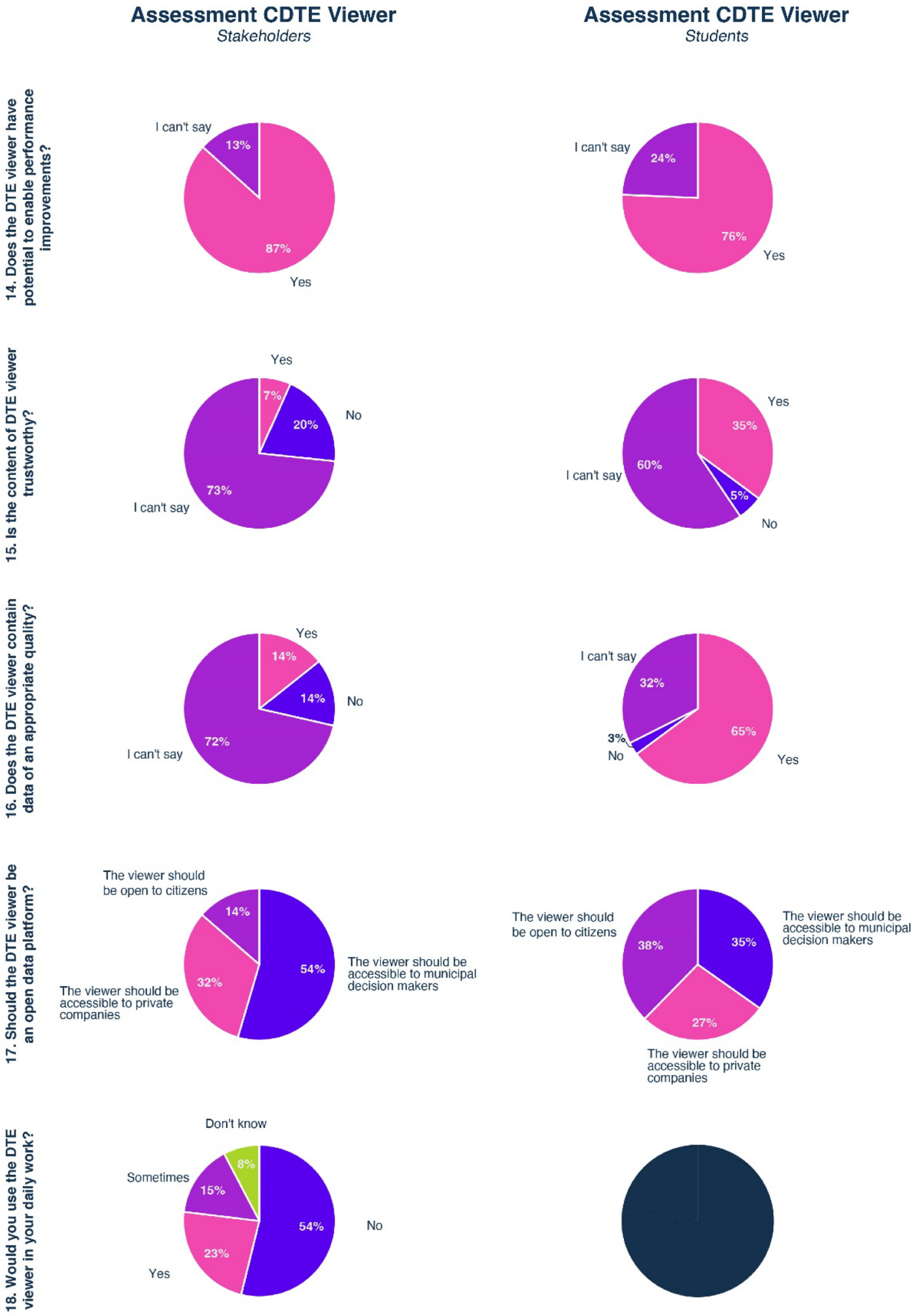




Assessment CDTE Viewer
Stakeholders
Assessment CDTE Viewer
Students
4. What makes you choose a tool?
Time efficiency in generating results
27%
41%
Relevance and clarity of the output
32%
User friendly interface
5. What kind of applications would the DTE viewer be relevant for?
Sharing information within my company
23%
50%
Communicating with other decision makers
27%
Analyzing a building before deciding on interventions
Other
1%
Sharing information within my company
24%
46%
Communicating with other decision makers
29%
Analyzing a building before deciding on interventions
6. How easy was it to access to the platform?
Not easy
7%
21%
Very easy
72%
Moderately easy
Not easy
5%
35%
Very easy
60%
Moderately easy
7. How easy was it to visualize scenario results?
Very easy
13%
Not easy
33%
54%
Moderately easy
Not easy
5%
33%
Very easy
62%
Moderately easy
8. How easy was it to visualize building details and graphs?
Very easy
7%
Not easy
36%
57%
Moderately easy
Moderately easy
49%
51%
Very easy



Assessment CDTE Viewer
Stakeholders
Assessment CDTE Viewer
Students
9. Which function was most useful for you?
Other
7%
Data plotting function
29%
64%
Scenario visualization
Other
3%
Data plotting function
11%
86%
Scenario visualization
10. How useful was the DTE viewer in understanding the energy performance of single buildings?
Not useful
14%
29%
Very useful
57%
Moderately useful
Moderately useful
46%
54%
Very useful
11. How useful was the DTE viewer in defining decarbonization strategies?
Very useful
7%
29%
Moderately useful
Not useful
64%
Not useful
Very useful
6%
11%
83%
Moderately useful
12. Is the purpose of the DTE viewer clear?
Very clear
7%
36%
Moderately clear
Not clear
57%
Not clear
5%
33%
Very clear
62%
Moderately clear
13. Does the DTE viewer have potential to be useful for the public?
No
27%
73%
Yes
I can't say
24%
No
14%
62%
Yes



Assessment CDTE Viewer
Stakeholders
Assessment CDTE Viewer
Students
14. Does the DTE viewer have potential to enable performance improvements?
I can't say
13%
87%
Yes
I can't say
24%
76%
Yes
15. Is the content of DTE viewer trustworthy?
Yes
7%
20%
No
73%
I can't say
Yes
35%
60%
I can't say
5%
No
16. Does the DTE viewer contain data of an appropriate quality?
Yes
14%
14%
No
72%
I can't say
I can't say
32%
3%
No
65%
Yes
17. Should the DTE viewer be an open data platform?
The viewer should be open to citizens
14%
54%
The viewer should be accessible to municipal decision makers
32%
The viewer should be accessible to private companies
The viewer should be open to citizens
38%
35%
The viewer should be accessible to municipal decision makers
27%
The viewer should be accessible to private companies
18. Would you use the DTE viewer in your daily work?
Don't know
8%
Sometimes
15%
54%
No
23%
Yes

Assessment CDTE Viewer

Stakeholders

19. What are the positive characteristics of the CDTE viewer ?

- Visualization of full city extent in 3D — 4
- Visualization and filtering of complex data with high level of detail — 4
- Flexible and good basis for discussions — 4
- Nice interface easy to use — 3
- Useful to highlight areas for inter-ventions — 2
- Other — 1

20. What are the negative characteristics of the CDTE viewer ?

- Difficult to understand how data is created and if can be trusted — 6
- Interface difficult to use and slow — 3
- Other — 3
- Purpose not clear — 1
- Need more data — 1
- Privacy — 1
- Slow — 1

21. For what purpose would you use the CDTE viewer in your daily work?

- Energy analysis and overview — 3
- Visualization — 2
- For strategic planning — 2

22. What other features or functions should be included to make the CDTE viewer more useful?

- Electricity and water demand, type of heating system, production, hourly demand and peak — 4
- More years of data — 2
- Data list and export function — 2
- More details about buildings / filter for type of buildings — 3
- Search function — 2
- Info about modeling and descripti-on of variables — 2

23. Who should be responsible for the maintenance of the CDTE viewer in the long term?

- City or public entity — 6
- Independent company — 3
- Expert in academia — 1
- Don't know — 1
- Property owners — 1

24. Any other feedback you would like to give?

- Important to know what's behind the calculation
- Good mix of people in the workshops
- Better to have multiple viewers for specific purposes rather than one viewer for many purposes

Assessment CDTE Viewer

Students

19. What are the positive characteristics of the CDTE viewer ?

- Nice interface easy to use — 9
- Useful information for renovations — 4
- Visualization of full city extent in 3D — 1
- Visualization and filtering of complex data with high level of detail — 3

20. What are the negative characteristics of the CDTE viewer ?

- Interface difficult to use — 14
- Slow — 5
- Purpose not clear — 3
- Need more data — 2

21. For what purpose would you use the CDTE viewer in your daily work?

22. What other features or functions should be included to make the CDTE viewer more useful?

- More data — 6
- More details about buildings / filter for type of buildings — 2
- Info about modeling and description of variables — 2
- Search function — 2
- Soluti-ons to decre-ase energy — 1
- Mobile plat-form — 1
- Real time change — 1

23. Who should be responsible for the maintenance of the CDTE viewer in the long term?

24. Any other feedback you would like to give?

- Data of ex how many windows would need to be changed for the building installation.
- It's very slow and the full map would not load. Also, the colors will freeze if you change too much.
- Design a easy manual for general use.