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Research paper

District energy modelling for decarbonisation strategies development—The case of a University campus

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ABSTRACT

University campuses can be considered as microcosms of urban districts, since they are typically located within or near a city and have a significant impact on the surrounding area. Moreover, they have a high energy consumption due to the large number of buildings, facilities, and services that use energy for transportation, heating, cooling, and lighting. This makes university campus as testing facility for decarbonisation strategies that can be replicated in other urban areas. The present study discusses a decision-making framework based on a digital twin model for analysing decarbonisation strategies of University College Dublin in Ireland. The thermal and electricity networks of the university campus are modelled to analyse the current status of energy consumption and associated carbon dioxide emissions. Five future development scenarios are explored to identify the optimum pathway for decarbonisation. Conclusions show that the campus can achieve a 10% reduction in emissions without the need for new generation units, while introduction of a new biomass CHP unit would increase this reduction to 17% compared to the baseline. Furthermore, Coupling this with the installation of 3 MW of solar photovoltaic, the calculated campus potential, a total reduction of 26% can be achieved.

1. Introduction

Accounting for more than 50% of the world's population living in them, urban areas are responsible for two-thirds of global energy consumption and more than 70% of carbon emissions worldwide (IEA, 2021). This makes the implementing of decarbonisation policies and strategies in urban areas one of the main global priorities to fight climate change. Over the last few years, a lot of efforts have been put on developing decarbonisation strategies for building blocks and urban districts. One key strategy is to promote the use of renewable energy sources, such as solar and wind power, in place of fossil fuels. This can be done through policies that incentives the use of renewable energy and support the development of renewable energy infrastructure (Arabzadeh et al., 2020). Moreover, the transport sector is another major source of carbon emissions in urban districts, and the transitioning to low-carbon forms of transportation can support the reduction of these emissions (Zawieska and Pieriegud, 2018).

Furthermore, the building sector is an important player since buildings are responsible for more than 40% of global energy consumption and nearly 65% of global greenhouse gas emissions (Pallonetto et al., 2021), with the majority of this energy consumption related to heating and cooling. One of the main challenges in reducing energy consumption in the building sector is the fact that buildings have long lifespans. This means that even if new buildings are constructed to be energy-efficient, the energy consumption of the overall building stock will continue to be high until older, less efficient buildings are retrofitted or replaced (Pallonetto et al., 2022). In order to effectively reduce energy consumption in the building sector, it is necessary to implement a combination of measures, including energy-efficient design and construction, building retrofits, and the deployment of renewable energy sources.

In this context, the development of energy modelling tools is an effective way to assess energy consumption and carbon emissions of urban districts, and to identify and evaluate decarbonisation strategies (Sola et al., 2020; Valencia et al., 2022). Generally, this type of modelling involves creating a detailed simulation of the energy system within a specific district or neighbourhood. The model takes into account factors such as the type and mix of energy sources being used, the location and size of buildings, the demand for energy, and the

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availability of renewable resources. By simulating different scenarios, district energy modelling can help urban planners and policymakers to identify the most effective decarbonisation strategies for their particular context. This can include identifying the optimal mix of renewable and non-renewable energy sources, determining the most cost-effective ways to reduce carbon emissions, and developing plans for implementing new technologies and infrastructure. For instance, Fonseca and Schlueter (2015) developed an integrated models to characterise the energy demand patterns of a urban neighbourhood. The model, which implemented dynamic building modelling (De Rosa et al., 2019) and energy mapping techniques, was integrated in a geographic information system (GIS) and tested against synthetic and experimental data of a Swiss city showing a good performance.

Over the last decade, a lot of interest has been raised by the so-called *digital twin* of urban districts (Shahat et al., 2021), a virtual replica of the physical district, created using data, building and system models and algorithms (Bampoulas et al., 2022). Generally, a digital twin consists of a detailed, 3D model of the campus, with geographical and physical information, as well as data on the various systems, components and features of a specific district. This may include information on building characteristics, heating, cooling and lighting systems, water and waste systems, electrical and mechanical systems, transportation and parking, etc. Digital twin may also exploit smart acquisition systems (Huang et al., 2022) to collect real-time data on occupancy, usage patterns and the types of activities inside the district, building energy consumption, renewable energy source generation, etc. Using this data, the digital twin can provide real-time information on the performance of the urban district, which can be used by district managers to assess and quickly intervene (Pallonetto et al., 2014), following any potential issues or inefficiencies affecting the district. Furthermore, digital twins can be exploited to investigate potential decarbonisation strategies - e.g., building retrofitting, renewable energy deployment (Zhang et al., 2021), community engagement (Nochta et al., 2021), demand side management and demand response strategies (Kathirgamanathan et al., 2020), etc. - in order to develop policy scenarios and energy master plan to support the sustainable transition in cities.

Several examples and pilot cases have emerged of digital twin models integrated into building information management systems (BIMs) (Olanrewaju et al., 2022). For instance, O'Dwyer et al. (2020) developed digital twin, based on machine learning modules and real-time IoT systems, aimed at coordinating and optimising multi-vector energy systems in smart cities. The system was tested for a case study located in the city of Greenwich, showing good predicting, controlling and coordinating capabilities. Lu et al. (2022) described a prototypes of a city-level digital twins for an university campus in Cambridge, merging socio-economic and digital solutions, showing that large dataset of information, which are currently unexploited, might be made available for community engagement and policy decision-making (Lu et al., 2020). Similarly, Zaballos et al. (2020) proposed a framework to investigate the integration of BIM and IoT tools into a digital twin of a university campus for environmental and comfort monitoring. The results showed the importance of the smart monitoring as a way to assess and improve the energy efficiency of the campus infrastructure, as well as to share information with the university community to foster the implementation of energy consumption and optimisation strategies and policies in the context of green campus initiatives.

In this context, since university campus are typically located within or near a city, they represent a urbanised district which have a significant impact on the surrounding area. Like other urban districts, university campuses have a high energy consumption due to the large number of buildings, facilities, and services they provide. They also have a large population of students, staff, and visitors that use energy for transportation, heating, cooling, and lighting. Furthermore, universities have a high potential for implementing low-carbon solutions, such as renewable energy and energy efficiency measures, which can have a positive impact on the surrounding urban area. Therefore, university campuses can be considered as microcosms of urban districts and can be used as a testing ground for decarbonisation strategies that can be replicated in other urban area (Karvonen et al., 2018; Vidal et al., 2023). Horan et al. (2019a) Horan et al. (2019a)described a method to assess potential decarbonisation technologies for university campuses in Ireland by harnessing publicly available tools and data. The authors determined the annual resource potential of buildings-integrated energy technologies, such as micro-wind and PV systems, showing that total production potentials of about 1.8 GWh from micro-wind and between 18.8 and 24.9 GWh from building-integrated PV systems, depending on the utilisation factor adopted. Moreover, digitalisation and information and communication technologies (ICT) play an important role in decarbonising university campus, as they allow for data acquisition and control strategies which are essential for the management, operation and optimisation of building energy systems, as outlined in Kourgiozou et al. (2021), where a systematic review of smart energy systems in the UK academic institutions was conducted. Therefore, implementing decarbonisation strategies of university campuses can play an important role to achieve the carbon emission reduction targets (Aghamolaei and Fallahpour, 2023).

Starting from these considerations, the present paper discusses a decision-making framework, based on the development of a digital twin for detecting and analysing decarbonisation strategies of the main campus of University College Dublin (Ireland). The campus is located in Belfield, Dublin and represents a large hub for education, research and innovation – with several facilities dedicated to teaching, research laboratories, residential and commercial services, sports and recreation facilities – which makes it a large openly-accessible urban district inserted into the Dublin metropolitan area. The main features and characteristic of the campus are outlined in Section 2.1, while Section 2.2 describes the energy system and infrastructure.

A campus energy model (Section 2.3) was developed in order to assess the current energy consumption and carbon emission figures (i.e., the baseline), and to investigate potential retrofitting measures for the energy infrastructure. The model is based on an intelligent virtual network representing the heat and electricity network with all generation and consumption nodes and their interconnections. The network is implemented into a 3D visual representation of the campus. Real-time series data of heat and electricity consumption collected by the building management system (BMS) are used to assess the current performance of the campus and to validate the digital twin model. Several retrofitting scenarios, which includes the substitution of energy generation systems and renewable energy system deployment, are investigated (Section 2.4). The results and conclusions are reported in Section 3 and Section 4.

The paper contributes to SDG7 (clean and affordable energy) and

2. Methodology

2.1. Description of the case study

The University College Dublin's main campus, located in Belfield, Dublin, is the subject of this case study. The campus is home to a wide range of public facilities, including those for education, research, sports, recreation, and culture. The heart of the campus is made up of academic buildings shared among six colleges, which include Arts and Humanities, Business, Engineering and Architecture, Health and Agriculture, Social Sciences and Law, and Science. Each college has its own dedicated lecture halls, offices, research facilities, and recreational amenities. Additionally, the campus offers a wide range of services such as gyms, swimming pools, playing fields, woodland walks, exhibition and cultural facilities, as well as shops, restaurants, and coffee shops for the convenience of students, staff and visitors.

Three distinct character areas have been identified within the campus, as shown in Fig. 1. These areas include education, research and innovation, sports and recreation, and residential. Although these areas

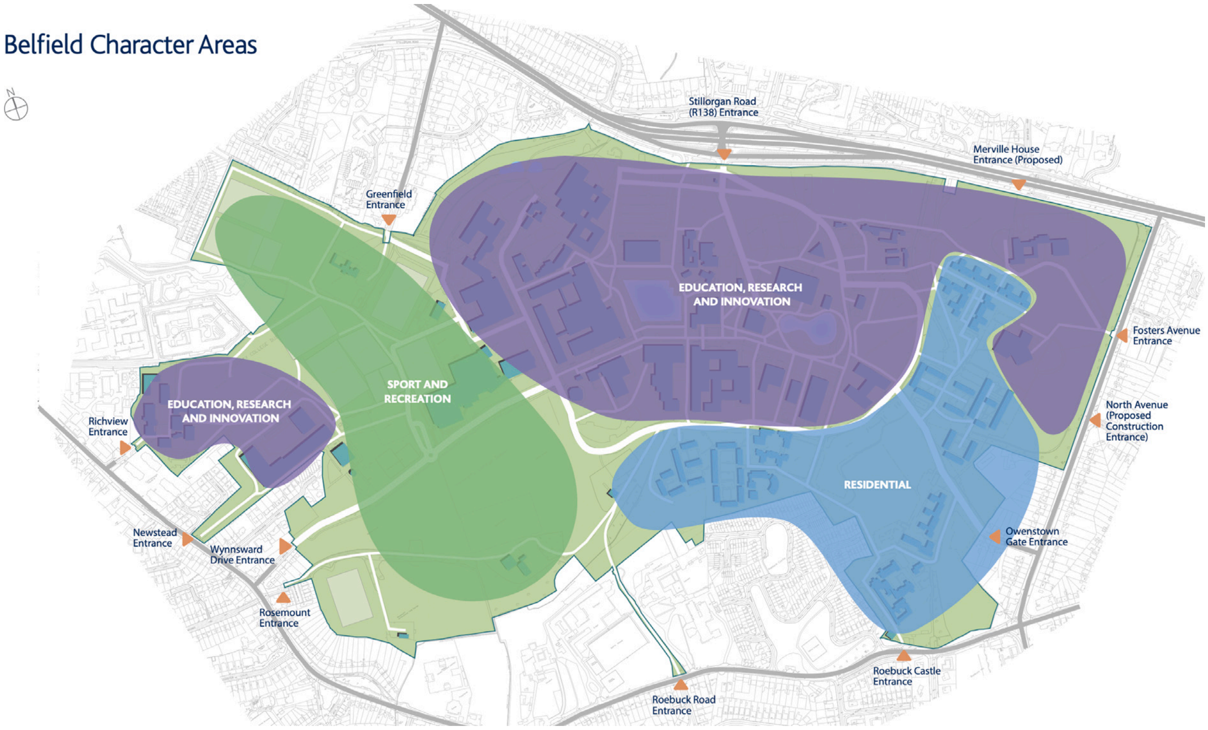

Fig. 1. UCD Belfield campus in Dublin and its character areas, Belfield, Dublin 4.

are interconnected, recognising the distinct zones allows to consider the unique identity and needs of each space. Each specific area has a primary use, along with complementary and supporting uses as needed, and are developed individually and connected through walking and cycling green routes. The car parks are located at the periphery of the Belfield campus, leaving the core of the campus as a pedestrian and cycle zone only.

Students, staff, faculty and visitors make up the population of the Belfield Campus, with approximately and average of 35,000 people attending the campus daily during the year. While campus accommodation is available for a portion of the students, the majority of the population commute to and from Belfield daily, making it one of the largest originators of journeys in the Greater Dublin Area. Therefore, the Belfield Campus contributes significantly to the quality of life in Ireland, acting as a hub for education, research and innovation, while also having a major positive impact on the Irish economy. The campus contains public accessible sports and recreation facilities within its open landscape and hosts events throughout the year. A high volume of visitors occupy the campus year round, particularly from September to May. Extensive infrastructure is in place to meet the resulting energy demand for heat and electricity, and to facilitate commuters, as outlined in following sections.

Regarding the building classification, over 30% of the building stock in Belfield was constructed during the 1960's and 1970's, 34% of which are in need of major refurbishment. UCD faces the challenge of improving the sustainability of these buildings and accommodating the growing demand for campus services, while working with limited space availability and the goal of preserving the existing green areas. Alongside with new buildings under construction, mainly students accommodation, a modernisation programme is under development to carry out the necessary refurbishments, aiming to utilise existing structures where possible and to minimise adding to the embodied energy of the building stock.

2.2. Energy infrastructure

2.2.1. Heat supply

Integrated and localised energy systems are employed to supply heat to the Belfield Campus. The District Heating Network (DHN) (Fig. 2) connects sixteen of the campus buildings to a central Energy Centre, as shown in Table 1.

The heat is produced by 3 gas boilers, 2 CHP systems and 1 biomass boiler. Five of the buildings currently connected to the district heating while they also have a share of their heat demand supplied by a local gas boiler. The details of the heat generation systems are provided in Table 2. Finally, heat is transported through the supply and return pipe networks at which the buildings are connected in series, with a sub-network fed through the science district.

2.2.2. Electricity supply

The main source of electricity for the campus is the national electricity grid, as shown in Table 1. The UCD Belfield Campus has a 10 kV connection via an ESB 38 kV station to the Dublin MV Network. From the main switchgear at the ESB substation, four 10 kV radials distribute power throughout the campus. These can be meshed manually at various points in order to facilitate maintenance. Each distribution substation employs either ABB SafeRing, Moeller GAE or Merlin Gerin RN2 gas insulated switch gear which have a one fault lifespan. The cables used across campus for the 10 kV runs are underground 3-core with 185 mm^2 or 95 mm^2 conductors. Some runs are armoured, as they are directly buried, while others are unarmoured and run in the campus' service tunnels or dedicated cable ducting. The system has 31 MV buses including the ESB supply bus, of these 27 have step-down transformers connected to distribute three-phase 380 V and single-phase 230 V to the buildings on campus.

Three CHP with a total nominal power of $3.4 MW_e$ are currently installed on campus which are primarily employed to provide heat, while a total of $239 kW_e$ of solar photovoltaic panels is installed across academic and residential buildings.

Table 1
Building energy systems in the UCD campus.

Building	Heating		Electricity	
	DHN	Local	Grid	Local
Agriculture & Food Science	x		x	
AIB building		x	x	
Ardmore House		x	x	
Arts Annexe		x	x	
Belfield house		x	x	
CRID building		x	x	
Computer centre		x	x	
Computer science	x	x	x	
Confucius Institute		x	x	
Conway/biotech/Charles/SBI		x	x	
Daedalus building	x		x	
Engineering		x	x	x
Health Science & MBRS		x	x	
Hopkins International Centre & Restaurant	x	x	x	
James Joyce Lybrary	x		x	
Moore Centre	x		x	
Newman Arts	x		x	
Newstead		x	x	
Nova UCD		x	x	
O'Reilly Hall		x	x	
Quinn School of Business		x	x	
Richview Campus		x	x	
Roebuck Offices		x	x	
Science East	x	x	x	x
Science Hub	x		x	x
Science North	x		x	
Science South	x	x	x	
Science West	x		x	
Sport Centre	x	x	x	
Student Centre	x		x	
Student Learning, Leisure & Sports Centre		x	x	x
Sutherland School of Law	x		x	
Tierney building	x		x	
Veterinary Science		x	x	
Woodview House		x	x	

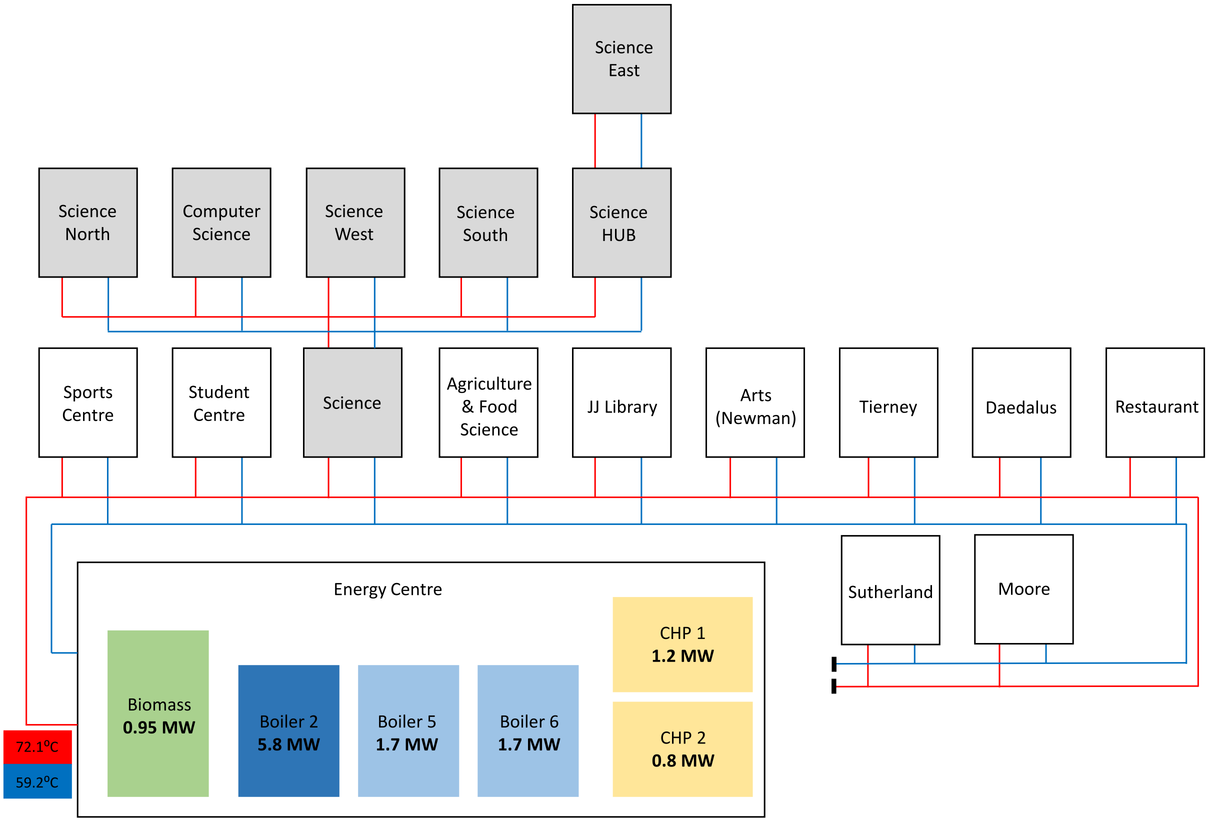

Fig. 2. Schematic of Campus District Heating Network.

Table 2
District heating network energy centre generators.

Generator	Capacity	Fuel type	Electric efficiency	Thermal efficiency	Notes
CHP 1	1.2 MW	Gas	0.436	0.433	Primary input: heat
CHP 2	0.8 MW	Gas	0.436	0.433	Primary input: heat
Boiler 5	1.70 MW	Gas	–	0.900	
Boiler 6	1.70 MW	Gas	–	0.900	
Boiler 2	5.80 MW	Gas	–	0.800	
Boiler X	0.95 MW	Biomass	–	0.900	Currently OFF

2.3. Campus energy model

Energy modelling was employed to carry out a baseline energy analysis and to investigate the impact of potential future scenarios on the campus CO_2 emissions. The steps carried can be summarised as follows:

1. Real time-series data for campus heat and electricity consumption and generation were extracted from the Building Management System (BMS), which provided electricity and heat consumption/generation profiles recorded in fifteen minute intervals and stored on a virtual dashboard. Data profiles for the year 2019 was chosen as the most representative one, since it was referred to a pre-pandemic period, thus, not affected by the safety measures introduced in 2020 and 2021. The meter readings were downloaded as .csv files and a visual investigation was carried out in the iSCAN platform (Integrated Environmental Solutions, 2023) to assess the quality of the metered data, checking for missing readings, seasonal and daily expected trends and outliers.
2. Creation of virtual representation (i.e., digital twin) of the UCD Belfield campus was developed by using the Intelligent Virtual Network (iVN) (Integrated Environmental Solutions, 2022), in combination with the iSCAN platform (Integrated Environmental Solutions, 2023), in order to obtain a complete representation of both heating and electricity networks. The 3D model was created in the iVN by defining the campus boundary and importing the contents from OpenStreetMap. Fig. 3a illustrates the three-dimensional (3D) model of the UCD Belfield campus, with the buildings within the campus area highlighted in yellow.
3. The data extracted from the BMS dashboard was used to assign the heat and electricity demand profiles to each building of the campus in order to create the baseline models. Information on generator specifications and control procedures were collected by data-sheets and internal operation and maintenance procedures. Both on-site heat and electricity generators were added to the model as network assets based on their capacity and efficiency specifications. Fig. 3b illustrates the heat nodes (in red) and the electricity nodes (in yellow) as implemented in the iVN model.

Simulation of the thermal and electricity network for the baseline models in order to matching demand and supply at each node. A schedule is required at each heat and electricity node to assign a priority list for generator dispatch. A minimum load requirement, below which they will not turn on, is also assigned to each generation unit which, therefore, will generate at any level required between this minimum and their rated power output. In case of electricity, if the connected generators do not have sufficient capacity to cover the load, the model can be instructed to acquire the remaining electricity demand from an external source (i.e., grid imports). For heat demand, no external source of heat entering the campus are available as a back-up source and, therefore, the balance of supply and demand is checked at each time-step and, if not verified, it ends the simulation with a shortfall in heat or electricity supply, meaning not all of the demand is met. The model outputs are the primary energy consumption and the CO_2 emissions occurred.

Given the complexity of the heat and electricity network of the UCD Belfield campus, a calibration was performed to ensure the accuracy of the numerical results obtained against the metered data available. As the demand profiles were assigned directly from this data, only the supply side required calibration. This process focused on the CHP units in the DHN Energy Centre as they are the key sources of heat for the campus. Furthermore, as heat is the primary output of the CHP generators, the calibration process focused on matching this to the metered heat output. ASHRAE acceptance criteria, typically employed for building models, was applied to the district model for calibration. In particular, the Mean Bias Error (MBE) was used, shown in Eq. (1), where m_i and s_i are the measured and simulated output respectively, while N is the number of data points. According to the ASHRAE standards, a limit of ±5% is considered acceptable (Mustafaraj et al., 2014).

$$MBE(\%) = \frac{\sum_{i=1}^{N}(m_i - s_i)}{\sum_{i=1}^{N} m_i} \tag{1}$$

The deviation between simulated and recorded total primary energy consumption for the all year was 15.4%. However, using the ASHRAE criteria, the calculated MBE was −3.53%, within the acceptable range. Therefore the model is considered calibrated and suitably representative of the heat and electricity networks of the campus.

2.4. Scenarios

The aim of the work described in the present paper is to provide achievable, evidence-based decarbonisation recommendations for the campus. As there is a wide range of technologies, measures and combinations of interventions that can be employed to reduce CO_2 emissions, a baseline analysis is required to direct the scenario development. This involved an investigation into the heat and electricity generation and consumption of the campus, which aimed to identify key energy consumers and opportunities for emissions reductions.

Once the target areas had been identified, the scenarios were created. The aim was that each scenario would build on the previous, making changes to network configurations, generators installed or dispatch schedules. The scenario development process was based on the literature reviewed, the baseline analysis and the information from UCD Estate Services to investigate the impact of realistic, achievable upgrades to the campus networks.

An overview of the scenarios modelled can be seen in Fig. 4. Starting from the baseline, five scenarios have been explored, two of which have sub-variations, as outlined here below:

- Scenario 1: the five local gas boilers in the buildings connected to the DHN have been removed and the full heat demand is supplied through the DHN. Local CHP units in these buildings, where applicable, are still present. This measure was chosen as it has been agreed by UCD Estate Services to be one of their next steps towards decarbonisation.
- Scenario 2: As in the first scenario, scenario 2 has the local gas boilers in the DHN-connected buildings removed. Additionally, the current 0.95 MW biomass unit has been turned on. Two variations of the second scenario exist, which differ based on the priority schedule in the DHN: (a) the biomass generator is at the

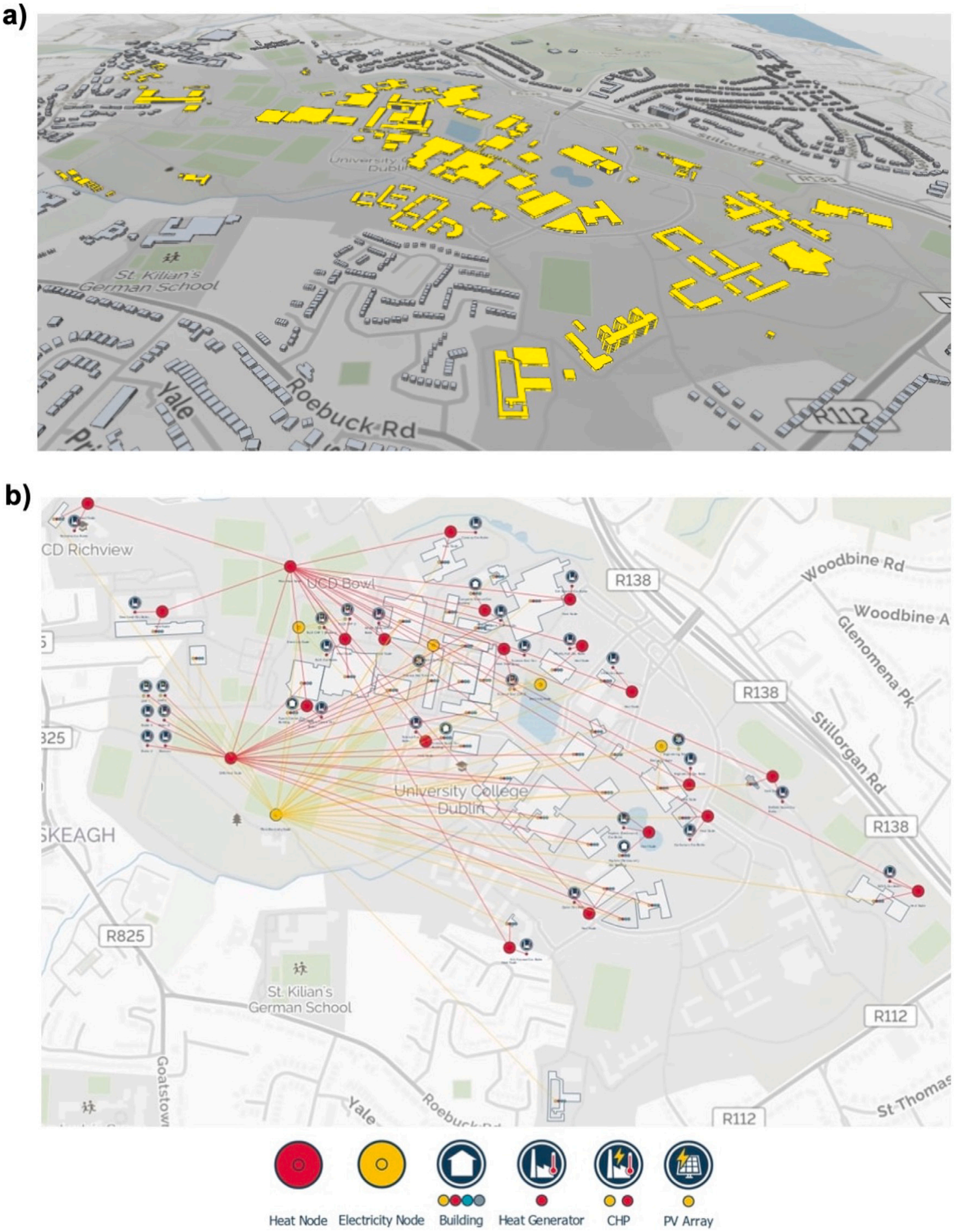

Fig. 3. (a) Full UCD Belfield campus model. (b) Identified model nodes in the iVN environment.

top of the dispatch order, followed by the CHP units and, finally, by the remaining gas boilers. (b) the two CHP units are kept at the top while the biomass boiler is placed as second in the dispatch order, followed by the gas boilers. These two variants were chosen to investigate whether the lower emissions factor of the biomass unit or the dual production from the CHP units resulted in lower overall CO_2 emissions.

- Scenario 3: as in the previous scenarios, the local gas boilers in the DHN-connected buildings have been removed. The current biomass boiler has been replaced by a biomass CHP unit with a rated heat output of 900 kW and a rated electricity output of 600 kW. This biomass CHP generator has been placed at the top of the priority dispatch list, followed by the current baseline sequence. The efficiency specifications for the biomass CHP unit can be found in Table 3, obtained from the supplier data sheets.
- Scenario 4: it investigates the impact of adding the biomass CHP unit from scenario 3, while also keeping the current biomass unit in operation. There are two variations, which differ based

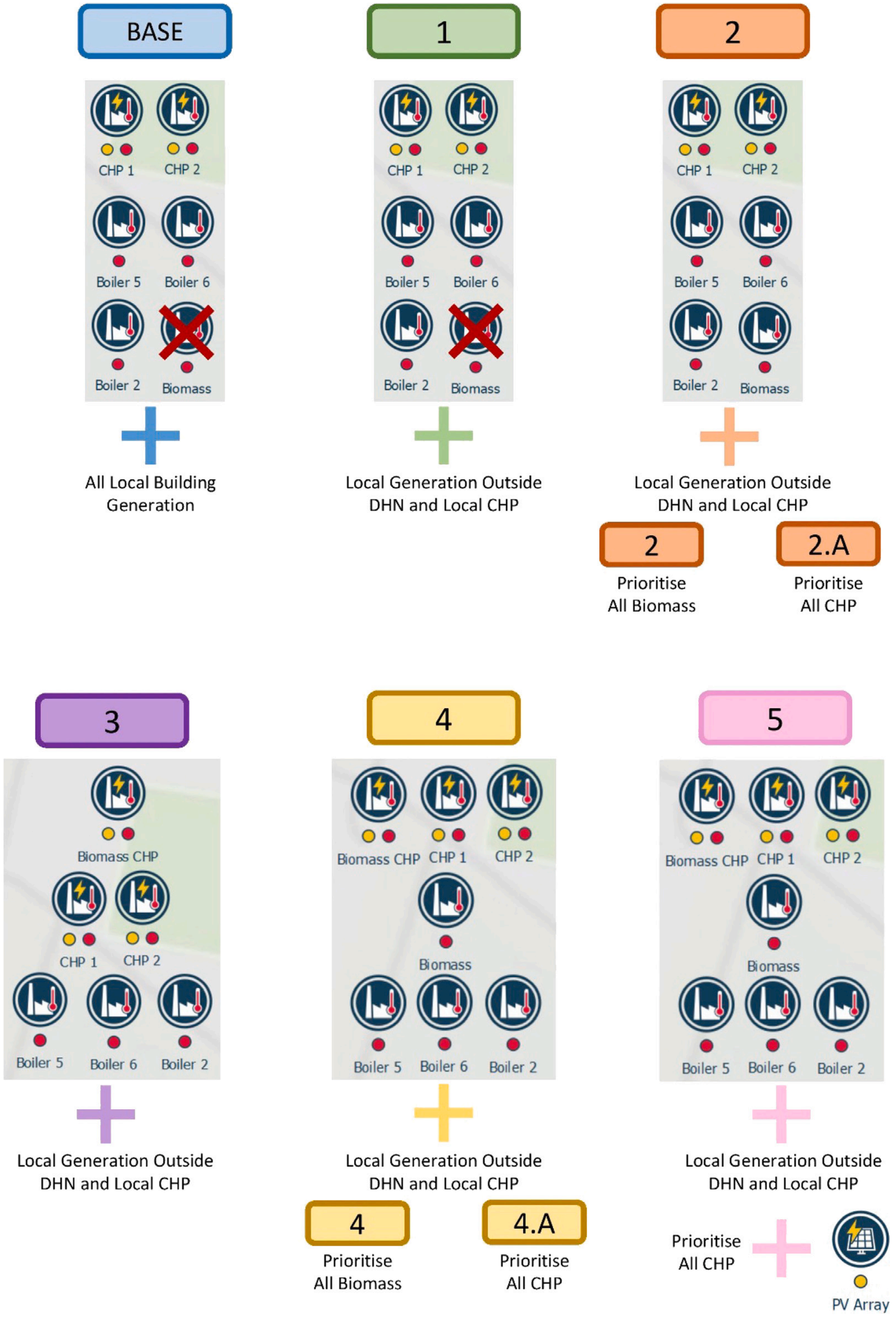

Fig. 4. Summary of the tested scenarios.

on the priority schedule in the DHW: (a) the two biomass units – i.e., biomass boiler and biomass CHP – are at the top of the dispatch order, followed by the two gas CHP units and the gas boilers; (b) the dispatch order gives the priority to the three CHP units, with precedence to the biomass CHP, followed by followed next by the biomass boiler and, finally, by the gas boilers. These two variations were explored to determine which configuration offered the greatest emissions savings.

- Scenario 5: starting from scenario 4b, this scenario considers the potential integration of solar photovoltaic (PV). The capacity of solar PV was calculated following the method suggested by Horan et al. (2019b). As a result, 3 MW of solar PV was installed and

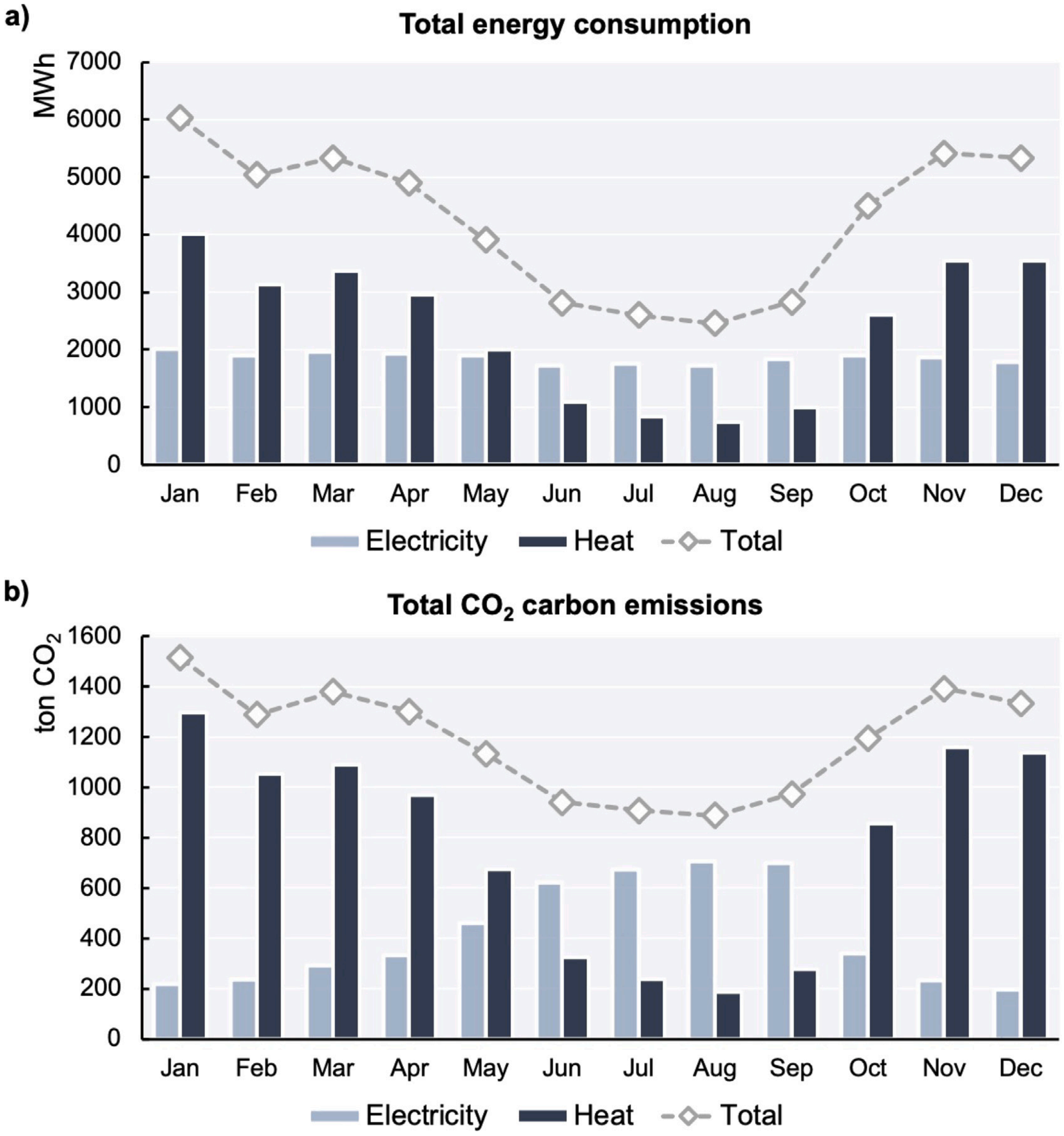

Fig. 5. Total energy consumption (a) and carbon emissions (b) of the UCD Belfield campus in 2019. Results elaborated by using the data extracted from the BMS dashboard. The greater equivalent carbon emissions in summer is associated to the lower usage share of CHPs during this period and the consequent increase of electricity drawn from the national grid.

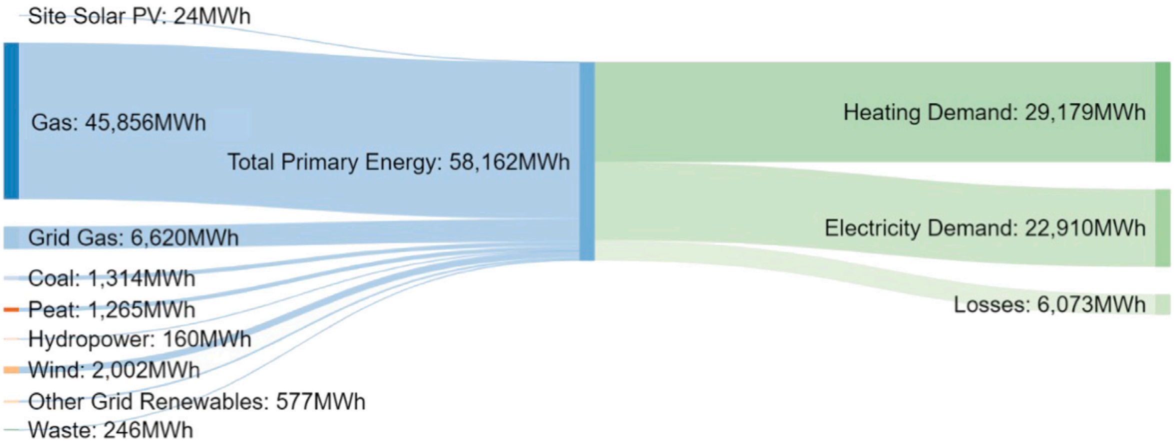

Fig. 6. UCD Belfield campus energy flow in 2019.

Table 3
Generation efficiencies of gas boiler, gas and biomass CHP units and carbon emission factors for fuels and electricity.

Parameter	Partial/Full load	Biomass CHP	Gas CHP	Gas Boiler
Electric efficiency	Partial load	0.22	0.40	-
	Full load	0.22	0.44	
Thermal efficiency	Partial load	0.76	0.43	0.85
	Full load	0.76	0.47	
Fuel CO_2 emission factor		0.025	0.203	0.203
Electricity CO_2 emission factor		0.409	0.409	–

electricity generation from solar PV is considered to have no associated emissions factor in this analysis.

3. Results

3.1. Baseline assessment

In the baseline analysis, CO_2 emissions are categorised as being from heat generation using natural gas, or electricity sourced from the grid. A first high-level analysis was carried out for the entire campus to assess the total energy consumption, energy generation the energy generation and the associated CO_2 emissions. The results are shown in Fig. 7, which reports the total UCD campus energy consumption for 2019 on a monthly basis (Fig. 7a) and the total carbon emissions (Fig. 7b). It can be noted that electricity consumption remains relatively stable throughout the year, decreasing slightly during the summer months, which is the period without in-class teaching and when a lower demand for lighting. On the other hand, heating-related emissions show a more seasonal variation with, as expected, a higher consumption during the heating season. Overall, heating accounts for more than half (56.1%) the total energy consumption of the campus. The breakdown of primary energy used for meeting both electricity and heating demands is illustrated in Fig. 6, which reports the Sankey diagram of the primary energy flows of the UCD Belfield campus related to the year 2019.

Fig. 5b shows the corresponding carbon emissions associated with the energy consumption for electricity and heating. Based on this analysis, the heating sector accounts for the greatest portion of the CO_2 emission produced on the campus and therefore is the main target of the reduction measures.

The next step in the baseline analysis was to identify the key buildings responsible for the campus CO_2 emissions. The emissions are quantified based on the amount of CO_2 emitted to generate and supply the energy demand of the building. It was found that six of the top ten CO_2 producing buildings are currently connected to the DHN. This indicates that decarbonising the DHN supply would result in widespread CO_2 emissions reductions. Furthermore, replacing or a installing system in the EC would be less disruptive than tackling individual buildings that are in use and may be less cost-intensive than adding multiple new units elsewhere. Therefore, a clear first step would be to improve the current DHN supply.

The DHN currently contains six generation units, as described in Table 2, although only five are in operation, with the biomass system turned off. The network currently supplies heat to sixteen buildings and produces electricity that is distributed around the campus. As shown in Table 1, five of the buildings have their own local heat supply. Both the DHN EC generators and the local units were analysed in terms of their CO_2 emissions. It was found that the CHP units in the DHN EC were responsible for the greatest share of CO_2 emissions. However, they also generated the most heat and had electricity as a useful by-product. Therefore, the emissions factors of the fuels would play a more significant role in the scenario development, rather than the current total CO_2 emissions from each generator.

Concluding, three main key findings resulted from the baseline analysis:

1. The generation of heat is responsible for a larger share of CO_2 emissions than the supply of electricity.
2. The buildings currently connected to the DHN are responsible for a significant portion of the campus CO_2 emissions.
3. There is evidence to suggest that decarbonising the current DHN, including removing the local gas boilers in the connected buildings, could result in a substantial reduction in CO_2 emissions, while also causing having a low impact on the campus in terms of physical change and disruption.

These results led to the definition of the scenarios described in Section 2.4, which are analysed in the following section.

3.2. Scenario analysis

The UCD Belfield campus digital twin 2.1 was used to analyse the different scenarios outlined in Section 2.4 and the results were compared with the baseline in terms of carbon emissions occurred to meet the electric and heat demand, as shown in Fig. 7.

Regarding the electricity, the CHP units, the solar PV installations and the grid supply electricity to the campus. A comparison of the emissions in each scenario can be seen in Fig. 7a. A common theme in the results is that the CO_2 emissions from electricity are lower when more CHP units are installed and used. This is due to the lower emission factor of gas and biomass, compared to the electricity on the grid. Scenario 1 experienced a reduction in electricity emissions as the CHP units on the DHN were used to supply a portion of the heat previously generated by local gas boilers, thus simultaneously generating electricity. In the first variation of Scenario 2, prioritising the biomass generator pushed electricity imports above the base case, while dispatching the CHP units first in the second variation produced the same amount of electricity as in Scenario 1. From Scenario 3 onward, the biomass CHP unit was added to the DHN. While this generator uses fuel with a lower emission factor, it has approximately half the electrical efficiency of the gas CHP units. This, combined with the lower capacity compared to CHP 1, the former first preference, causes an increase in the need for imported electricity. However, Scenario 5 shows that the addition of a local electricity source, in this case 3 MW of solar PV, can reduce this reliance on imports, achieving a 29% decrease from the baseline.

Fig. 7b illustrates the carbon emission associated with the heat generation, mainly due to the gas consumption of the CHP, gas and biomass boilers. As expected, the introduction of a biomass generator reduces the CO_2 emissions associated with gas, as its consumption is decreased. In contrast to the electricity emissions in Fig. 7a, the prioritisation of the biomass generator, which produces only heat, has a positive impact. Clearly, any switch from gas will result in a reduction in gas associated CO_2 emissions. *i*th the exception of Scenario 1, where the lower thermal efficiency of the CHP units in the DHN EC compared to that of the local boilers resulted in an overall increase in heating emissions, the scenarios each achieved a reduction. The greatest reductions were achieved where the biomass generator, which produces only heat, was placed above the gas CHP units in the priority schedule (scenario 4a). However, it has been shown that this has the opposite impact on the emissions associated with the electricity supply.

In order to have a complete picture of the carbon emissions of the UCD Belflield campus, Fig. 8 shows the total CO_2 emissions. All the identified scenarios show an improvement in relation to the baseline (i.e., current configuration). This means that, the increment of the

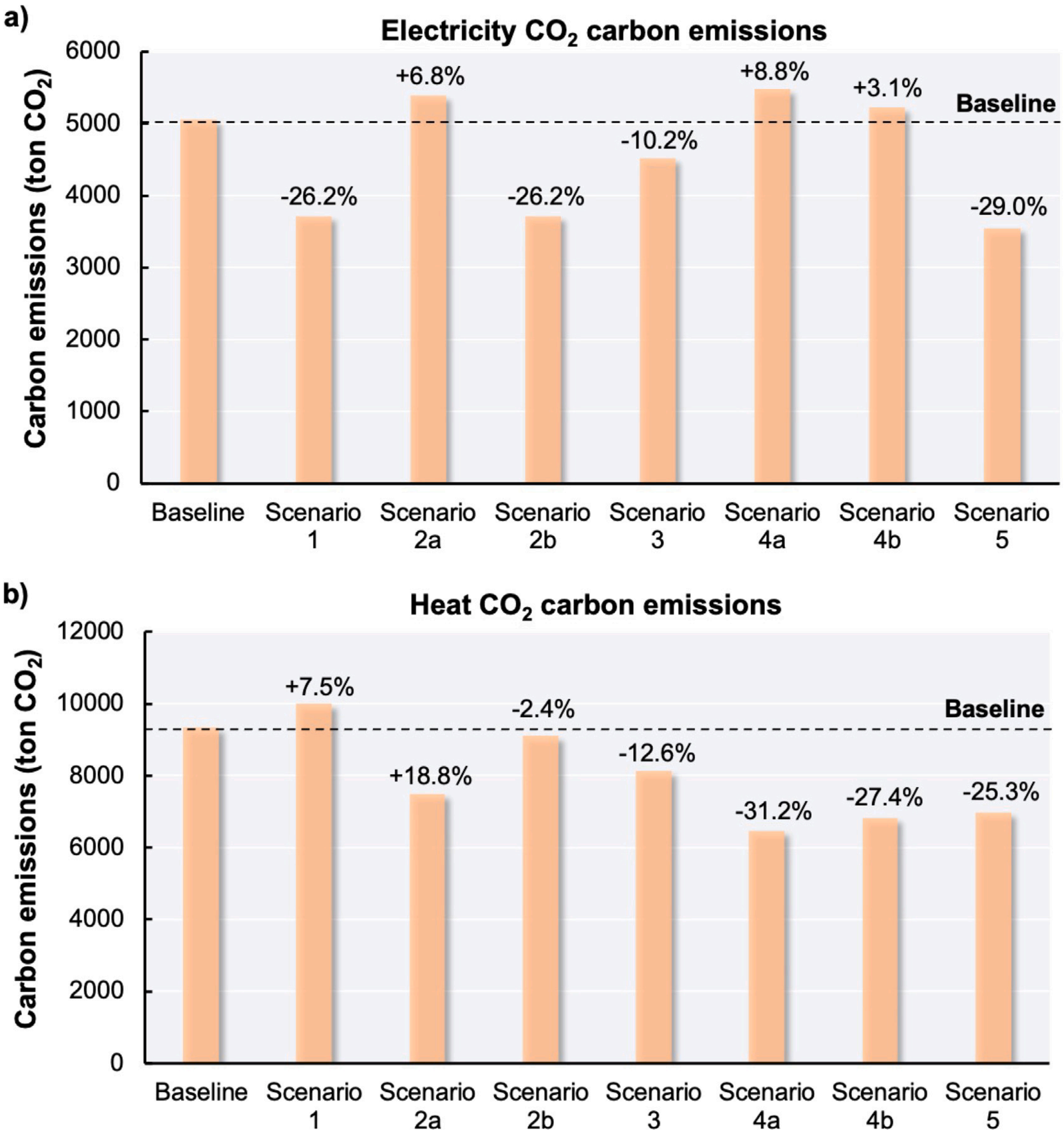

Fig. 7. Yearly (a) electricity and (b) heat carbon emissions of UCD Belfield campus for all scenarios analysed.

electricity-related emissions, occurring in scenario 2-4a-4b (Fig. 7a) are compensated by a reduction at the heat-generation side. It can be seen that there is the potential to reduce the total CO_2 emissions of the campus by up to 10.74% with the generation units currently available in the DHN. Should the opportunity arise to install an additional unit, this analysis recommends the use of a biomass CHP unit, which can result in a CO_2 emissions reduction of approximately 17%. On the other hand, particular attention must be given to the source of the biomass: the recommendation extracted from the present analysis is to source the feedstock locally, including biomass collected from on-site maintenance of the grounds.

The majority of the CO_2 emissions reduction is a result of a change in the heating of the campus. An opportunity remains to tackle the electricity sector with renewable electricity generation. This work has identified the potential for 3 MW of solar PV on the campus, which would result in almost a 10% additional reduction in carbon emissions. This would bring the total CO_2 emissions reduction to 26.61%, approximately a quarter of the way to a full decarbonisation of the UCD Belfield campus.

4. Conclusions

University College Dublin is committed to the continued reduction of CO_2 emissions across the Belfield campus, with plans extending beyond the first year of the energy master plan. The Belfield campus is already well developed, with a range of existing buildings and infrastructure. Thus, UCD is aware that upgrades and refurbishments will play an even greater role in decarbonisation than plans for new builds. In this context, the present work analysed different energy efficiency scenarios at the generation level to support the decarbonisation of the UCD Belfield campus. A number of actions have been identified by UCD Estate Services to undertake during the first year of the new energy master plan. To support the increased demand on the DHN and to introduce a more sustainable heat source, it is planned to have the 0.95 MW biomass generator fully operational within the year. It is expected that the combined impact of these measures will be almost a 10% reduction in the total CO_2 emissions.

The analyses conducted until this point concerns the interventions on the UCD Belfield campus already planned by the UCD Estate Services. However, since the district heating network has been identified

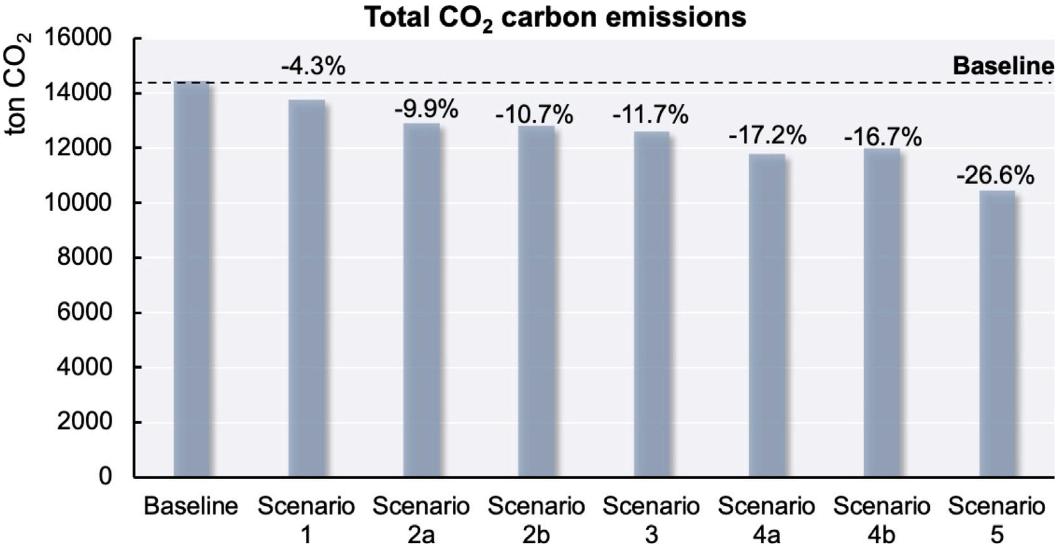

Fig. 8. Yearly total carbon emissions of UCD Belfield campus for all scenarios analysed.

as having a key role in meeting the heat demand of the campus, further decarbonisation opportunities can be exploited. Over the coming years, preliminary energy retrofitting plans have been drafted based on the installation of heat pumps at large scale, starting with 1 MW to 2 MW on the district heating network and progressively remove all the gas boilers.

In terms of long-term planning, further decarbonisation opportunities can arise by implementing energy efficiency measures at the demand side. Despite being outside the scope of the present analysis, it is worth to mention that almost a third of the building stock at Belfield was constructed in the 1960's and 1970's, many of which are now in need of major refurbishment. Given the embodied energy of these buildings, levelling the site and building an NZEB in its place is not a viable option. Currently, the Building Energy Rating (BER) of the buildings varies greatly across the campus, reaching as low as a G-rating. Therefore, implementing refurbishment measures to increase the energy-rating of the existing campus buildings is a fundamental step to reduce the energy demand of the campus, particularly in terms of space heating. In this context, the results outlined in the present paper needs to be complemented by extensive analyses on refurbishment opportunities across the UCD campus. Throughout the next years, plans to make continuous energy management improvements, prioritising a reduction in emissions and optimisation in the control of campus systems and processes are in place. This must also consider that UCD campus is expected to expand in terms of both building floor area and population. While steps will be taken to ensure that all new UCD buildings are of net-zero energy building (NZEB) standard, by involving engagement in Energy Efficient Design (EED) and procurement, including a carbon life-cycle evaluation, for all projects, future analysis should also consider aspects such as transports, mobility and overall impacts of the UCD campus on adjacent neighbourhoods to define a comprehensive and integrated plan towards sustainability.

The present paper is aligned with SDG7 and described the results obtained by analysing several decarbonisation strategies for energy systems of an university campus. The adopted methodology and results obtained, although they refer to a specific case study, represent a useful reference for carrying out the assessment of decarbonisation strategies in similar setting – i.e., university campus – and for urban districts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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