ESTIMATING OPERATIONAL GREENHOUSE GAS EMISSIONS IN THE BUILT ENVIRONMENT USING AN URBAN DIGITAL TWIN

Sustainable City Management Tool for Decarbonisation of Cities

PRADEEP ALVA[1], MARTIN MOSTEIRO-ROMERO[2] and RUDI STOUFFS[3]
[1,3]*National University of Singapore.*
[1]*Future Resilient Systems (FRS), Singapore-ETH Centre.*
[2]*Delft University of Technology.*
[1]*akipaa@nus.edu.sg, 0000-0001-7997-1894*
[2]*m.a.mosteiroromero@tudelft.nl, 0000-0001-7160-0298*
[3]*stouffs@nus.edu.sg, 0000-0002-4200-5833*

Abstract. With climate change strategies and action plan policies, many countries pledge to reduce greenhouse gas (GHG) emissions in their long-term vision for efficient urban processes and operations. An Urban Digital Twin (UDT) integrates multiple disciplines on a digital platform and assists with city management. However, UDTs that explore GHG emissions-related policy development or decarbonisation initiatives for cities are limited. To support decarbonisation policies, smart cities require UDTs with state-of-the-art control and management systems that demonstrate emissions accounting and administration. In response to these concerns, our paper introduces a web-based UDT application dedicated to estimating and managing GHG emissions in the built environment using a 3D city dataset created from open data sources. The 3D city dataset is combined with energy modelling results to calculate buildings' operational GHG emissions. Forecasting is proposed to estimate energy use and GHG emissions along with alternative scenarios for the future. Additionally, we describe how we calculate energy demand and GHG emissions. We introduce user input parameters in the interactive dashboard to generate alternative scenario outputs different from the business-as-usual state. As a result, the UDT dashboard can assist decision-makers and stakeholders involved in carbon-neutral strategies, GHG emission reduction, and policy development.

Keywords. Decarbonisation of cities, Energy demand forecasting, City dataset, Urban analytics.

1. Introduction

The climate change strategies and action plan policies of many countries include the

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goal of reducing greenhouse gas (GHG) emissions as part of a vision for efficient urban processes and operations. Additionally, these nations have committed to achieving carbon neutrality goals within a short duration. The lack of appropriate tools for presenting integrated urban energy data to decision-makers and stakeholders at multiple spatial scales is a major obstacle to climate change adaptation and mitigation under the Paris Agreement and Sustainable Development Goals (Miralles-Wilhelm, 2016; Santhanavanich et al., 2022). Therefore, GHG emission mitigation strategies require technical support in the form of tools and applications that demonstrate emissions accounting and management.

An Urban Digital Twin (UDT) integrates multiple disciplines on a digital platform and assists with city management. UDTs virtually represent physical components and systems in the urban built environment such as buildings, critical infrastructure, etc., along with information on their operation through remote sensing (Ferré-Bigorra et al., 2023; Jeddoub et al., 2023). This temporal data is then used to create scenarios to optimise and manage the physical component. Various UDT use cases are found in the literature, including operational optimisation, participatory planning, and emergency planning for the built environment (Alva et al. 2022a). However, UDTs that explore GHG emissions-related policy development or decarbonisation initiatives for cities are limited (Papyshev and Yarime, 2021; Yu et al., 2022). To support decarbonisation policies, smart cities require UDTs with state-of-the-art control and management systems.

Consequently, there is a need to understand how UDTs can help decarbonisation initiatives, and how their user experience (UX) can be effectively used as a tool by city planners and other decision-makers. To address these concerns, our paper introduces a UDT application dedicated to accounting for and managing GHG emissions in the built environment using a 3D city dataset created from open data sources. Based on a

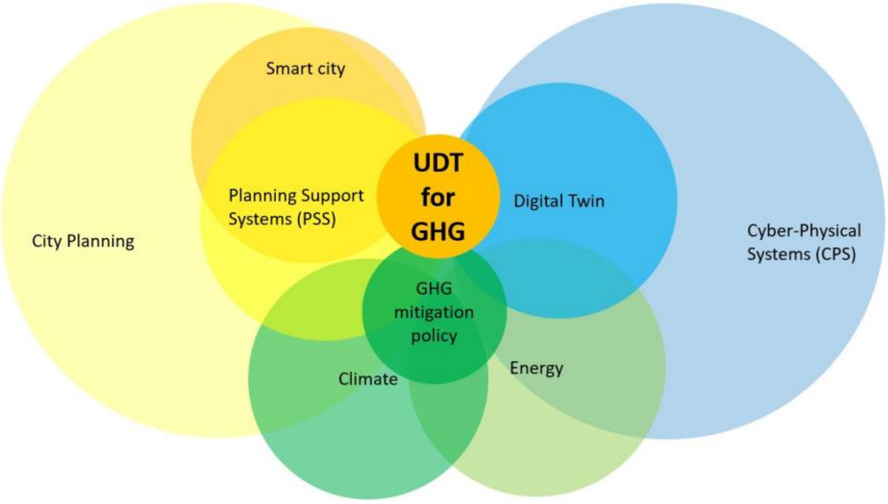


Figure 1: The diagram represents the UDT use case dedicated to GHG emissions in various domains.

literature review and previous case studies, a methodology is proposed for developing a UDT use case for the estimation of building operational GHG emissions.

Deng et al. (2017) systematically review the literature on the co-benefits of GHG mitigation, documenting 1554 academic research articles and classifying the co-benefits into the types and sectors they belong to. The co-benefits of GHG mitigation are listed, such as effects on ecosystems, economic activity, air pollution, resource efficiency, health, resilience to conflicts and disasters, etc. The research finds that limited papers study co-benefits such as energy security and others in sectors such as building and industry. With this study, we can infer that there is a need for research on GHG mitigation, especially, in the built environment sector. Our research on UDTs (Alva et al. 2023; Alva et al. 2022a; Alva et al. 2022b) and the development of the tool dedicated to the estimation of GHG emissions (https://ghg.app.frs.ethz.ch/) try to fill the aforementioned research gap (see Figure 1). The proposed use case represents a wide range of domains, including city planning with its subsets of smart city initiatives and planning support systems (PSS); climate and energy, with its subset of GHG mitigation policies; and cyber-physical systems (CPS) with urban digital twins evolving from the conventional digital twin concept. The proposed UDT is distinctly unique in terms of its goal towards helping decarbonisation initiatives for cities; methods for forecasting energy use and GHG emissions of buildings; and providing open access to the created 3D integrated city energy dataset and dashboard.

As part of the UDT development, two pilot case studies on district and city scale (Singapore), respectively, were created. A COVID-19 scenario case study with 300 buildings at a university campus is demonstrated in the district-scale pilot (Alva et al., 2022b). Four unique use cases using an integrated 3D city dataset with around 119k objects representing the built environment of Singapore are demonstrated in the city-scale pilot (Alva et al., 2023). We elaborate on the methodology for calculating operational emissions of greenhouse gases for the built environment in the following section as a continuation of our research. We then describe how our forecasting method generates alternative scenarios. We describe the development of our custom User Experience (UX) platform in Section 3, as well as providing public access to the developed platform and its potential users. The results and conclusions are presented in Section 4 and Section 5, respectively, along with a discussion of certain datasets that will be considered for future research.

2. Methodology

A UDT dashboard is created as a 3D map web browser application with customised UX and rapid access to the dataset (refer to Section 3). The methodologies to calculate operational GHG emissions and generate alternative scenarios for the UDT dashboard creation are explained in Sections 2.1 and 2.2, respectively.

2.1. CALCULATING OPERATIONAL GHG EMISSIONS FOR THE BUILT ENVIRONMENT

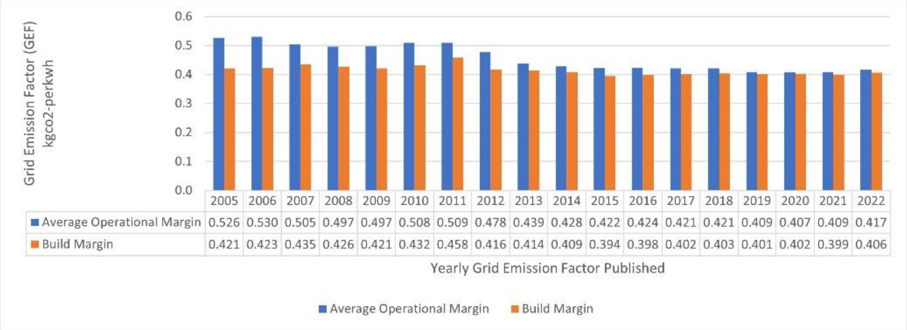
For the development of the UDT use case of operational GHG emissions in buildings, the standard methodology for calculating operational GHG emissions from Mechanical, Electrical, and Plumbing (MEP) equipment used in buildings is studied as part of the research. Based on the UDT literature review (Alva et al. 2022a) and pilot case study, a conceptual architecture is proposed for developing a UDT for the estimation of building operational GHG emissions. Consequently, the results from the energy modelling and 3D dataset are combined to calculate the building's operational GHG emissions (Og) using a linear equation:

$$Og = D_{el} \cdot \sum_{i} \varepsilon_{el,i} \cdot GWP_i$$

where D_{el} = electricity demand; $\varepsilon_{el,i}$ = electricity grid emission factor for greenhouse gas i; GWP_i= Global Warming Potential for each greenhouse gas i.

The emissions that result from the use of energy to operate mechanical, electrical and plumbing systems, such as heating, cooling, lighting, ventilation, water supply and wastewater are accounted for. Singapore's historical average electricity use is available for residential buildings as provided in the annual Singapore Energy Statistics (SES) reports by the Energy Market Authority (EMA) along with a breakdown per planning area and dwelling type (public housing 1-room, 2-room, 3-room, 4-room, 5-room, and executive; landed properties; private apartments and condominiums) (EMA, 2023).

In power generation, the electricity grid emission factor measures the amount of GHG emissions per unit of electricity generated. These factors may vary depending on the source and location of the energy supply and can be obtained from national governments or organisations such as the International Energy Agency (IEA). By calculating the Grid Emission Factor (GEF) for the Operating Margin (OM), we can determine the average amount of CO_2 emitted by the grid-connected power units by each unit of net electricity generation in the system. In Singapore, OM GEF includes electricity generation technologies from primary power producers (such as combined cycle power plants and waste-to-energy plants) as well as autoproducers (such as solar energy systems and embedded co-generation plants). The Build Margin emission factor (BM) is the generation-weighted average emission factor in the year *(y)* by the most recently constructed sample group of power plants *(m)* (UNFCCC, 2018). As a result of the recent construction of new power plants, Singapore's BM emission factor tends to be lower than the OM emission factor. A slightly higher OM GEF was registered in Singapore in 2022, rising to 0.417 kg CO_2/kWh from 0.409 kg CO_2/kWh in 2021. Diesel consumption increased in 2022 as natural gas markets worldwide



	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Average Operational Margin	0.526	0.530	0.505	0.497	0.497	0.508	0.509	0.478	0.439	0.428	0.422	0.424	0.421	0.421	0.409	0.407	0.409	0.417
Build Margin	0.421	0.423	0.435	0.426	0.421	0.432	0.458	0.416	0.414	0.409	0.394	0.398	0.402	0.403	0.401	0.402	0.399	0.406

Figure 2: Annual Grid Emission Factor published in Singapore Energy Statistics (SES) 2023 by Energy Market Authority (EMA), Singapore

tightened, contributing to a higher OM GEF (EMA, 2023). We refer to the latest yearly publication of the SES report for BM GEF values (0.406 kg CO2/kWh) to calculate GHG emissions using the linear equation (see Figure 2).

The Global Warming Potential (GWP) for each of seven major GHGs [carbon dioxide (CO_2), methane (CH_4), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6), nitrous oxide (N_2O), and nitrogen trifluoride (NF_3)], compares the contribution of a given mass of a GHG to that of CO_2 in terms of global warming impact over a definite time frame (for instance, 100 years). The GWP values for the most common GHGs (CO_2, CH_4, N_2O) can be found in the Intergovernmental Panel on Climate Change (IPCC) reports (IPCC, 2021).

In Singapore, water heaters (11%), refrigerators/freezers (17%), and air conditioners (24%) account for about 52% of a household's total electricity use, according to the weighted energy use profile for all housing types (NEA, 2021). Therefore, MEP equipment has major potential in reducing energy use and related GHG emissions. Accordingly, datasets related to MEP equipment used in the buildings are required. Specifically, an Environmental Product Declaration (EPD) or use-stage Life Cycle Assessment (LCA) for MEP equipment and a catalogue of MEP equipment currently used in every building in Singapore is required. Using the EPDs and MEP equipment catalogue, a breakdown of building operational GHG emissions from MEP equipment can be estimated (Georges et al., 2015; Frischknecht et al., 2020).

However, the datasets mentioned above are not all fully available. There is a lack of a catalogue for MEP equipment used in all the buildings in Singapore, especially for older buildings. EPDs are rarely available for MEP equipment that is installed locally. Further, electricity demand and cooling load information are openly available for only a limited number of buildings in Singapore.

For the missing EPD and LCA for MEP equipment used locally, the EPD of MEP equipment globally available with comparable specifications is adopted. For instance, Midea published the world's first EPD for split air conditioners using a representative model, weighing 37kg with a service life of 20 years and R32 for refrigerant usage involving electricity use and leakage (The International EPD System, 2022). The global warming potential (GWP) of the downstream process which includes the use stage of the air conditioning unit is 0.0867 kg CO_2eq/kWh and a total GWP of 0.0936 kg CO_2eq/kWh as per the EPD document. Similarly, EPDs available for refrigerators and water heaters around the globe are used.

In case of a missing EPD, the "basic" calculation methodology explained in standard document TM65 (Harnot, 2021) by the Chartered Institution of Building Services Engineers (CIBSE) is used to estimate GHG emissions for each MEP equipment. The GHG emission (kg CO_2eq/kWh) calculated per equipment is then applied to the entire building depending on the total number of MEP equipment used to find the total building operational GHG emissions. For example, a typical 4-room public housing unit in Singapore may have one refrigerator, one or two water heaters depending on the number of bathrooms, and three to four air conditioning units. Predicting the total number of equipment used within a typical residential unit is relatively easier than for complex typologies such as mixed-use, commercial, and industrial typologies. Hence, MEP equipment-based emissions study and archetype development for various typologies beyond residential buildings are still in progress.

Historical electricity use and cooling load datasets for buildings in Singapore are further used to create future scenarios of high and low energy use (with a breakdown of energy use of air conditioners, refrigerators/freezers and water heaters) and calculate respective operational GHG emissions in buildings. The missing energy-use data for buildings and forecasts are simulated in City Energy Analyst (CEA) with the methodology explained in the following section.

2.2. GENERATING ALTERNATIVE SCENARIO OUTPUTS FROM A FORECASTING METHOD

The 3D city dataset is used to simulate energy demand using the City Energy Analyst (CEA) software. Building footprints, heights, and number of floors are taken directly from the 3D city dataset. Building typologies are adapted from the 3D city dataset, mapping each building or land use type in the 3D city dataset to a CEA typology. Infeasible height and floor combinations (e.g., floor-to-floor heights of 1 meter or heights of more than 20 meters) were resolved by assuming an average floor-to-floor height of 4 meters for all building typologies. Some mixed land use descriptions are encountered, which are assigned mixed typologies in CEA: "residential with commercial at 1st story" (assigned accordingly) and "mixed" (assumed 50% residential and 50% office for simplicity). All unconditioned building use types are assigned the "parking" typology in CEA to ensure no space conditioning is provided.

In order to assign construction materials and envelope properties, CEA requires a construction standard to be selected. These are assumed as follows: public housing is assigned STANDARD1 ("residential, reduced conditioned areas"), private housing is assigned STANDARD2 ("residential, increased conditioned areas"), non-residential buildings are assigned STANDARD3 ("commercial default"), except buildings that are tagged as having green roofs, which are assigned STANDARD5 ("commercial green roofs"). Typical occupancy patterns, building operation parameters, internal gains, and electricity demands for each building typology are assigned based on the CEA archetypes database. This results in a country-scale CEA model for Singapore.

Each island-scale scenario simulation comprises a yearly solar irradiation simulation (carried out using DAYSIM) followed by a building energy demand simulation. In order to reduce the computational time and parallelise the simulations, for every run of the simulations, the country-scale model is split up into smaller projects for each planning area. These computationally expensive simulations are executed by onboarding a processor onto ASPIRE2A—an AMD (Advanced Micro Devices) based Cray EX supercomputer at the National Supercomputing Centre (NSCC), Singapore. The simulation is carried out in serial batch jobs based on different Planning Areas. The results from the energy modelling and 3D dataset are combined to calculate buildings' operational GHG emissions using the equation.

Subsequently, a forecasting method is proposed to estimate energy use and GHG emissions along with alternative scenarios for the years 2030 and 2040 (leading to a net zero emissions target for 2050). For each future scenario, a new energy demand simulation with updated weather files due to the effects of climate change, varying building operation schedules and system parameters can be carried out to assess the effect of various country-scale policies on the achievement of net zero emissions targets.

3. Customised User-Experience (UX), public access and potential users

As a crucial part of UDT development, User-Experience (UX) through a UDT dashboard is set up as a web browser application (https://ghg.app.frs.ethz.ch/) using *Cesium Ion*. A demonstration of the UDT use case of building operational GHG emissions with user querying options within the dashboard is created from a rapidly streamed integrated 3D city dataset. Using three categories of filters –planning area (spatial dimension), built year (temporal dimension) and typology (functional dimension) – users can query the building stock in any part of Singapore (see Figure 3).

Figure 3: Three categories of filters users can apply to query a building stock on the dashboard.

The UDT dashboard along with the UX is set up as a web browser application using *Cesium Ion* and Javascript libraries to generate charts and visualisations based on the output of GHG emissions calculation. Calculated operational GHG emissions and electricity use trends for individual buildings selected by users can be visualised in the form of charts.

Additionally, the dashboard displays individual charts showing operational GHG emissions related to air conditioners, refrigerators and water heaters used in various unit types of residential buildings (see Figure 4). This sets the baseline for dashboard development. The proposed technique will add new scenarios such as low/high energy use and usage of refrigerants with low global warming potential in refrigerators and air conditioners on top of the baseline scenario (current energy use, technology and the refrigerant used in MEP equipment). Charts are generated with these scenarios for every building when a user selects the building (using mouse left-click) on the UDT dashboard. In addition, the energy use forecasts for the years 2030 and 2040 simulated in CEA will be displayed with the present-day energy use.

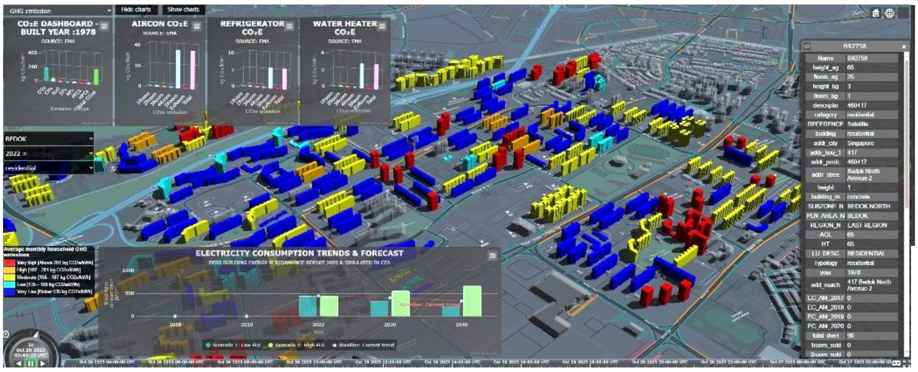


Figure 5: Dashboard with building electricity use and operational GHG emissions trends.

Through Nationally Determined Contributions (NDCs) under the Paris Agreement, both developed and developing country governments apply policies related to GHG mitigation action. Calculating and reporting GHG emissions helps in decision-making and policy towards climate finance and low carbon development; improves awareness and wider acceptance by stakeholders and the public; and can advise on policy assessment that can help in evaluating the efficacy of the mitigation actions. Therefore, users that are anticipated to use the UDT dashboard are stakeholders interested in decarbonisation and policy-making, such as city planners, facility managers (operation and management), energy efficiency engineers, net-zero energy developers (building, estate, district, etc.), architects, sustainability managers, policymakers, etc.

4. Results and Discussion

Users can query a building stock and click on each of the buildings in the UDT dashboard to interactively see all the resultant scenarios of electricity use trends and GHG emissions for each building (see Figure 5). The output charts can easily be downloaded in image, PDF or spreadsheet format using the toggle button on the chart.

Reliable data sources are expected from open-source government websites and other researchers in the future. Furthermore, based on historical and available data, the results will be refined over the next stages of research (https://udtghg.github.io/). Additionally, the model will be improved with access to granular climate data (microclimate) provided by other research projects. Data about the built environment along with occupancy, traffic, climate, and evolving technologies (for instance, usage of new refrigerants or the latest MEP equipment with low Global Warming Potential) are considered for future inclusion. Currently, in the dashboard, these are represented as parameters providing an alternative scenario output that is different from the business-as-usual state. In principle, the demonstrated use case and integrated 3D city energy dataset can be applied to cities around the world. A city-scale UDT may be used to collect operational GHG emissions for training data used in forecasts and other applications, leading to a global inventory (collection of datasets) accessible to the research community.

The next stage of the research will focus on engaging potential stakeholders and collecting user feedback on the usage of the UDT dashboard created. The research will gather data and analyse participants' choices based on their usage and preferences for the dashboard. The data will help evaluate preferences for spatial, temporal, and functional dimensions, for example. Additionally, feedback on user-friendly features and suggestions for improving the dashboard will be collected. Finally, an ideal stakeholder group for the dashboard application can be established based on feedback received. Following user feedback, the current dashboard will be iteratively improved, and more use cases will be demonstrated. One of the current use cases helps users prioritise low-carbon building system rejuvenation in the built environment through intervention analysis. Consequently, the UDT dashboard can help decision-makers and stakeholders involved in carbon-neutral strategies, GHG emission reduction, and policymaking.

5. Conclusions

The mitigation of greenhouse gases in the built environment sector has numerous benefits and further investigation is required. Digital tools can be used to account for and mitigate GHG emissions, thereby providing momentum for executing existing strategies related to decarbonisation. Additionally, UDTs can keep an account of the implementation of net-zero carbon emissions policies such as renewables infrastructure and energy system replacement and maintenance cycles. With a robust UDT user-experience dashboard which has input scenarios modelled along with visualisation to read the energy-use data based on historical behavioural patterns, there is a great potential for UDTs to be used by decision-makers and help in decarbonisation initiatives for cities.

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