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Gothenburg Digital Twin. Modelling and communicating the effect of temperature change scenarios on building demand

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Abstract. The article presents the first prototype of a web-based City Digital Twin (CDT) viewer developed for the city of Gothenburg to promote the understanding of the interrelation between the spatial, energy and climate change domain related to building stocks and to support stakeholders' collaboration. The focus is on the development process of the viewer and decisions taken to target the users. 3d spatial data about the current city combined with building energy demand modelling following the Intergovernmental Panel on Climate Change scenarios provide the basis that potentially allows local actors to take informed decisions about decarbonization measures in a long-term perspective. First, future climate conditions are modelled for Gothenburg following the IPCC pathways 2.6, 4.5, and 8.5 for the year 2050. Second, a Building Stock Model is employed to simulate the energy use of buildings by using the climate scenarios as climate boundary conditions. Finally, results are visualized in the CDT viewer showing that future climate conditions contribute to an overall decrease in final energy demand up to 18% in spring and autumn months and an increase up to 1.5% in summer months.

1. Introduction

Cities around the world are engaged in developing plans and strategies to reduce greenhouse gas emissions and increase the energy efficiency of the built environment. Yet, often the plans identify measures without looking at their robustness and their capacity to deal with a changing climate. The city of Gothenburg, Sweden, has recently published an energy plan that identifies lines of actions and measures to implement by 2030[1]. The plan clearly states that one of the main challenges to address concerns the effect of a warmer climate on building energy demand and specifically the possible pressure on district cooling and electricity network.

As previous examples have demonstrated, City Digital Twins (CDT) can be used to represent, model, and simulate urban systems [2]. Existing literature extensively focuses on technological and framework development of CDTs (level of accuracy of digital models, data structure and standards), while a growing number of studies highlight the potential of using Digital Twin in urban planning and design processes [3]. Applications in different domains have shown that CDTs can offer strategic information when dealing with risk and environmental management, support planning, as well as boosting economic, social, and environmental practices [4]. However, the question is how CDTs can guide short- and long-term urban transformation facilitating the decarbonization process while addressing multiple temporal dimensions including climate change related ones. Thus, this article presents a workflow to include spatial, climate and energy dimensions in a web-based CDT viewer and presents energy demand results for different climate scenarios accompanied by reflections on possible implications in decision-making practice.

2. Methodology

The methodology for data processing, climate and energy modelling and visualization in the CDT viewer developed for Gothenburg can be structured in following four steps: data pre-processing, climate modelling, energy demand modelling, and digital twin visualization.

2.1. Data pre-processing

In this first step 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 [5], property map [6], LiDar data [7], company registry [8], and building energy performance certificates [9].

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 [10]. Additional relevant input data for the energy demand assessment of buildings was derived from the energy performance certificate (EPC) database: type of HVAC 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.

2.2. Climate modelling

In order to assess energy demand in different future scenarios, Representative Concentration Pathways (RCP) are traditionally used [11]. 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. This stochastic weather generator [12] allowed to use CMIP6 data to predict climate variables and create a Typical Meteorological Year (TMY) weather file with hourly temporal resolution. For this 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 [11], 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 ºC by 2100. RCP 4.5 Wm^{-2} likely implies a temperature increase of around 3 ºC, while RCP 8.5 likely will result in a warming of at least 4 ºC by 2100.

2.3. Energy demand modelling

The generated building stock dataset was assessed using a Building Stock Energy Model (BSEM) developed in previous studies [13-15] which 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.). The useful energy demand for space heating is based on the simple hourly method according to the norm ISO EN 52016-1 (ISO, 2017).

To calculate the energy demand in the BSEM supplementary inputs were added mainly concerning envelope characteristics and parameters of building usage. The U-values of envelope components were assigned based on the component type, year of construction, and building function; while system efficiency was assigned based on the system type and the estimated age of the installation following the existing categorizations [16]. Parameters of building usage such as indoor temperature, occupancy, hot water consumption and electricity demand were assigned based on the usage types. These data complete the data inputs required to estimate the energy demand of buildings through the BSEM.

In this study, the 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.

2.4. Digital Twin visualization

The city model was generated using the previously described datasets and additional cadastral data. 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 in LOD1. Simulation data derived from the BSEM are then appended to the building objects. In order 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 CDT 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 color 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.

3. Results and discussion

3.1. Climate warming in Gothenburg

The first set of results regards the stochastic weather generation for the city of Gothenburg obtained through Meteonorm modelling. In Figure 1 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 ºC compared to the 2018. Following the pathway RCP 4.5 air temperature increases between 1 ºC and 1.6 ºC, while the RCP 2.6 results in warmer climate up to 1.6 ºC. Overall, the time distribution along the year indicates that in the latest scenario larger variations are observed during spring and summer months.

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.

3.2. City energy demand for buildings

The computation of final energy demand for the buildings in Gothenburg was carried out through the BSEM on an hourly base. For the TMY 2018 the total annual demand is calculated to be 4263 GWh.

Lower yearly demand is observed for the climate scenarios RCP 2.6, 4.5 and 8.5 pathways, which led to a final energy demand of 4085 GWh, 3919 GWh, and 3751 GWh, respectively.

Figure 1. Monthly mean air temperature values in the four scenarios (left); variation in air temperature between TMY 2018 and the three RCP scenarios (right)

Figure 2 (left) shows that, on a monthly basis, the largest final energy demand is, not surprisingly, found during winter months. In TMY 2018 the maximum total demand of 680 GWh is observed in January, while the minimum demand of 118 GWh is observed in August. A similar pattern can be seen in all RCP scenarios. RCP 2.6 leads to a maximum final demand of 684 GWh in January and 117 GWh in June, while RCP 4.5 and 8.5 see the maximum demand in January of 644 GWh and 609 GWh respectively, and the minimum in August of 117 GWh and 118 GWh respectively.

For the whole city of Gothenburg, the analysis of the monthly variation between TMY 2018 and the RCP scenarios confirms that final energy demand generally decreases in future warmer scenarios. As shown in Figure 2 (right) this trend is observed for all months except for the summer months July and August. The largest reduction of final energy demand is calculated in spring and autumn months which overall become milder and result in a lower energy consumption for building heating. The pathway RCP 8.5 represents the highest reduction compared to the baseline case, reaching 18% decrease in April and September. Following, the energy demand estimation shows a decrease between 3.7% and 17.3 % in RCP 4.5, and between 2% and 11.5% in RCP 2.6. Contrarily, in the summer months the final energy demand increases for all the RCP scenarios up to 1,5%, likely because of the increased need for building cooling.

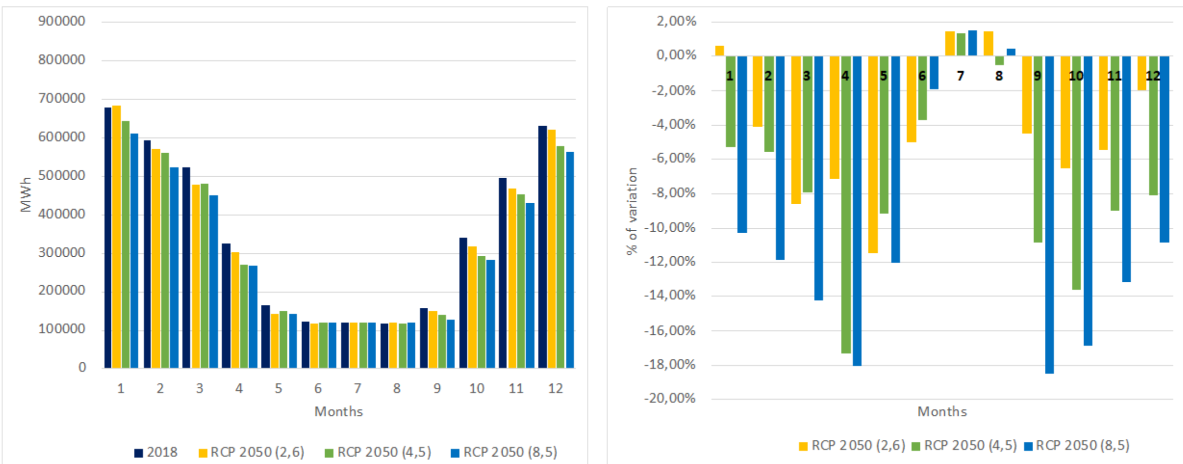

Figure 2. Monthly final energy demand (left); variation in final energy demand between TMY 2018 and the three RCP scenarios (right)

3.3. Building energy demand variation

The results for single buildings are visualized in the CDT viewer for example through classification of the final energy demand in kWh/m^2 per year (Figure 3). Users can customize their visualization by selecting the RCP and related energy demand results. Energy demand varies according to the characteristics, envelope, level of efficiency of the energy system installed, and function of the building. A comparative analysis of buildings with different use shows that the impact of climate warming is the strongest on multifamily houses which expect a decrease in mean annual demand of 4.4%, 8.3% and 12.4% in RCPs 2.6, 4.5 and 8.5 respectively. Cultural, sport and community buildings follow with a final energy decrease in a range of 2.9-9.20%. Finally, office buildings show a much lower variation in energy demand ranging between 1.2% and 4.80% when considering future climate scenarios. Although at the city scale the energy demand for building cooling is observed to increase up to 1.5% in summer months, simulations show that the daily cooling demand (during hot days) in RCP 8.5 can increase up to 300% compared to the baseline scenario. In this scenario, for the majority of the buildings the cooling demand increases between 25% and 50%.

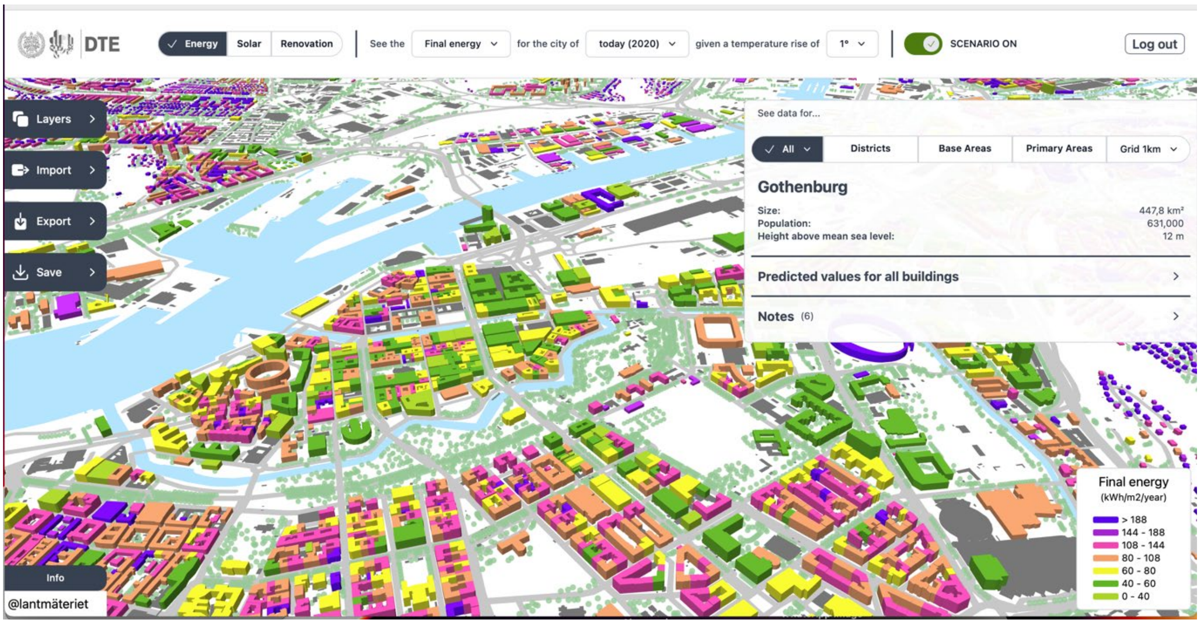

Figure 3. Screenshot of the visualization of the web-based City Digital Twin Viewer interface

4. Conclusions

The CDT for Gothenburg and its energy module provides 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. Considering the RCP climate scenarios when modelling building energy demand, results show generally a lower final energy demand in the spring, autumn and winter months up to 18% and a general increase in summer months up to 1.5%. At the building level such a variation might change in a range of 10-40% annually according to the single building characteristics of use, envelope conditions, and energy system; while on a daily base cooling demand can increase up to 300% during hot days.

The developed workflow demonstrates the capacity of integrating climate and energy models in a CDT. 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 CDT 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 in order 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. Finally, future studies should be performed to test the possible use of the CDT by decision-makers and broader involvement of local actors involved in the energy planning of the city and especially the update of the Gothenburg energy plan.

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