Digital twin for supporting decision-making and stakeholder collaboration in urban decarbonization processes. A participatory development in

Citation for the original published paper (version of record):
Maiullari, D., Nägeli, C., Rudena, A. et al (2024). Digital twin for supporting decision-making and stakeholder collaboration in urban
decarbonization processes. A participatory development in Gothenburg. Environment and Planning B: Urban Analytics and City Science. http://dx.doi.org/10.1177/23998083241286030

Special Issue: Digital Twins for Cities – Perspectives, Methods and Applications

Urban Analytics and City Science

EPB: Urban Analytics and City Science
2024, Vol. 0(0) 1–25

DOI: 10.1177/23998083241286030
journals.sagepub.com/home/epb
Sage

Digital twin for supporting decision-making and stakeholder collaboration in urban decarbonization processes. A participatory development in Gothenburg

Daniela Maiullari
Delft University of Technology, Netherlands

Claudio Nageli
Sinom, Sweden

Andreas Rudena
Paramountric, Sweden

Åsa Isacson and Giliam Dokter
Chalmers University of Technology, Sweden

Ilse Ellenbroek
AMS Institute, Netherlands

Holger Wallbaum and Liane Thuvander
Chalmers University of Technology, Sweden

Abstract

City Digital Twins have emerged as pivotal tools for representing and modelling urban systems. While existing literature emphasizes technological and framework development, limited attention has been given to the practical usability of digital twins in urban planning and decision-making processes. This paper addresses this gap by presenting a participatory approach for a city digital twin (CDTE) development, specifically tailored for supporting stakeholder communication and decision-making in the urban energy transition domain. The study, conducted in three phases, utilizes participatory methods, involving local stakeholders in the development process. The focus is on the Swedish city of Gothenburg, which is actively pursuing climate-neutral goals by 2030. The research

Corresponding author:
Daniela Maiullari, Delft University of Technology, Julianalaan 134, Delft 2628 BL, Netherlands.
Email: d.maiullari@tudelft.nl

Data Availability Statement included at the end of the article

integrates quantitative energy modelling and the creation of a web-based interface for the CDTE. The scenarios, grounded in local needs and challenges, explore the impacts of urban development models, climate warming and renovation measures on the building stock. The CDTE, developed and tested through workshops with diverse stakeholders, proves to be effective for the visualization and the discussion of various decarbonization scenarios. Key findings from users' assessments underscore the significance of clarity and readability in scenario content and user interface for fostering interactions among different administrative spheres. This research contributes to the broader discourse on leveraging City Digital Twins for informed decision-making in urban contexts, providing insights into the practical application of digital twins in addressing the complex challenges of urban energy transition.

Keywords
Digital twin, energy scenarios, building stock model, Gothenburg, decision support

Introduction

City Digital Twins (CDT) are increasingly used to represent, model, and simulate urban systems (Deng et al., 2021; Schrotter and Hurzeler, 2020). Existing literature extensively focuses on CDT technological and framework development (level of accuracy of digital models, data structure and standards), while a growing number of studies highlight the potential of using CDT in urban planning, management and decision-making processes (Weil et al., 2023), and the importance of socio-technical perspective on developing CDTs (Nochta et al., 2021). Applications in different domains have shown that CDT can offer strategic information when dealing with risk and environmental management, as well as economic, social, and environmental practices (Ketzler et al., 2020). Many scholars have indicated CDT potentials to coordinate public and private actions concerning management of the existing built environment or development and implementation of new urban strategies (e.g. Shahat et al., 2021). Research also indicates that CDTs can provide a collaborative environment, for example, facilitate the engagement of citizens in urban development processes and support the exchange of knowledge among stakeholders with different roles and expertise (Nochta et al., 2021; Youngjib and Jaeyoon, 2020). However, only a few studies have investigated the usability and use of CDT in urban planning and decision-making processes (Weil et al., 2023). According to Lehtola et al. (2022), addressing cities' needs implies making can 'be ensured only by safe and usable systems'.

Local governments and municipalities around the globe are exploring the possibility of developing and implementing CDTs to tackle environmental challenges (Weil et al., 2023). Many European cities are implementing decarbonization measures to fulfil European and national energy and climate goals in general and for buildings in particular. The *European renovation wave* initiative (European Commission 2020) asks to double the renovation rate by 2030 and the *Fit for 55* initiative (European Council 2021) targets reduction of net GHG emissions by at least 55% by 2030. Existing buildings are one of the important urban structures to deal with in urban energy transition with considerable energy-saving potentials intertwined with energy supply and mobility structures. When it comes to the energy domain, there is comprehensive knowledge about energy systems and their climate impact; however, the knowledge is often scattered among different companies and municipal administration, and the knowledge exchange within organizations is limited. Thus, knowledge is not efficiently implemented. Alongside the scattered knowledge, we also have competing business logics with different timelines for planning and transformation of energy systems 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; while the development of robust urban strategies requires analyses and instruments to support cohesive decision-making.

As one of the 100 European cities to become climate-neutral by 2030, the Swedish city of Gothenburg is now increasingly addressing the challenge related to decarbonization. The city has identified a set of measures to be implemented between 2022 and 2030 in an ambitious energy plan (City of Gothenburg 2022) and Environment and Climate Programmes (City of Gothenburg, 2021). However, as a study by Maiullari et al. (2022b) reveals, key aspects for further development of the energy plan are, among others, better coordination between energy and urban planning, improved communication between stakeholders and tools to support decision-making processes for decarbonization. In order to achieve a zero-climate footprint, the city aims to reduce the consumption-based emissions by at least 7.6% annually by 2030 (City of Gothenburg, 2021). This means an overall reduction of greenhouse gas emissions per inhabitant and year from 4.2 tons in 2018 to 1.1 tons in 2030. For example, for residential buildings and facilities, the target for primary energy consumption is a reduction per inhabitant from 16 MWh in 2018 to 12 MWh in 2030 and for residential buildings from 117 kWh/m2*year in 2017 to 95 kWh/m2*year in 2030. Thus, drastic reductions are needed. The city is also developing a Virtual Gothenburg, a CDT to assess scenarios of change in the close and long future concerning city development and the impacts on social, environmental and climate domains (Jeansson, 2019). So far, the Virtual Gothenburg does not include the urban energy and climate impact perspective.

Addressing this implementation gap, this paper presents a participatory approach for the Gothenburg CDT development to support stakeholder communication, collaboration, and decision-making processes in the urban energy transition domain. The study reports and discusses the development process of a CDT to support municipal pathways towards decarbonization from the needs analysis over selection and implementation of energy demand scenarios to the development and test of the CDT user interface. Specifically, the research aims to assess the application of a digital twin platform by engaging users (decision-makers) in the development process and reflects on the interactivity, usability, and openness of a CDT.

First, the paper provides background description and presents existing digital twin research and efforts related to cities, development processes, and decision-making in the energy domain. Second, applied methodology for the development of a digital twin of the case city is introduced. Third, the results related to the development process, scenario results, and evaluation of the digital twin are presented. Finally, the research and its implications are discussed indicating directions for future work.

Background

The concept of a City Digital Twin (CDT), simplified a digital representation of a physical system (Ketzler et al., 2020) and the connection between the two (Grieves, 2023), is a rapidly evolving area of research. CDTs connect data, analytics, and visualizations (Lohman et al., 2023) and allow for analysis, prediction, and optimization, creating better and more-informed decisions (Adade and De Vries, 2023). CDTs are increasingly being developed in many cities around the world (Ketzler et al., 2020) and are applied to a wide range of use cases for management and development of cities, including transport and traffic, energy, waste, water, building, climate action, and disaster (Weil et al., 2023).

While some municipalities chose to partner with large software vendors to implement digital twin solutions, others have been building their own based on decades of experience in the GIS domain. A more recent development is the notion of federated digital twins as opposed to a monolithic centralised system. The Centre of Digital Built Britain introduced an 'ecosystem of connected digital twins' (Gemini Council and Lamb, 2022) and Ricci et al. (2022) highlight open, distributed, interoperable systems by introducing the perspective of a web of digital twins. An example of a modular framework for an energy management tool for control and coordination of interconnected energy assets in a smart city or district is presented by O'Dwyer et al. (2020). Overall, research suggests that CDTs have the potential to transform urban planning and management of cities, but further development and integration of various data sources are needed as well as cooperative systems of interconnected digital twins. As stated by Weil et al. (2023), there is currently a lack of proven implementation of CDT.

CDT in the energy domain

Decarbonization strategies connected to the energy performance of buildings and buildings stocks are recurring applications in CDTs. The focus varies and includes, 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). Research studies on a city level are often descriptive, understanding existing buildings' energy performance and use of energy sources, for comparisons and identification of improvement potentials (e.g. Ruohomäki et al., 2018). Other studies focus on selected parts of the energy system such implementation potentials of renewable energy or analyses of electric grids connected (e.g. Leopold et al., 2023).

Similarly, on the district level, CDT research addresses buildings electricity consumption based on smart meter data (Francisco et al., 2020) but also decarbonization pathways studies explored through scenarios and energy modelling for limited stocks of buildings (Pierce et al., 2024). Few CDT developments integrate building stocks on the city level including all types of buildings. Srinivasan et al. (2020) use Urban Energy Modeling methodology to study the impact on cities residential building owing to climate change with focus on demand response and data, thus not all buildings are included. O'Dwyer et al. (2020) combine retrofit and heating system electrification in part of the social housing stock and interventions in the transport sector through increased EV charger installation as well as the introduction of renewable generation capacity in the form of PV panels. Maiullari et al. (2023) present a first prototype of a CDT to model the effect of temperature change scenarios on building energy demand to promote the understanding of the interrelation between the spatial, energy and climate change domains related to building stocks.

CDTs in the energy domain are also increasingly explored at the district levels to support energy communities and positive energy districts (PEDs). By 2025, the European Union aims to have supported the design, deployment and replication of 100 PEDs through its Strategic Energy Technology (SET) Plan. According to JPI Urban Europe/SET Plan Action 3.2 (2020), a PED is 'an urban neighbourhood with annual net zero energy import and net zero CO_2 emissions working towards a surplus production of renewable energy, integrated in an urban and regional energy system'. Here, CDT will play a key role as it is currently demonstrated in several applications around Europe and beyond (Bâra and Oprea, 2024; Coors and Padsala, 2024; Hedman et al., 2021; Malakhatka et al., 2024).

Collaboration, participatory approaches, and decision-making

Many CDTs are developed with the purpose of visualizing or analysing data to support urban planning decisions and the ambition to improve collaboration between stakeholders or citizen participation in urban planning. So far, technical challenges related to CDTs has been given more attention than to the socio-technical perspective (Weil et al., 2023) but scholars increasingly deal with the socio-technical dimension. Nochta et al. (2021) consider the development of CDTs as a socio-technical process driven by a need for a more strategic, policy-outcome orientation and they point at the importance of interdisciplinary insights and participative processes in conceptualizing what digital twins of cities could and should represent, and how. Thus, the development process should involve potential users, those planning and managing cities and those living and working in them.

Several studies report a stated potential of CDTs, for citizen engagement and feedback in urban planning and management, to monitor and predict the dynamics of the urban system, coordinate and communicate with stakeholders, and test urban planning strategies (Adade and De Vries, 2023; Gil, 2020; Hämäläinen, 2021; Ketzler et al., 2020; Shahat et al., 2021; White et al., 2021). However, the stated potentials find proof in very limited studies and scholars are increasingly emphasizing a lack of evidence that CDTs really foster collaboration (Weil et al., 2023). An example of a digital twin for decision-making is CDT developed for the city Herrenberg in Germany (Dembski et al., 2020) for participatory processes and to engage citizens in design. A CDT of the Docklands area in Dublin, Ireland has been tested for urban planning of skylines and green space allowing users to interact and report feedback on planned changes (White et al., 2021). Nochta et al. (2021) applied a participatory process for the developing a CDT prototype for the Cambridge city region, involving a variety of prospective users. This study aims to contribute along with these mentioned studies to further explore the implementation and use of CDT in the urban energy domain, reporting the results of the testing and evaluation by users involved in energy-related decision-making.

Methodology

This study is based on the participatory development of a CDT for urban energy transition and implementation of decarbonization strategies with a focus on building stocks and front-end development, that is, the interface of an online viewer hereafter called City Digital Twin Energy (CDTE) Viewer. The research has been conducted in three phases including scenario modelling, development of an online viewer through workshops, and user tests for viewer evaluation.

Critical scenario selection and modelling

The first phase focused on developing the content of the CDTE Viewer. Qualitative scenarios were developed by combining literature studies and co-creation activities followed by a selection of the most relevant scenarios translated into quantitative scenarios through modelling. The qualitative scenarios were elaborated through an interviewed-based review of Gothenburg's energy plan (Maiullari et al., 2022a), and workshops carried out with invited local stakeholders, representing energy supplier(s), municipal administrations (city planners, environmental department), and researchers (Maiullari et al., 2022b). Participants were asked to share their reflections on the local-specific challenges for decarbonization and to formulate sets of possible visions founded on potential measures and external drivers of change.

Three sets of scenarios were identified as critical for creating robust decarbonization strategies and were further developed and quantified in the CDTE (Table 1). The scenarios focus on the understanding of the energy demand impacts of i) the future city development model, ii) climate warming, and iii) the implementation of energy efficiency measures on existing buildings. The scenarios were modelled through the use and further development of a Gothenburg Building Stock Model (BSM) (Nägeli et al., 2018, 2019; Österbring et al., 2019) based on the assumptions described in Table 1.

Table 1. Scenarios and related assumptions implemented in the Gothenburg digital twin.

Scenario	Description	Assumptions
1. City development scenarios		
1.1 Current city	This scenario represents the city as built in 2020	Building characteristics are retrieved from multiple sources
1.2 Future city	This scenario describes the city development as reported in the Gothenburg comprehensive plan	Building usage of new buildings is assigned based on size: 1000 m^2 floor area and less than 5 stories: Retail building. Larger than 60 m height: 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[a] 2.6 (IPCC[b] report)	
2.3 1.5°C Warming	Scenario representing the future climate based on the RCP[a] 4.5 (IPCC[b] report)	
2.4 2°C Warming	Scenario representing the future climate based on the RCP[a] 8.5 (IPCC[b] report)	
3. Renovation scenarios		
3.1 Reference	Reference scenario describing the current state of the building stock	
3.2 Climate shell (façade and roof)	Focus on envelope components: roof, wall and windows aimed at reducing heating demand	All buildings built before 2010 are renovated: - Walls: +200 mm insulation - Roof: +300 mm insulation - Windows: U-value 0.8 W/m^2K
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	

[a]RCP: Representative Concentration Pathways.
[b]IPCC Sixth assessment report (IPCC, 2021).

The BSM uses a bottom-up approach to estimate the energy demand of each building, considering various energy services and greenhouse gas emissions. Based on a hierarchical structure, the energy demand is calculated according to different system boundaries (primary energy, useful energy, final energy, delivered final energy, and greenhouse gas (GHG) emissions) and the calculated energy demand and GHG emissions are differentiated for different energy services (i.e. space heating, hot water, ventilation, appliances, lighting and auxiliary building services, e.g. pumps, etc.). The useful energy demand for space heating is based on the simple hourly method according to the norm ISO EN 52,016-1 (ISO, 2017).

The 3D city model for Gothenburg's building stock that functioned as an input to the BSM was created by integrating and cleaning data from various public sources, including the Swedish property registry, LiDar data, and energy performance certificates (see Table 2). Key building characteristics like footprint, construction year, and function were extracted, with building heights estimated using LiDar data and the 3dfier tool. Energy demand inputs were derived from the energy performance certificate database Gripen, supplemented with data from the company registry for non-residential buildings lacking certificates. This generated the initial state of the CDTE and was the basis for modelling the baseline scenario for each scenario group (scenario 1.1, 2.1 and 3.1 in Table 1). In order to assess the future development scenario (scenario 1.2) the CDTE was modified by adding and removing buildings based on the city development plan which outlines buildings to be added until 2050 including their size and location. Data regarding the future city development were retrieved from the city urban planning department that shared spatial datasets indicating building footprint and height for the new development Table 2.

To model the effect of different climate scenarios, the climate data used for the energy modelling was adjusted based on the Representative Concentration Pathways (RCP) trajectories, established in the IPCC report (IPCC, 2021), which were translated into temperature changes using the Meteonorm Weather Generator. For the modelling of the renovation scenarios, the initial state of each building in the stock was modified based on renovation scenarios as outlined in Table 1. This included adjusting the U-values of the building envelope components, replacing heating and ventilation technologies as well as improving the efficiency of existing systems (heating, ventilation, and cooling), as well as adding solar cells on roofs where possible.

CDTE viewer development workshops

In the second phase, the User Interface (UI) of the CDTE Viewer was iteratively developed through multiple workshops with researchers and stakeholders involved in urban decision-making processes: city planners, energy providers and municipal property owners (Table 3).

Requirements for development of the visual communication platform, the CDTE viewer, were easy to use, facilitate multi-actor decision-making processes, and provide relevant information for decarbonization process for the targeted stakeholders. This should be enabled through well-designed visualizations, data coordination and exchange, and linking of the BSM to scenario simulations.

The 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 visualization 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 organized around a mock-up of the viewer and a first visualization 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.

Table 2. Input data for the CDTE.

Nr	Dataset	Description	Attributes	Source
1	Property registry (fastighetsregister) 2020	Official records on individual buildings and properties as well as linked addresses	Building attributes include construction year, building type, floor area, linked addresses, coordinates properties attributes include property type, taxation purpose, owner	Lantmäteriet (2020b), Lantmäteriet (2020)
2	Property map (fastighetskarta) 2020	Official GIS-data of building footprints and property boundaries	2D-building footprints and property boundaries	Lantmäteriet (2020a)
3	LiDar data (Laserdata)	Point cloud data through airborne laser scanning of the terrain	Height data	Lantmäteriet, Laserdata NH (2020c), Lantmäteriet (2020)
4	Company registry (företagsregister)	Registry of companies and their workplaces according to economic sector and size	Workplaces per company, economic sector (NACE code), size of workplace, coordinates, address	SCB, Foretagsregistret (2020)
5	EPC database (gripen)	National database of energy performance certificates	Floor area, building type, number of floors, energy demand, heating system, ventilation system, renewable energy systems	Boverket, Energideklaration (2020)
6	Så byggdes villan 1890–2010/Så byggdes husen 1880–2000	Architectural description of historical construction practices for typical buildings according to building periods	Construction type, make-up of building components	Björk et al.(2009); Björk, and Kallstenius (2003)
7	BETSI study	Survey study of the energy use, technical status and indoor environment of Swedish buildings	Floor area, building type, surface area building components, make-up and u-values of building components, energy demand, heating system, ventilation system, renewable energy systemsetc.	Boverket (2010, 2015)

(continued)

Table 2. (continued)

Nr	Dataset	Description	Attributes	Source
8	Sveby user data	Standard user data for building energy demand simulations for different building usages and types	Indoor temperature, hot water consumption, ventilation rate, electricity use of both residential and non-residential building usages	Andréasson et al.(2012), Hot et al. (2016); Blomsterberg et al. (2013); Österbring et al. (2019)
9	STIL studies	Survey and measurement studies of different non-residential buildings with data on the heat use, electricity use and U-values of non-residential buildings	Heat use and electricity use per energy service, U-Values	Nägeli et al. (2018, 2019)

Participants in each workshop expressed their opinions about the features presented and further answered questions regarding their specific needs in using the viewer. The workshops resulted in several iterations of the viewer UI. The versions of the mock-ups were prepared and documented on a Miro board.

CDTE evaluation

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 (Figure 1). 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 CDT and general reflections on the characteristics and the maintenance of the platform.

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 CDTE viewer. At the end of the assignment, participants completed the survey and evaluated their experience of the viewer for decision-making.

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 CDTE 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

Table 3. Viewer development workshops.

Workshop # and setting	Purpose	Participant groups	Focus/questions
1 Online zoom	Identify possible characteristics of the UI to develop an initial version of the UI	Researchers	Brainstorm design proposals for screen, buttons, toggles, icons, and other visual elements for the users to interact with Open questions: What are potential user needs? What should the basemap contain? What scale and time resolutions are relevant?
2 Physical	Assess relevance of proposed options for basemap content, UI functions, and data visualization	Reference group	Score the relevance of the basemap elements (layers in basemap, view style, selection options) of different functions (saving and exporting, data plotting) of data visualization elements (levels of detail, energy indicators)
3 Online zoom 4 Physical 5 Physical	Discuss digital twin applications in participants field, test and discuss further development of the CDTE viewer	Municipal property owners Energy supplier Municipal urban planning and environmental department	Related to vision: Have you used digital twins in your work? How do you think digital twins can be used in your field? What is the most important property of a digital twin? Related to development: A) Demonstration and exploration of the first online version of the CDTE viewer B) Mock-up - LEARN what you can do (what type of introduction do you need for the platform?) - SET-UP your scenario (which energy scenario options would be relevant for you? Are there other types of scenarios that could be useful to you?) - CUSTOMIZE your view and seen data (are the limitation options address, owner, district, selection relevant, clear and useful to you? Which timespans would be interesting for you to see under 'planned developments'? 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?) - USE the results (which saving and exporting formats would be useful to you?) - COLLABORATE with your own data (would this be useful? What data formats and kind of data would you like to import?)

Figure 1. Questions of the viewer assessment survey based on Gemini framework (Bolton et al., 2018).

decarbonization measures to implement by using the CDTE to retrieve data about the current status and future scenarios and finally at the end complete the evaluation survey. The assessment of the CDTE with students was conducted in two steps. Firstly, the students explored the CDTE and their first-hand experiences were evaluated through an initial survey, before any introduction or clarification of the CDTE and its functionality. Secondly, the CDTE purpose and functionality were clarified in a presentation, and a workshop was organized with students in which the DTE was used to explore, discuss, and negotiate renovation measures for three different areas 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.

Results

The CDTE of Gothenburg was developed to support stakeholder communication and decision-making processes in the urban energy transition domain. This result section thus describes the viewer platform developed through a participatory process with local stakeholders, followed by a summary of the main phase of its UI development (4.1). In section 4.2, the CDTE content is presented through the description of the energy scenarios based on the BSM results. Finally, section 4.3 illustrates the results of the CDTE assessment done by two groups of test users.

CDTE viewer description

The CDTE developed provides a city model enriched by simulated energy scenarios' data. The design of the interface, iteratively modified after workshop sessions, has finally been structured to provide users with the necessary functions to interact with and understand the virtual representation of the city. Based on the results of workshops 1 and 2, the interface was divided into four parts establishing a clear visual hierarchy. The larger central part of the interface is occupied by the 3D model, while the borders are occupied by a scenario bar (top), a plotting dropdown window (right) and a setting column (left).

At the opening of the online interface, the digital twin appears as a simple 3D model of the city featuring building objects in a neutral colour on a 2D base map showing street, water and tree features. To access energy performance data about the building stock the scenario bar can be used allowing the visualization of energy demand classes overlayed to the 3D model, in addition to explanatory data charts in the dropdown window. From a technical perspective, this visualization is possible because scenarios' data obtained from the BSM is appended to the building objects. To efficiently handle the substantial volume of data and minimize visualization time, a vector tiling system was employed. This system enables the subdivision of a physical space into smaller tiles, facilitating storage and analysis at a more granular level. When using the CDTE viewer, tile loading is triggered during zoom operations within the interface. This initiates the querying of x, y georeferenced values, allowing the loading of between 1 and 16 tiles simultaneously. For visualizing energy demand classes, data is transformed into colour scale images using a customized style. The pre-calculation of values and ranges for each energy indicator helps reduce both rendering and visualization time.

The content of the three sets of scenarios as well as the elements to navigate this section, were extensively discussed during workshops. Specifically, during workshops 1 and 2 the two major aspects debated were the energy indicators and time scales. Among the different variables that can describe energy-related aspects, a few were indicated to be fundamental for providing a complete understanding of buildings' energy performance: final energy demand, heating demand, cooling demand, primary energy, delivered energy and greenhouse gas emissions. Additionally, one of the main challenges in the energy domain was found to be the richness of time dimensions when deciding on decarbonization strategies. The three sets of scenarios already introduce two of these dimensions such as the time of city development (and the consequent spatial configuration of the current city and the city envisioned by the comprehensive plan) and the time horizons of climate change. The other dimensions regard the time resolution of the single energy indicators which can express building performance on a yearly, monthly, daily or hourly base. As a result of the co-creation process, the CDTE proposes a hierarchical order to facilitate the navigation giving the possibility of selecting, in the scenario bar, the scenario of interest together with the time of city development, climate horizon and a specific energy indicator, while visualizing the yearly and monthly values for the selected energy indicators in the dropdown window.

The plotting dropdown window is also the section of the platform designated to aggregate or filter the results. From a spatial perspective, results in the CDTE can be visualized on building, area and grid units. Users can select one of the homonymous three buttons in the upper part of the window and continue with a second level of filtering. For example, when selecting buildings the secondary options allow to visualize scenarios results on 'All', 'specific selection' or 'only one building'. For the former option, energy values of the selected scenario will be visualized both in the

3D model and data charts, while for the two latter options, additional details will be displayed. Users in the specific selection panel can choose which buildings they want to analyse by using dropdown lists reporting types of use, heating or ventilation systems installed, ownership, and energy carriers, while in the case of selecting 'only one building' can choose one building directly by clicking in the 3D model. In both cases, after the selection an additional description of the building stock is reported in the dropdown window, followed by the data charts reporting the aggregated results. This structure of the dropdown window, as well as the filter and aggregation categories, emerged from the series of debates during workshops 4–6. Among the key needs, users highlighted the importance of having a flexible tool able to support analyses at multiple spatial scales according to the phase and type of decision to take. Additionally, being able to filter results for buildings with similar characteristics was found particularly relevant for public property owners who are interested in finding standardized solutions to reduce energy demand on a large building stock.

Finally, the setting column on the left side of the platform reports several collaborative functions corresponding to single buttons for importing, exporting, and saving the digital twin data. While participants in workshops 3–5 overall expressed the need to save user settings and export results in other formats (csv, geodatabase, jpg) the function for importing data was highly debated. The reason does not concern the usefulness of the function but rather the security and the ownership of the data. In Gothenburg as in many other cities energy consumption data are sensitive due to privacy regulations, thus representatives of energy providers and building owners highlighted the impossibility of importing data to a public open platform.

Furthermore, this column contains an info button with details about the CDTE and the project. After the first evaluation of test users, a link with additional informative materials has been added to address the comments of the users. Specifically, the comments highlighted the necessity of better understanding the modelling behind the platform, including data sources and data pre-processing, assumptions used in the simulations and calculation methods. Together with this documentation, the CDTE offers a detailed list of definitions for the key terms used in the scenarios (such as energy variables and renovation measures) which is accessible from the scenario bar.

For supporting decision-making processes, the development of a digital twin with a user-friendly interface is crucial. The design of CDTE online interface evolved over 2 years project being iteratively updated to match the feedback received during the five workshops. A summary of the iterative development of the viewer is illustrated in Figure 2.

Scenarios results in the viewer

Modelling through the BSM linked to the digital twin allowed to estimate changes in building energy demand dependent upon urban development plan, climate warming, and the application of building renovation measures.

Current and future city. The first set of scenarios provides a comparison between the energy demand of the existing building stock and the future one envisioned by the comprehensive plan 2050 using the TMY 2020. The latest, based on a sustainable compact development model for the city, implies the increase of built density as an alternative to a horizontal expansion. 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 showing that the city plan for 2050 will contribute to higher energy demand by 13,50%. Figure 3 highlights that this variation is largely influenced by the increase in heating demand (including hot water) estimated at around 10,5% while cooling demand remains quite stable accounting for 69 GWh per year in both scenarios.

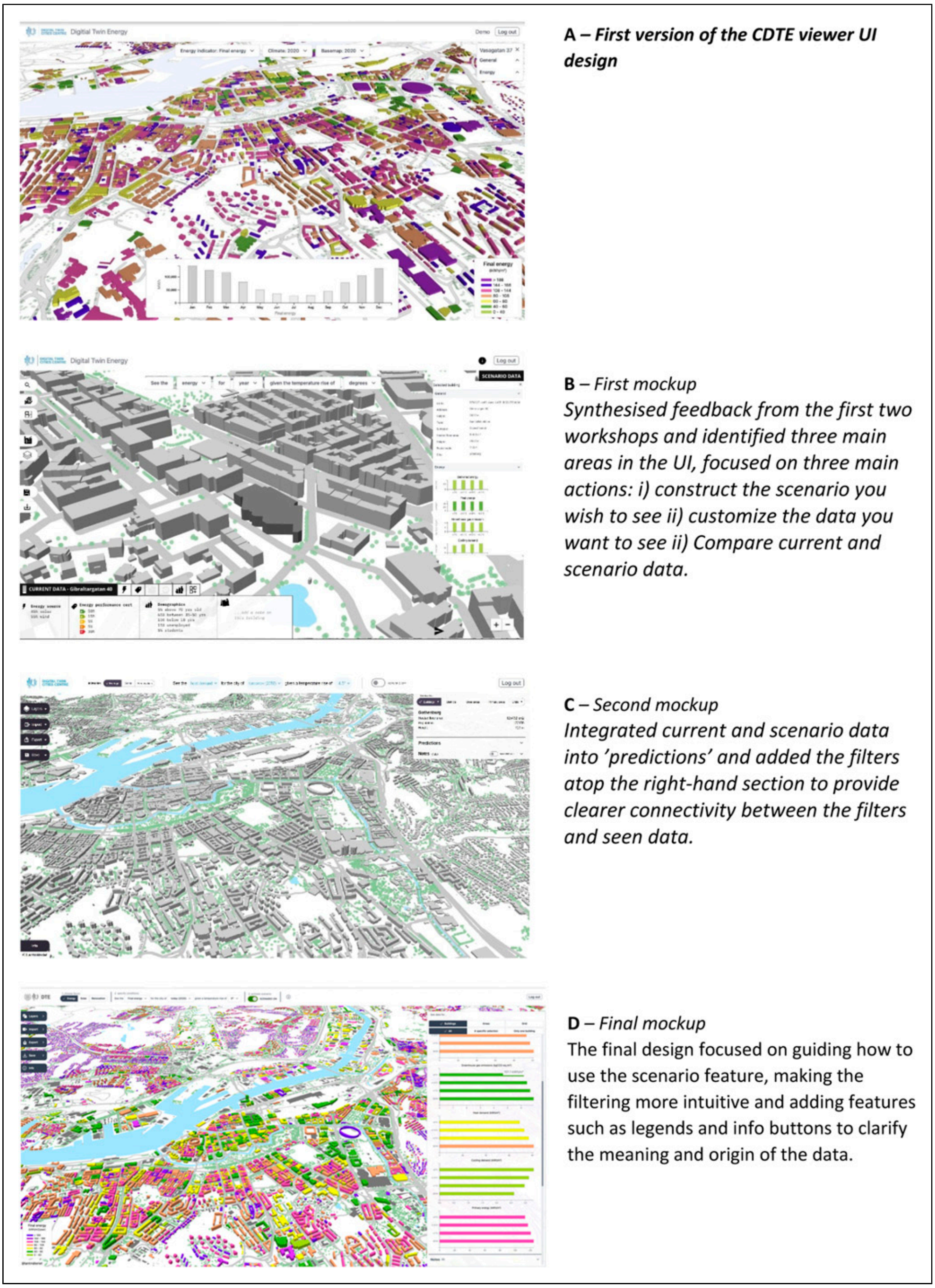

Figure 2. Mock-ups of the iterative development of the viewer.

Climate warming impact on current and future city (2018–2050). The second set of scenarios addressed the impact of climate warming on building energy demand following IPCC climate scenarios RCP 2.6, 4.5 and 8.5 for the year 2050. For these scenarios, temperature pathways modelled in Meteonorm were used as climate boundary conditions in the BSM. Compared to the Typical Meteorological Year 2018, average monthly air temperature values increase up to 2.2°C in RCP 8.5, between 1°C and 1.6°C in RCP4.5 and up to 1.2°C in RCP 2.6.

Modelling results of both scenarios are visualized in the DTE accompanied by comparative data plotting. In Figures 4 and 5 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 comprehensive plan, the analysis of the monthly variation between TMY 2018 and the RCP scenarios confirms that, in future warmer scenarios, final energy demand

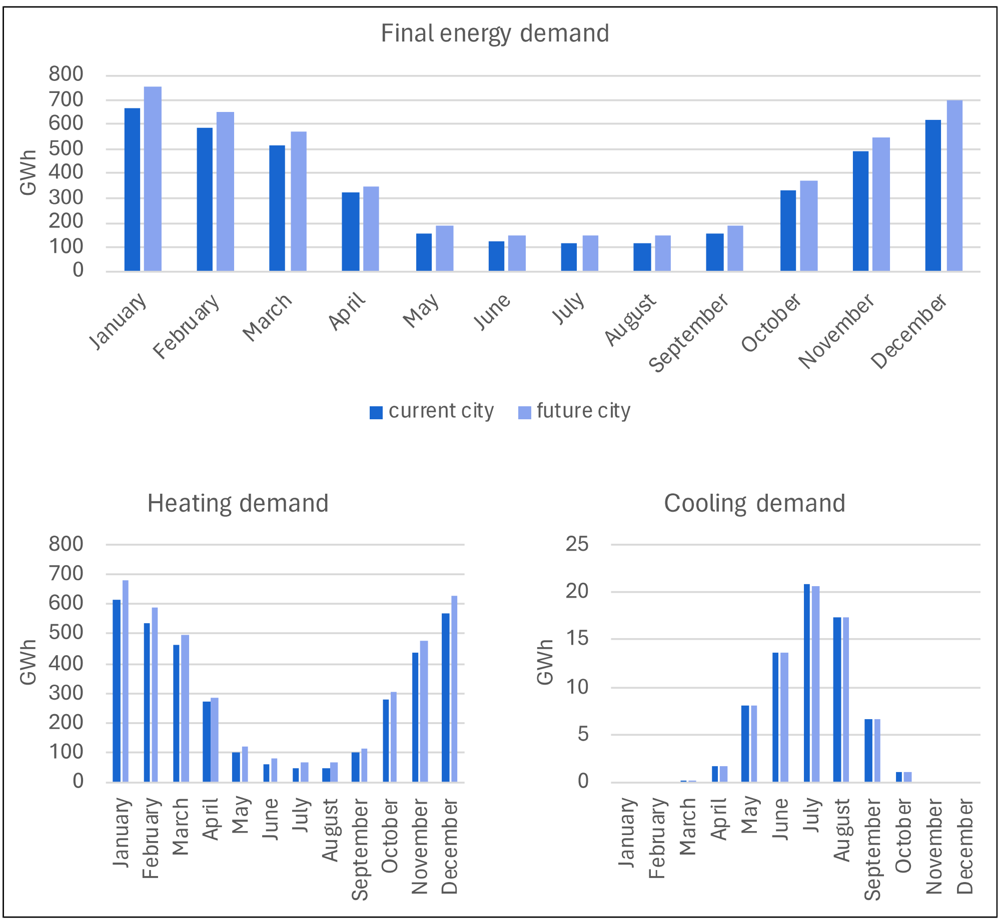

Figure 3. Monthly energy demand at the city scale for the current city and future city scenarios.

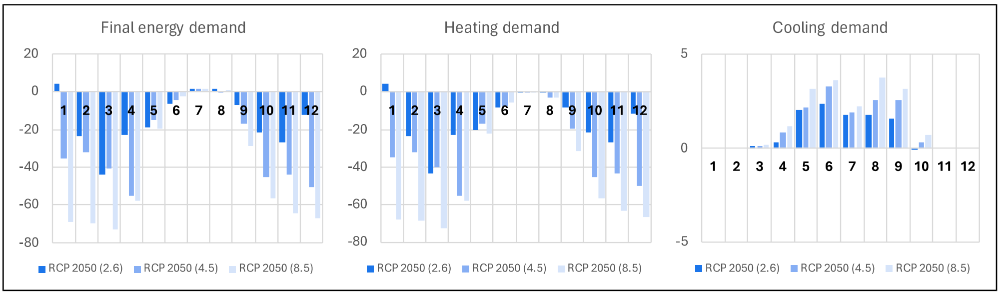

Figure 4. Climate warming impact on building energy demand in the city of today.

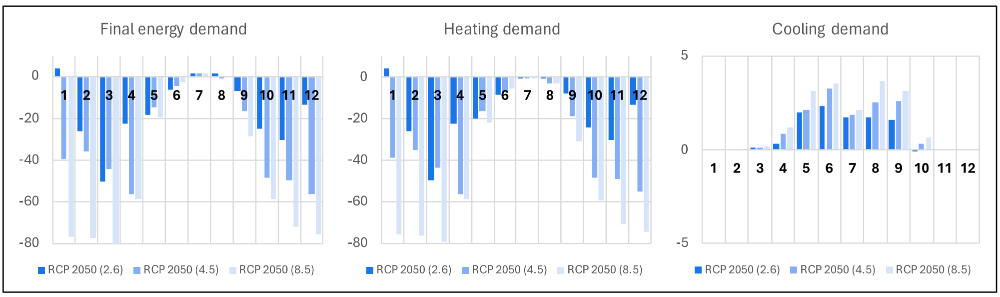

Figure 5. Climate warming impact on building energy demand in the city envisioned by the Comprehensive Plan 2050.

and heating demand generally decrease, while cooling demand increases. It is specifically during winter and spring months then 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 in final and heating demand compared to the baseline case. Cooling demand increases for both 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 results 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 CDTE shows the results of energy simulations at the building level. Despite the description of a general pattern at the city level 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. In the CDTE the visualization of the building's characteristics and the comparison of scenario data through plotting, further facilitate the analysis of each case to better understand the single building performance.

Renovation measures. The third set of scenarios addresses the implementation of renovation measures and the impacts on building energy demand on the current building stock. The scenarios were based on different renovation approaches: A scenario focusing on improving the climate shell (e.g. insulating the walls, roofs and replacing windows), one focusing on building installations (replacing HVAC systems and adding energy generation through solar cells where suitable) as well as a deep renovation scenario which combines the two approaches (see section 3 for a detailed description of the scenarios and the underlying assumptions).

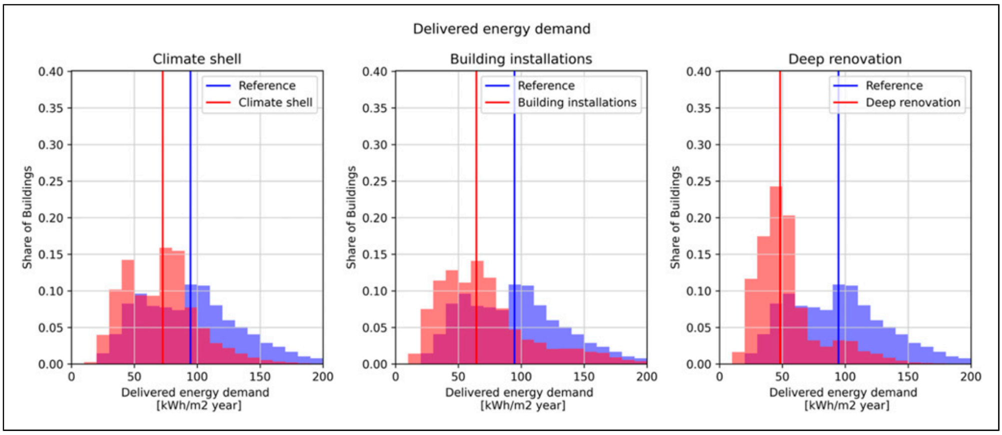

Figure 6. Distribution in the yearly delivered energy demand of the different renovation scenarios (red) and the current building stock in (blue). The vertical line indicates the median energy demand in the building stock.

The results, also in this case, can be visualized on single buildings within the CDTE and are here summarized at the full city scale. Figure 6 shows the difference in the distribution of the yearly energy demand of the buildings and compares the distribution of the different scenarios (in red) against the demand of the current building stock (in blue). In the Climate Shell scenario, the average energy demand results in a reduction of about 20kWh/m^2 and year, suggesting that interventions such as enhanced insulation, efficient windows, and roof upgrades can greatly reduce heating requirements. The Building Installations scenario shows an even more significant decrease in the median demand of almost 30 kWh/m^2 and year, highlighting the large energy-saving potential of more efficient installations as well as energy generation through solar cells. Finally, the Deep Renovation scenario shows the potential for energy reduction by combining both former scenarios, highlighting a decrease in the median energy demand of buildings by almost 50% down to 50 kWh/m^2 per year.

CDT user assessment: Surveys

Detailed results of the assessments are shown in Appendix A where the answers of the two groups to the survey are compared. The assessment took place during two workshops engaging different target groups. The difference in expertise and background of the two groups of participants 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 the difference in background, similar answers among the groups 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, around one quarter saw the relevance in analysing a building before making decisions on interventions and the last quarter acknowledged the potential relevance in the DTE for sharing information within companies.

The results of the survey indicated that the DTE was generally considered easy to use by the survey respondents (both the stakeholders and students). Accessing the platform, visualizing scenarios results and visualizing building details and graphs were found predominantly easy (questions 6,7,8). However, the stakeholders in particular found it more challenging to visualize scenario results and build details and graphs (around one-third reported that this was not easy).

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

Similarly, a discordance between the two groups is found regarding the usefulness of the DTE to define decarbonization strategies. The answers to question 11 indicate that 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. However, these results seem to contradict the general agreement found among the two groups about the potential of the DTE in enabling (energy) performance improvements (question 14). Finally, the majority of the respondents responded positively regarding the potential of DTE viewer to be useful for the public (question 13).

The workshop 6 participants (stakeholders) were not sure about the reliability and quality of the data (questions 15–16), which they pointed out as negative characteristics highlighting the difficulty in understanding how data is created. This could also explain, for example, why relatively few found the CDT useful for defining decarbonization strategies (difficult to make decisions based upon uncertain data reliability). After the first assessment with stakeholders, UI optimizations were made to promote data reliability. In this phase, info buttons were integrated into the interface to explain functions, scenarios and calculation methods, correlated to additional 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 to be part of the nature 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). In both assessments, a third of the respondent 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 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, the respondent of the two groups had the possibility of sharing their opinion on the positive and negative characteristics of the DTE and giving 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, the assessment groups gave suggestions about future functions that should be included to make the DTE viewer more useful. Answers to the open question 22 highlighted the need for including richer datasets (for example, electricity and water demand) and offer scenarios results with higher time resolution (hourly demand) and for multiple years (for example, 2030). Other respondents have reconfirmed the need for having clearer information about building characteristics, modelling and variables in the scenarios function. The search function also seems to be a bit hidden in the interface and should offer more options according to the respondent.

Discussions and limitations

This paper presented the participatory development process of a CDT for building energy to support municipal pathways towards decarbonization using the Swedish city of Gothenburg as case. The application the CDT was assessed by engaging users (decision-makers) in the development process through a series of workshops contributing to content development and reflecting on interactivity, scalability, and openness of the CDT.

The workshop sessions brought enriching debates in the CDTE development process. Unfortunately, a few suggestions of the local stakeholders could not be implemented within the time limits of the project. A few of those also represent technical challenges that should be considered in future DT development. Among the challenges, sharing of existing consumption data is a great one. Being able to have a publicly accessible digital twin implies the open access of data sources and thus the possibility of sharing geographical data as well as, in the case of the energy domain, consumption data measured at the building or household level along with scenarios' results. However, often energy-related data cannot be publicly shared due to privacy policies and functions such as importing data is feasible only by restricting a part of the platform to private use allowing internal data exchange for companies. As reflected in the European Data Strategy and the Data Governance Act (European Parliament, 2022), data privacy is an important objective to enable fair data access and data-driven innovation. The Common European Data Spaces initiative is framed by a collection of references that points to specific digital frameworks and infrastructure to facilitate a trusted environment for data interoperability and sharing. The energy sector is one of the areas where several data spaces have already been initiated. This is a path to consider in the future CDT development when sensitive data is involved as the data governance is built into the software reference architecture of data spaces and supported by legislation on European level. EU member states must carry out the transition to open data which in Sweden is handled by Lantmäteriet, a public authority belonging to the Ministry of Rural Affairs and Infrastructure. According to the Swedish government, Lantmäteriet will have to make their Geodata, for example, properties, buildings, lakes, roads, vegetation and population open without charging fees until 9 February 2025 the latest (Lantmäteriet and Lee (2023)).

The CDTE further highlight the potential of digital twins in providing scenarios of possible futures and envisioning long-term potential changes in energy demand when taking decisions on robust decarbonization measures. Along with the scenarios modelled in the CDTE, local stakeholders indicated other data of key relevance 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) and on daily and monthly periods, the potential of energy production through renewable sources, supply capacity of powerplants and networks. Long debates interested specifically the definition of building energy demand and its evolution in the electrification transition of the mobility sector. As private electric cars/vehicles are expected to be connected more and more to private chargers, 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. The time scales should also be further discussed in the development of 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 city energy plan 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. Additionally, while current results underscore the potential energy savings in the building stock, which are hypothetically achievable by applying the indicated renovation strategies, the renovation scenarios are applied to all buildings without considering constraints such as cultural heritage value or economic feasibility. Results are thus showing the technical potential for energy reduction in the Gothenburg building stock. Richer datasets may be included to facilitate the assessment of the feasibility of the measures.

The testing and the assessment of the CDTE highlighted that reliability is a very important factor for users. Showing scenarios' results seems to be not sufficient to gain trust in the tool without complementary sources and documentation that explain in detail the modelling methods and the assumptions behind the calculations. How to promote data reliability in digital twins is a key topic to address in future studies. A second important factor is the previously debated usability of the viewer. As for other technological tools, the learning curve might vary according to age and natural predisposition to using digital environments. This might explain why the answers of the two groups of users are sometimes contradictory. Further testing should include additional background questions to try to explain these variations.

Finally, while the CDT in this study focussed on information about building stocks, related energy use and climate impact, future development of the CDTE should consider adding real-time data from sensors (for operational energy, connection to electric vehicles for energy storage or supply). From a broader perspective, the methodological approach for the CDTE development and use of the CDT has the potential to be extended beyond scenario-construction purposes. Future testing should explore the development of CDT for supporting crisis management through real-time data on a diverse set of systemic and environmental issues such as traffic, flooding, drought, heat waves, wind flows. These explorations should also help to identify spatial datasets to enrich viewer platforms and users' experiences.

Conclusions

The paper presents a participatory approach used for the development of the CDTE of Gothenburg as a tool to support stakeholder communication and decision-making processes in the urban energy transition domain. The study describes the development process including co-creation workshops, the modelling of energy scenarios, the development of the user interface and finally reports on the evaluation by test users. The results further show the relevance of engaging future users in such a process to build a baseline understanding of needs and limitations in using digital twins for decision-making.

Three sets of scenarios were selected through previous workshops and showed the importance of enriching data that describe current city characteristics with data that envision possible future conditions and that can support more robust choices in the energy sector. Scenarios should emerge from the needs of local actors and municipalities to address the most relevant concerns and the variety of spatial and temporal scales required in different phases of energy-related planning. In the Gothenburg case, energy scenarios addressed the changes in energy demand due to planning models, climate warming and renovation measures applied to the building stock. Additional energy scenarios should include the cost of delivered energy and renovation measures, peak consumption during extreme climate events (heatwaves and coldwaves) and on daily and monthly periods, the potential of energy production through renewable sources, supply capacity of powerplants and networks, and the demand of charging electric cars.

The development of the online CDTE viewer further confirmed the necessity of co-creation and constant feedback loops with potential users. The assessment results showed that the implemented scenarios were perceived as relevant by the different user groups and most of the interface functionalities were valuable and intuitive for all stakeholders. Aspects highlighted as the most important were the visualized scenarios in the CDTE and their ability to start and guide the discussions between the different stakeholder groups and communicate different perspectives including goals, conflicts and overlaps. Local stakeholders, by exploring possible uses of the CDTE in decision-making, indicated that clarity and readability of the scenarios' content are key values for boosting interactions among different administrative spheres. Further observations on the reliability and quality of the data pointed out that it is fundamental to build trust in the tool by giving access to detailed documentation about simulation methods, data sources and pre-processing, as well as modelling assumptions.

Finally, future research, while continuing to improve the technological solutions for digital twins should promote the interactively involvement of users along the development of more user-friendly interfaces. Developing Digital Twins interfaces is still often addressed as a solely technical matter assuming experts as general users. However, digital twins are the key instruments for better planning in many domains including the energy one, and many decision-makers with different roles, different levels of digital capability and expertise should be able to use them. Digital twins are important instruments for the future planning of our cities and have the potential to surpass the traditional sectionalization and compartmentation of knowledge to finally offer shared bases to facilitate synergic decisions between cities, energy providers, companies and citizens.

Acknowledgements

This work is funded by Göteborg Energi ABs Foundation for Research and Development under project number 20-11 and it is part of the Digital Twin Cities Centre supported by Sweden's Innovation Agency Vinnova under Grant No. 2019-00041. The authors would like to express their gratitude to all the participants of the workshops and interviews. Thank you for insightful discussions, and dedication of your time to make our research relevant.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the Göteborg Energi ABs Foundation, Sweden's Innovation Agency Vinnova under Grant No. 2019-00041.

ORCID iDs

Daniela Maiullari https://orcid.org/0009-0006-8906-5311
Claudio Nageli https://orcid.org/0000-0003-2094-4482
Andreas Rudena https://orcid.org/0000-0003-2285-3947
Asa Isacson https://orcid.org/0009-0001-8650-3789
Giliam Dokter https://orcid.org/0000-0002-5667-3293
Holger Wallbaum https://orcid.org/0000-0001-5809-9400
Liane Thuvander https://orcid.org/0000-0002-9031-4323

Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Supplemental Material

Supplemental material for this article is available online.

References

Adade D and De Vries WT (2023) Digital twin for active stakeholder participation in land-use planning. *Land* 12(3): 538.

Andréasson I, Bergqvist B, Dalman C, et al. (2012) *Brukarindata Bostäder*. Stockholm, Sweden: SVEBY.

Bâra A and Oprea SV (2024) Enabling coordination in energy communities: a digital twin model. *Energy Policy* 184: 113910.

Björk C and Kallstenius P (2003) *Så Byggdes Husen 1880-2000: Arkitektur, Konstruktion Och Material I Våra Flerbostadshus under 120 År [So Were the Buildings Built 1880-2000: Architecture, Construction and Materials in Our Multi-Family Buildings during 120 Years]*. Stockholm, Sweden: Stockholms stadsbyggnadskontor.

Björk C, Reppen L and Nordling L (2009) *Så Byggdes Villan: Svensk Villaarkitektur Från 1890 till 2010 [So Were the Houses Built: Swedish House Architecture from 1890 to 2010]*. Stockholm, Sweden: Formas.

Blomsterberg Å, Dalman C, Gräslund J, et al. (2013) Brukarindata Kontor.

Bolton A, Butler L, Dabson I, et al. (2018) *Gemini Principles*. Cambridge: CDBB.

Boverket (2010) *Teknisk Status I Den Svenska Bebyggelsen – Resultat Från Projektet BETSI*. Sweden: Karlskrona.

Boverket (2015) Beskrivning av databasen BETSI.

Boverket (2020) Energideklaration. https://www.boverket.se/sv/energideklaration/ (accessed 10 November 2020).

City of Gothenburg (2021) Environment and climate programme for the city of Gothenburg 2021–2030.

City of Gothenburg (2022). Göteborgs Stads energiplan 2022-2030.

Coors V and Padsala R (2024) Urban digital twins empowering energy transition: citizen-driven sustainable urban transformation towards positive energy districts. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 48: 51–56.

Dembski F, Wössner U, Letzgus M, et al. (2020) Urban digital twins for smart cities and citizens: the case study of herrenberg, Germany. *Sustainability* 12(6): 2307.

Deng T, Zhang K and Shen ZJ (2021) A systematic review of a digital twin city: a new pattern of urban governance toward smart cities. *Journal of Management Science and Engineering* 6(2): 125–134. DOI: 10.1016/j.jmse.2021.03.003.

European Commission (2020) A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. Communication from the Commission to the Eurporean Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM 662.

European Council (2021) Fit for 55. European Council. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/ (accessed January 2024).

European parliament (2022) REGULATION (EU) 2022/868 of the EUROPEAN parliament and of the council of 30 may 2022 on European data governance and amending regulation (EU) 2018/1724 (data governance Act). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022R0868 (accessed on 6 July 2024).

Francisco A, Mohammadi N and Taylor JE (2020) Smart city digital twin–enabled energy management: toward real-time urban building energy benchmarking. *Journal of Management in Engineering* 36(2): 04019045.

Lamb K, Gemini Council (2022) Gemini Papers: what are connected digital twins. *Centre for Digital Built Britain*.

Gil J (2020) City information modelling: a conceptual framework for research and practice in digital urban planning. *Built Environment* 46(4): 501–527.

Grieves MW (2023) Digital twins: past, present, and future. In: Crespi N, Drobot AT and Minerva R (eds) *The Digital Twin*. Cham, Switzerland: Springer International Publishing, 97–121.

Hämäläinen M (2021) Urban development with dynamic digital twins in Helsinki city. *IET Smart Cities* 3(4): 201–210.

Hedman Å, Rehman HU, Gabaldón A, et al. (2021) IEA EBC Annex83 positive energy districts. *Buildings* 11: 130. DOI: 10.3390/buildings11030130.

Hot J, Claesson J, Kuldkepp T, et al. (2016) *Brukarindata Undervisningsbyggnader*. Stockholm, Sweden: SVEBY. Available at: https://www.sveby.org/wp-content/uploads/2016/05/Sveby-Brukarindata-undervisning-1.0-160525.pdf.

International Organization for Standardization (2017). Energy performance of buildings - Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads.

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of working group I to the Sicth Assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Jeansson E (2019) Virtual Gothenburg – a digital twin of the city. https://geospatialworldforum.org/speaker/presentions2019/Virtual-Gothenburg-A-digital-twin-of-the-city-Eric_Jeansson.pdf

JPI Urban Europe/SET Plan Action 3.2 (2020) White paper on PED reference framework for positive energy districts and neighbourhoods. https://jpi-urbaneurope.eu/ped/

Ketzler B, Naserentin V, Latino F, et al. (2020) Digital twins for cities: a state of the art review. *Built Environment* 46(4): 547–573. DOI: 10.2148/BENV.46.4.547.

Lantmäteriet (2020a) Fastighetskartan. https://www.lantmateriet.se/sv/Kartor-och-geografisk-information/geodataprodukter/produktlista/fastighetskartan/ (accessed 10 November 2020).

Lantmäteriet (2020b) Fastighetsuttag. https://www.lantmateriet.se/sv/Kartor-och-geografisk-information/geodataprodukter/produktlista/fastighetsuttag/ (accessed 10 November 2020).

Lantmäteriet (2020c) Laserdata NH. https://www.lantmateriet.se/sv/Kartor-och-geografisk-information/geodataprodukter/produktlista/laserdata-nh/ (accessed 10 November 2020).

Lantmäteriet (2023) Nytt regeringsbeslut kring öppna data. https://www.lantmateriet.se/en/about-lantmateriet/press/news/nytt-regeringsbeslut-kring-oppna-data/ (accessed on July 6, 2024).

Lehtola VV, Koeva M, Elberink SO, et al. (2022) Digital twin of a city: review of technology serving city needs. *International Journal of Applied Earth Observation and Geoinformation* 114(June): 102915. DOI: 10.1016/j.jag.2022.102915.

Leopold U, Braun C and Pinheiro P (2023) An interoperable digital twin to simulate spatio-voltaic power output and grid congestion at neighbourhood and city levels in Luxembourg. *The International Archives of the Photogrammetry, Remote Sensing and Spatial InformTemporal Photoation Sciences*, 48, 95-100.

Lohman W, Cornelissen H, Borst J, et al. (2023) Building digital twins of cities using the Inter Model Broker framework. *Future Generation Computer Systems* 148: 501–513.

Maiullari D, Palm A, Wallbaum H, et al. (2022a) Pathways towards carbon neutrality: a participatory analysis of the Gothenburg's energy plan. In: *IOP Conference Series: Earth and Environmental Science*. Bristol, UK: IOP Publishing, 012041.

Maiullari D, Palm A, Wallbaum H, et al. (2022b) Matching energy targets, stakeholders' needs and modelling choices in developing urban energy scenarios. *IOP Conference Series: Earth and Environmental Science* 1078(1): 012087. DOI: 10.1088/1755-1315/1078/1/012087.

Maiullari D, Nageli C, Rudena A, et al. (2023) Gothenburg Digital Twin. Modelling and communicating the effect of temperature change scenarios on building demand. *Journal of Physics: Conference Series* 2600(3): 032006. DOI: 10.1088/1742-6596/2600/3/032006.

Malakhatka E, Wästberg D, Wallbaum H, et al. (2024) Towards positive energy districts: multi-criteria framework and quality assurance checklist for digital twin concept development. In *IOP Conference Series: Earth and Environmental Science*. Bristol, UK: IOP Publishing, 1363, p. 012085.

Nägeli C, Camarasa C, Jakob M, et al. (2018) Synthetic building stocks as a way to assess the energy demand and greenhouse gas emissions of national building stocks. *Energy and Buildings* 173: 443–460. DOI: 10.1016/j.enbuild.2018.05.055.

Nägeli C, Farahani A, Österbring M, et al. (2019) A service-life cycle approach to maintenance and energy retrofit planning for building portfolios. *Building and Environment* 160: 106212. DOI: 10.1016/j.buildenv.2019.106212.

Nochta T, Wan L, Schooling JM, et al. (2021) A socio-technical perspective on urban analytics: the case of city-scale digital twins. *Journal of Urban Technology* 28(1–2): 263–287. DOI: 10.1080/10630732.2020.1798177.

Österbring M, Nägeli C, Camarasa C, et al. (2019) Prioritizing deep renovation for housing portfolios. *Energy and Buildings* 202: 109361.

O'Dwyer E, Pan I, Charlesworth R, et al. (2020) Integration of an energy management tool and digital twin for coordination and control of multi-vector smart energy systems. *Sustainable Cities and Society* 62: 102412.

Park J and Yang B (2020) GIS-enabled digital twin system for sustainable evaluation of carbon emissions: a case study of Jeonju city, South Korea. *Sustainability* 12(21): 9186.

Pierce S, Pallonetto F, De Donatis L, et al. (2024) District energy modelling for decarbonisation strategies development—the case of a University campus. *Energy Reports* 11: 1256–1267.

Ricci A, Croatti A, Mariani S, et al. (2022) Web of digital twins. *ACM Transactions on Internet Technology* 22(4): 1–30.

Ruohomäki T, Airaksinen E, Huuska P, et al. (2018) Smart city platform enabling digital twin. In: 2018 international conference on intelligent systems (IS), Funchal, Madeira, 25-27 September 2018: IEEE, 155–161.

SCB (2020) Foretagsregistret. https://www.foretagsregistret.scb.se/ (accessed 10 November 2020).

Schrotter G and Hürzeler C (2020) The digital twin of the city of Zurich for urban planning. *PFG - Journal of Photogrammetry, Remote Sensing and Geoinformation Science* 88(1): 99–112. DOI: 10.1007/s41064-020-00092-2.

Shahat E, Hyun CT and Yeom C (2021) City digital twin potentials: a review and research agenda. *Sustainability* 13(6): 3386. DOI: 10.3390/su13063386.

Srinivasan RS, Manohar B and Issa RR (2020) Urban building energy CPS (UBE-CPS): real-time demand response using digital twin. *Cyber-Physical Systems in the Built Environment*. Cham: Springer, 309–322.

Weil C, Bibri SE, Longchamp R, et al. (2023) Urban digital twin challenges: a systematic review and perspectives for sustainable smart cities. *Sustainable Cities and Society* 99: 104862.

White G, Zink A, Codecá L, et al. (2021) A digital twin smart city for citizen feedback. *Cities* 110: 103064.

Youngjib H and Jaeyoon K (2020) Participatory sensing and digital twin city: updating virtual city models for enhanced risk-informed decision-making. *Journal of Management in Engineering* 36(3): 4020005. DOI: 10.1061/(ASCE)ME.1943-5479.0000748.

Daniela Maiullari is an Assistant Professor in the Department of Urbanism at the Delft University of Technology. Her research interests are in the areas of climate-sensitive design and planning, environmental and energy impacts of urban development models, and socio-technical transitions towards decarbonized built environments.

Claudio Nageli is a co-founder of Sinom and has a PhD from Chalmers University. He has extensive experience in the energy and real estate sectors through his work as a consultant and researcher. His research at Chalmers focused on analysing the energy and climate impact of building stocks. He has broad knowledge of energy issues, both technically and economically, and expertise in Life Cycle Assessment (LCA), statistics, data analysis, and visualization.

Andreas Rudenå is the founder of Paramountric and specializes in software for sustainable value chains and built environment. He has over a decade of experience building software for energy simulation, BIM, GIS, and sustainable material flows.

Åsa Isacson is a PhD candidate in the Department of Architecture and Civil Engineering at Chalmers University of Technology. She looks at how the toolbox for decentralized, small scale communities

has changed in the last 20 years, exploring new digital layers that can support and strengthen the role of such communities as laboratories of change.

Giliam Dokter is a postdoctoral researcher at the Department of Industrial and Materials Science at Chalmers University of Technology. His research interests concern the area of sustainable and circular design, particularly focusing on the implications of a circular economy for design practice and the role of participatory design and co-creation in enabling circular design and innovation.

Ilse Ellenbroek is a recent graduate from the master's program Metropolitan Analysis, Design and Engineering, which is a collaborative program between Delft University of Technology and Wageningen University and Research. Her research interests are climate resilience and urban development, in particular thermal conditions in urban environments.

Holger Wallbaum is Full Professor in Sustainable building at the Department of Architecture and Civil engineering at Chalmers University of Technology in Gothenburg, Sweden. His research is related to ecological and economic life cycle assessment of construction materials, buildings and infrastructures, sustainability assessment tools for buildings as well as building stock modelling for entire cities.

Liane Thuvander is Professor in Architecture and sustainable building at the Department of Architecture and Civil engineering at Chalmers University of Technology in Gothenburg, Sweden. Her research interests are on development of methodologies for spatial value mapping linked to visualization strategies to support stakeholder dialogue and decision-making in transformation and decarbonization of building stocks and urban neighbourhoods.