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Strategies towards reducing carbon emission in university campuses: A comprehensive review of both global and local scales

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ABSTRACT

Universities and other Higher Education Institutions (HEIs) have a key role to play in promoting decarbonisation and sustainable development. The implementation of low-carbon and energy-efficient strategies in colleges and University Campuses (UCs) is of utmost importance, as the number of these buildings continues to grow rapidly worldwide. This paper uses an organized search strategy for reviewing the most impactful previous studies regarding decarbonisations strategies in UCs in different climate contexts. This research presents a comprehensive overview of influential parameters, which are practical to be considered in designing new or retrofitting existing UCs which has not been done before and also highlights relevant policies and guidelines required to implement these parameters. These factors are spatial planning and landscape, renewable and clean energy, energy systems, thermal envelope, green transportation, management and control, human-related performance and smartness. This review also explores the recent trends in the decarbonisation of UCs such as the application of smart technologies and implementation of real-time data-based control and management technologies. Finally, this review presents the research gaps, future trends and technologies which will facilitate the decarbonisation of UCs. This review would help researchers and designers to facilitate the transition towards net-zero carbon future in university campuses.

Nomenclature and abbreviation

AI	Artificial Intelligence
CHP	Cmbined-heat-and-power
DV	Displacement Ventilation
EIO-LCA	Economic Input-Output Life Cycle Assessment
EV	Electric Vehicles
GHG	Greenhouse Gases
HEI	Higher Education Institution

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HVAC	Heating, ventilation, Air conditioning
HRES	Hybrid RE System
ICT	Information and Communication Technology
IoT	Internet of Things
MLPANN	Multilayer Perception Artificial Neural Network
NV	Night Ventilation
NSGA-II	Nondominated Sorting Genetic Algorithm-II
PEEM	Passive Efficiency Measure
RE	Renewable Energy
UC	University Campus

1. Introduction

The rapid growth of urban populations, combined with their significant contribution to Greenhouse Gases (GHG) emissions, highlights the important impact cities have on environmental sustainability challenges [1]. The attention has shifted to analysis of energy and related greenhouse gas emissions from built environments. As a result of increasing environmental concern and global warming [2]. Human activities are responsible for a 1.0 °C increase in global warming compared to pre-industrial levels, and if current trends continue, global warming is estimated to increase by 1.5°–2 °C by 2052 [3]. Therefore, critical actions are needed to limit GHG emissions by 45% below 2010 levels by 2030 in order to reach the goal of zero net emissions by 2050 [4]. In particular, buildings are currently responsible for 39% of global energy related carbon emissions: 28% from operational emissions, from energy needed to heat, cool and power them, and the remaining 11% from materials and construction [5].

Universities and other Higher Education Institutions (HEIs) have a key role to play in promoting decarbonisation and sustainable development due to their social and educational role in training future leaders, as well as their large-scale energy consumption and resource usage [6,7]. For example, in the US, universities are responsible for about 2% of total GHG emissions, which is equivalent to the emissions from commercial aircraft or landfills [8]. Therefore, achieving carbon neutrality in the HEIs sector could have a significant impact on the environment.

The implementation of low-carbon and energy-efficient strategies in University Campuses (UCs) is of utmost importance, as the number of these buildings continues to grow rapidly worldwide. Research has examined the potential for UCs to reduce GHG emissions, improve energy efficiency, and promote sustainable urban growth. Recent years have seen several review articles on decarbonisation in UCs. For example, Kourgiozou et al. reviewed the opportunities and challenges associated with the application of smart energy systems in UCs, focusing on policies in the UK [9]. Dlouhá et al. studied the challenges and driving forces behind sustainability policies in UCs and HEIs in Eastern and Central European countries [10]. Another study analysed the common obstacles and challenges to implementing green building initiatives in HEIs, examining the perspectives of various stakeholders [11]. Ali et al. reviewed the impact of South African UCs on GHG emissions and Renewable Energy (RE) generation and found that current participation was not impactful enough, highlighting the need for new green campus initiatives and guidelines from African governments [12]. Amaral et al. conducted a comprehensive review of environmental actions and initiatives used by UCs to identify key metrics that impact environmental and sustainability performance in HEIs [7]. Finally, Mohamed, Noor, and Sing analysed the adoption of sustainability indicators in three UCs in Malaysia using the UI GreenMetric, a World University Ranking, focusing on indicators such as setting and infrastructure, energy and climate change, waste, water, transportation, and education and research [13].

Comprehensive review of the current body of literature shows that a limited number of review papers have analysed subjects related to decarbonising of UCs [14–17]. Existing review papers investigated some combinations of major factors related to UCs decarbonisation topics such as “energy efficiency”, “carbon emission”, and “policies and green initiatives”, and the corresponding influential parameters that affect these domains. However, none of these review papers have included all these domains and related parameters for assessing carbon emissions of UCs. Also, another novel point of this paper is to review more advanced trends such as smartness and data-driven control and management systems which are barely assessed in previous UCs studies. Furthermore, limited studies have reviewed “international policies and initiatives” regarding the application of energy efficiency and carbon-neutrality strategies in the UCs. Finally, existing studies are mostly focused on a specific location or weather condition and not universal factors facilitating decarbonisation of UCs.

Accordingly, the main novelty of this review is to present a comprehensive overview of influential and advanced parameters for reducing carbon emission of UCs, which are practical to be considered in designing new or retrofitting existing UCs. Furthermore, this study will highlight relevant policies and guidelines required to implement these parameters in context of UCs. Moreover, this review has not been restricted to UCs with specific scales or climatic contexts. To reach this aim, this paper contributes to the existing literature by addressing the following topics:

- This study identifies and categorises the most influential parameters regarding decarbonisation of UCs with relevant metrics and software used.
- This study reviews important policies and initiatives regarding decarbonisation of UCs.
- This review explores the recent trends in decarbonisation of UCs such as application of smart technologies and implementing of data-driven-real time data-based control and management technologies.

- Finally, this review presents the research gaps, future trends and technologies which will facilitate the decarbonisation of UCs.

The structure of the paper is as follows: Section 2 reviewes the most recent and relevant policies and initiatives regarding decarbonisation of UCs; Section 3 presents the review methodology and the required steps to conduct a comprehensive and systematic review; Section 4 illustrates a detailed review of selected studies to investigate the influential parameters and impactful and related policies; Section 5 includes a detailed discussion of the research gaps, future trends and concise conclusion.

2. International policies and pledges

Because of the important role of HEIs in delivering sustainability, HEIs are encouraged to teach sustainable development concepts, encourage research on sustainable development issues, green their campuses, and support sustainability efforts in their communities [18]. International policies, guidelines and regulations are outlining the most important objectives and areas and related strategies that needed to be addressed by HEIs. In addition to these polices and guidelines that help UCs to design their pathways to a green future, there are some international pledges that show the commitments of these UCs towards their green and decarbonised future. These pledges and policies are reviewed in more detail in the following paragraphs.

As one of the most important sustainability forums, at the Times Higher Education Climate Impact Forum, 1050 UCs from 68 countries made a range of commitments to reach net-zero emissions by 2050 and transform their impact on nature. As one of these commitments, an initiative named Nature-positive Universities was issued showing the education sector's leadership before COP26 in Glasgow, UK [19]. Nature-positive Universities is an initiative developed and launched by the United Nations Environment Programme (UNEP) in collaboration with the University of Oxford. This initiative is a global network of universities in order to support the prioritisation of nature restoration within the HEI sector, in operations and supply chains, on campuses and within our cities. People in over 400 universities have expressed an interest in joining this network, which will form a major contribution to the UN Decade of Ecosystem Restoration and the Sustainable Development Goals [20,21].

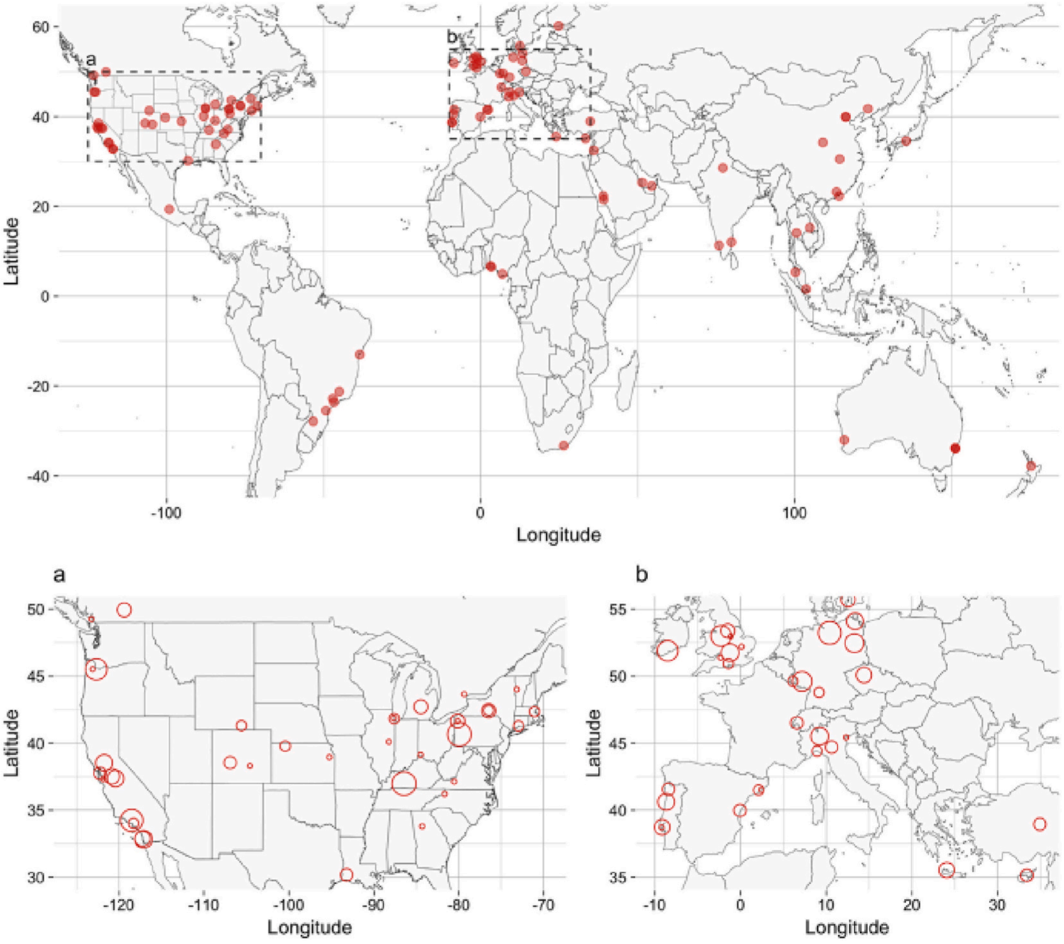

Fig. 1. Association between the number of initiatives and institutions by country, and the ratio of the participating HEIs and the total number of HEIs by country [7]. Red circles shows the weighted distribution of the HEIs involved in the initiatives found on literature. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

In another international pledge, academic institutions from across the globe have signed up to the UN's Race to Zero campaign, committing to reduce their carbon emissions to zero by 2050 at the latest. The initiative has been led by the Environmental Association for Universities and Colleges (EAUC) and Second Nature with support from UNEP [20]. In this regard, the 1050 HEIs who made pledges for the Race to Zero, and who represent close to 10 million students – or 4.5% of the world's 220 million students – must be consistent with the criteria provided by the Race to Zero's Expert Peer Review Group [20].

In terms of individual initiatives and policies, UCs have realized this collective potential, and as such different UCs all around the world have contributed to preparing and signing sustainability and decarbonisation initiatives. For instance, in the US, in 2007 over 600 HEIs, representing over 30% of U.S. higher education enrolment, signed the American College & University Presidents' Climate Commitment (ACUPCC) and committed to carbon-neutrality [22]. The University of California (UC) has pledged a sector-wide scope 1 and 2 decarbonisation targets of being carbon neutral by 2025 on its 10 campuses [20]. Another example is the Liberal Arts Campus located in Morris, Minnesota, part of the University of Minnesota in which this campus is able to meet 60% of its energy demand through its wind turbine farm by implementing RE resources [23]. Also, Los Angeles Community College District (LACCD) has taken a major step along with the American Association of Sustainable Higher Education (AASHE) with its goal to advance the utilization of advanced energy technologies to make all college campuses operate at "net-zero energy consumption" and "climate neutral" [23].

In the UK, University of Glasgow, which has set a net-zero target of 2030, was the first university in the UK to declare it would divest from fossil fuels within a decade. The Association of Colleges and the Environmental Association for Universities and Colleges (EAUC) in the UK, launched a Climate Commission for UK Higher Education (HE) and Further Education students and leaders to meet the desire for the HEI sector carbon emission reduction [24]. Based on the IPCC recommendations, they propose that Further and HE institutions should aim to achieve net-zero Scope 1 and 2 emissions by 2030 and Scope 3 no later than 2050.

In Canada, the University of Toronto has committed to develop a low-carbon action plan by 2030 with a range of interventions planned. In Ireland, currently, there is a gap in the academic literature and government policy relating to how HEIs may best facilitate a national transition towards a low-carbon society by capitalising on synergies between government policy, private sector commercialisation, and HEI living lab resources. Although the National Development Plan (NDP) has allocated €2.2 billion exchequer funding to the HEI sector for campus infrastructure construction and upgrades [25]. In Asian UCs, the Japanese university of Chiba become the first university in Japan to run exclusively on RE before 2025, as well as to establish the Renewable Energy University League of Japan.

A recent review study by Amaral et al. reviewed the sustainability initiatives in 106 UCs from 31 countries around the world. They showed that among these HEIs North America and Europe are the regions with the highest number of identified institutions [7]. When comparing the total number of existing HEIs listed in Scimago (2018) and the number of identified HEIs, these represent 3% of a total of 3234. As may be observed in Fig. 1, the ratio between participating and total HEIs by country is notably low. As an example, the USA is by far the country with the most reported publications and actions; however, when compared to the national panorama, only 34 out of 432 institutions were identified, which represents about 8% of American HEIs. Fig. 1 shows the distribution of these initiatives across the globe highlighting the higher number of initiatives in Europe and North America [7].

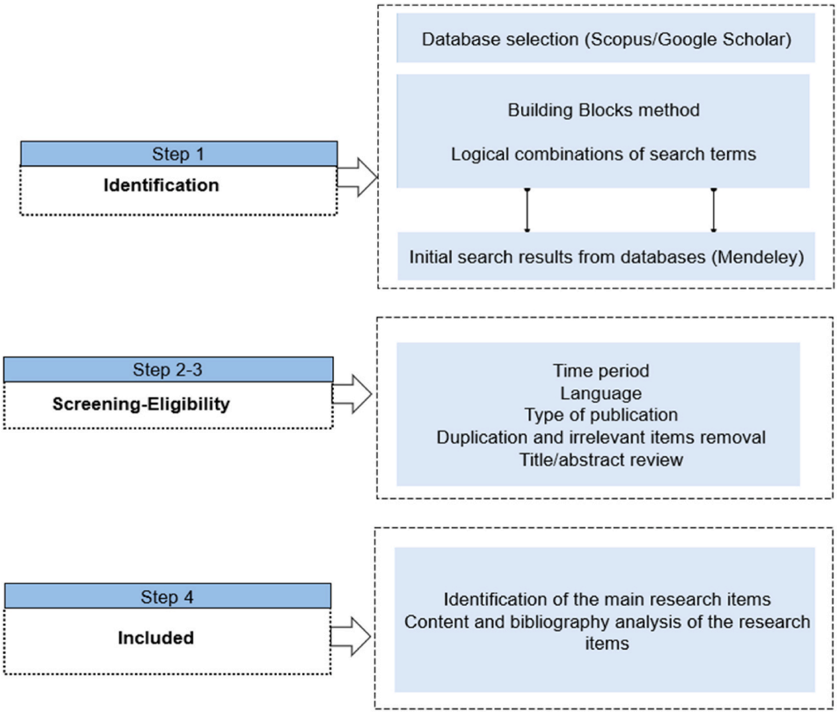

Fig. 2. The search strategy for identifying and reviewing related literature.

3. Review methodology

3.1. Scientific database searched

This paper uses an organized search strategy for reviewing the related literature as it is challenging to conduct a manual review of energy efficiency and decarbonisation in buildings and urban areas studies due to the broad scope of this field. The study uses Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) methodology to be able to investigate interactions between different dimensions and parameters and how they will develop the research framework [1]. The PRISMA-based search strategy incorporates four steps including identification, screening and eligibility and finally included studies which are discussed in more detail in the following paragraphs.

In the first step, this study recognises related resources, studies and search engines. In this regard, an organised strategy is used to combine keywords and search terms. The logical combinations of search terms facilitate the identification of relevant articles in Scopus and Google Scholar, as the main bibliographic databases. The selected keywords for this study are: “University campuses” AND (“energy efficiency” OR “carbon emission” OR “decarbonisation” OR “policy”, OR “renewable energy” OR “smart” etc. These domains are subsequently combined to formulate multiple search attempts in the selected databases.

Then in the screening and eligibility steps, two criteria are used to enhance the research results: first, papers are screened to ensure that search results are limited to peer-reviewed journals (research and review papers) with the removal of presentations in conferences. Then, the search results are screened to remove duplicate articles and irrelevant subject areas (for instance biochemistry, chemistry and so on). Second, search results are screened based on the title and abstract to confirm that selected papers are in compliance to search keywords. Also, studies that have analysed educational buildings other than UCs such as schools are excluded. This study uses Mendeley software to facilitate the refining process and screening of the search results by scanning titles, abstracts, and keywords of these papers.

At the last step, as a result of these three steps, final studies are carefully selected to enter the review process. By applying the methodology, 390 studies are identified from the databases and after applying screening and eligibility criteria, 63 studies are included to start the review process. The workflow diagram of this review is presented in Fig. 2.

3.2. Bibliographic analysis

Analysing the publication sources of selected studies shows that the top publication sources are Applied Energy, Journal of Building Engineering and Renewable and Sustainable Energy Reviews from Elsevier. A detailed analysis of these journals and also publication type of each study is depicted in Fig. 3.

Analysing the chronological trend of selected research shows a sharp increase in the number of publications from 2020 to 2022 although the number of decarbonisation studies for UCs is still not comparable to other building types such as residential or commercial buildings. This growing pattern points out that the interest in studying energy performance and decarbonisation strategies in UCs is growing and hence affirming that this field has great potential for future research (Fig. 4).

4. Decarbonisation of UCs

This section first highlights relevant international policies and pledges and then presents a comprehensive overview of influential parameters, which are practical to be considered in assessing and designing retrofit strategies of UCs.

4.1. Influential factors

To identify and provide a more in-depth analysis of the reviewed papers, the authors proposed important factors based on reviewed papers’ research content and keywords. These factors to lower the carbon emission from these UCs are categorised into spatial planning and landscape, renewable and clean energy, energy systems, thermal envelope, green transportation, management and control, human-related performance and smartness (Fig. 5).

For each of the factors, representative research works are described and discussed in this section.

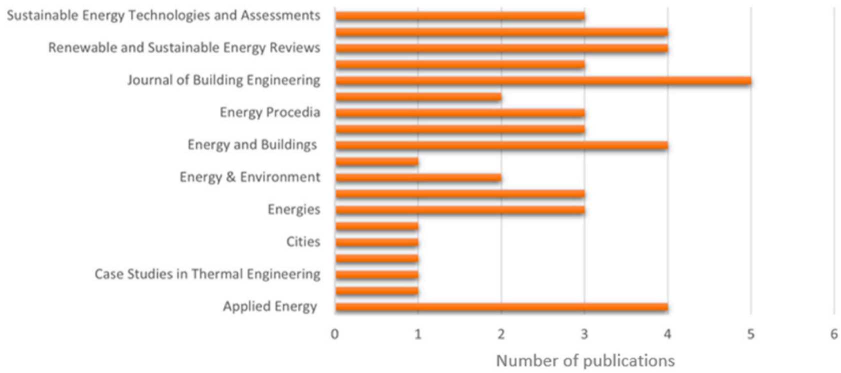

Fig. 3. The publication sources of selected papers.

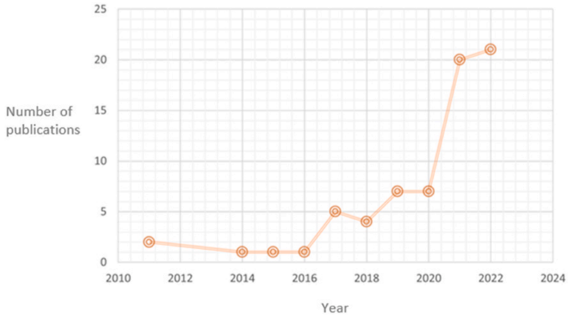

Fig. 4. Number of papers published in selected databases investigating energy efficiency and decarbonisation in UCs.

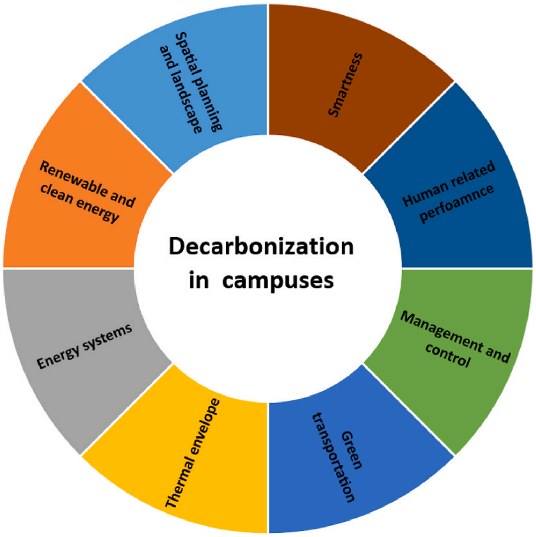

Fig. 5. The most important investigated parameters in the literature review.

4.1.1. Spatial planning and landscape

UCs are small-scale cities with a significant impact on CO_2 emissions and sustainability criteria due to their form and landscape. The structure of land use, infrastructure construction, transportation, and carbon sinks all can be affected by UCs form, ultimately affecting energy consumption and CO_2 emissions in both direct and indirect ways [26]. Since UCs form usually does not change rapidly after construction, they, therefore, have a gradual effect on CO_2 emissions in a long-term process. An unsuitable form will have serious socioeconomic and environmental consequences [27]. Furthermore, UCs landscape may aid in mitigating some of the fossil fuel consumption and potentially reducing energy demand through designing some elements such as canopy shading and wind breaks and also including more green areas in the UCs [28]. Therefore, a great effort is required in the spatial planning of UCs during construction or in later stages of renovation and retrofitting to ensure sustainability indicators are met.

In this context, different studies have investigated the impact of the form and landscape of buildings on their energy consumption and carbon emission. For example, a design-driven analysis employing parametric modelling was carried out in Ref. [29] to assess the impact of multiple scenarios of form on the sustainability performance of buildings. The results demonstrated that the building coverage ratio should be greater than 0.17 and the sky view factor should be at least 54.17% in order to preserve the optimal solar potential and energy savings. In addition, a recent study at Tsinghua University examined the impact of expanding plant covering as a strategy to boost the campus's capacity to absorb CO_2 in an effort to attain carbon neutrality [30]. In this study, the quantity of CO_2 absorption from covering the campus's vacant land with vegetation (trees, grass, etc.) as well as the vertical surfaces of buildings with a particular kind of creeping plant was investigated. Results showed that by growing plants on the east, west, and north surfaces of the buildings (up to the 5th floor), keeping the current plants and installing PV panels on the roof and the south surface of the structures carbon neutrality can be achieved.

4.1.2. Renewable and clean energy

Decarbonizing energy sources by moving towards green and clean energy resources in UCs is an important strategy to have a more sustainable and green future. Reviewed study showed a high contribution of renewable and clean energies to the energy performance of UCs. Although renewable and clean energies measures are not specific to UCs, the considerable impact on energy consumption or carbon emission reduction makes it worthwhile to investigate their performance in UCs. One of the big challenges to implementing RE and clean energies are their capital and maintenance cost. However, due to declining installation costs of RE resources and growing environmental concerns, the use of RE in the generation of electrical energy is becoming more widespread.

Clean energy sources, however, are still in the early stages of energy paradigm shifts in multi-energy and large-scale cases such as UCs. Particularly, large-scale RE integration technologies and approaches lack the sophistication needed for intelligent control management and maintenance [31]. Reviewing the literature on RE reveals that several studies are carried out with the goal of evaluating the impact of RE on the energy performance of UCs and as such different strategies and approaches are introduced. These strategies are based on different factors such as access to RE resources and technologies, socio-economic feasibility, climate, etc., Following paragraphs show the potential of implanting renewable and clean energies in UCs in more detail.

Reviewing the literature showed that although RE is the most prevalent option for reducing carbon emissions for UCs, only a minority of UCs have integrated renewable technologies into their energy systems. Kourgiozou et al. [9] in Fig. 6 displayed the map of RE generation from on-site and off-site sources in UCs of UK as a percentage of their total energy consumption in the UK, indicating that UCs located in suburban areas have the highest proportions of renewable generation, while UCs in urban areas have less renewable generation rate. This figure shows the high potential of adopting RE technologies in more compact and dense urban contexts in addition to suburban areas.

Harvesting solar energy is as one of the most common and applicable strategies to implement RE in UCs. Different studies evaluated the impact of solar PV panels on the total rate of energy generation, financial benefits and potential environmental impacts. In Japan, it was shown that Tsinghua University can become carbon neutral by 2030 by implementing photovoltaic (PV) panels and boosting building-mounted plants, which can offer guidance for other UCs seeking to become carbon neutral as well [30]. Another study looked into the development of an on-grid PV power system at Hitit University's Vocational Colleges Campus. The findings indicated that the installed capacity on-campus can reach 76 MW. A study in Ireland showed that Irish HEI parking lots as open spaces are a good opportunity for using solar energy in UCs. In this study, due to solar and architectural limitations, a 0.5 utilization factor was adopted, with 0.16 kW/m2 for the open carpark area, resulting in a potential installed capacity of 35 MW [25]. At a UC in Madrid, Olivieri et al. [32] assessed the potential impact of installing PV distributed systems on electricity generation, carbon reduction, and economic viability. Their findings demonstrated that this system could cover roughly 40% of total electricity use, save 30% on emissions, and be an economically advantageous enterprise.

To demonstrate the important role of technological innovation in integrating the installation of photovoltaic systems into the production of power in campus buildings, Ref. [33] conducted an analysis of the various electrical parameters such as load voltage and intensity, and power supplied to/from the grid, along with system performance indicators based on the international standards for the evaluation of the energy performance of photovoltaic systems (IEC 61724), achieving at very optimal values for this kind of renewable solution. Using web-based PV system design software, a study at the Vocational Colleges Campus, Hitit University [34] integrated a simulated PV system with a gas-fired-trigeneration system to examine prospects for solar hydrogen generation without energy storage on campus. Results demonstrated that PV systems might provide up to 25% more electrical energy than the current system, with a payback period for that energy estimated to be 6.47–6.94 years throughout the 20–25-year lifespan of the PV plant.

In another study on the campus of King Abdulaziz University, a number of crucial steps that must be taken to improve the institution's energy efficiency were introduced, as shown in Fig. 7, and a conceptual master plan for solar energy integration has been created for power generation [35]. The results of this study showed that the cooling and electrical energy demand may be significantly reduced, leading to a significant improvement in overall efficiency for both local and shared renewable and non-renewable energy production [35].

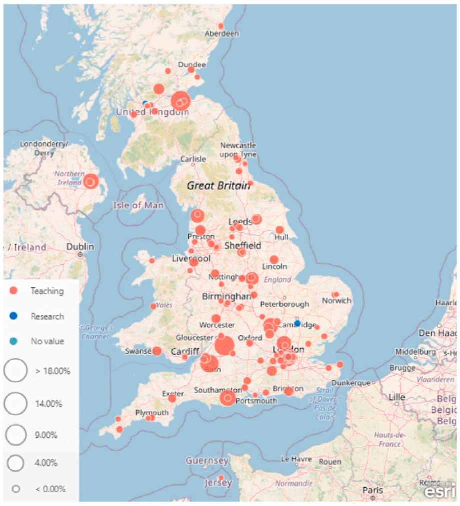

Fig. 6. Ratio of renewable energy (both on-site and off-site) production to total energy use in UCs across UK [9].

a) Solar energy

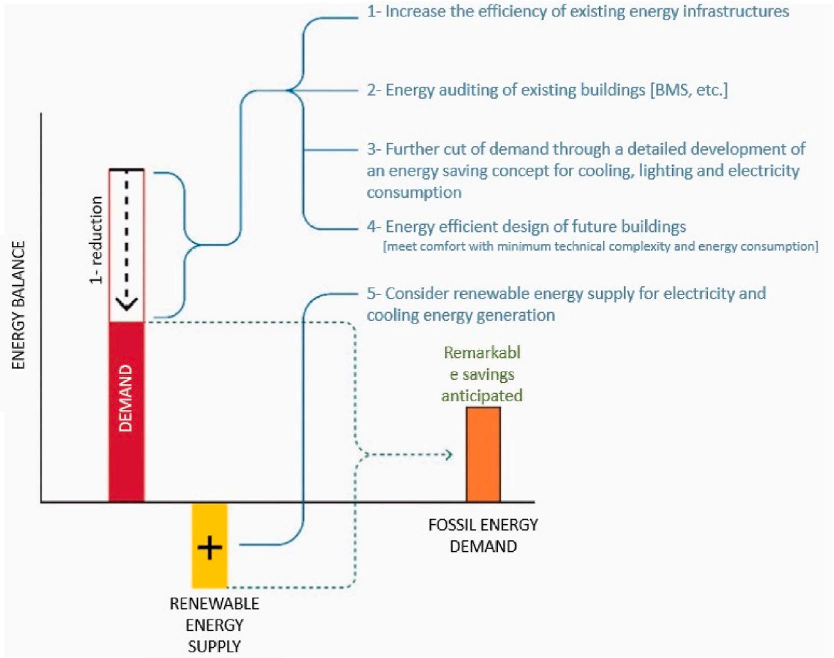

Fig. 7. Important steps to increase the campus's energy efficiency and reduce its reliance on fossil fuels which was taken on the campus of King Abdulaziz University [35].

b) Biomass sources

In addition to solar energy, the feasibility of producing green and clean energy by using biomass sources is also studied. Using combined-heat-and-power (CHP) stations is one of the identified decarbonisation strategies that are widely used in UCs. Focusing on the techno-economic benefits and challenges of the CHP concept, a recent study at the University of Lueneburg showed that renewal of CHP station and conversion to biomethane instead of fossil fuels is an optimal solution for carbon-neutrality and a substantial cost decrease due to feed-in tariffs [36].

Besides, the reduction in GHG emissions and disposal costs resulting from the use of clipped branches as fuel for biomass power generation for campus energy usage at a Japanese university were quantified [37]. UC Berkley's action plan suggests using biogas to replace 50 to 100% of natural gas to help meet the 2025 carbon neutral goal by 45 and 91%, respectively, as 63% of the UC system's carbon emissions result from the onsite combustion of natural gas, the largest source of UCs emissions [38]. For instance, in Ref. [39] the potential for energy generation for heating and CO_2 emission from the solid waste of the University of Victoria and the neighbouring areas is explored. The CHP system based on biomethane was also investigated in another research [40], in terms of energy efficiency of the University of Warwick.

c) Geothermal sources

Moreover, earth source heat and lake source cooling as the REs were considered in Ref. [41] for the evaluation of carbon-neutral energy systems, with the objective of determining the optimal energy systems configuration, seasonal operations, energy mix, and corresponding capacity of technologies while meeting seasonal demand for electricity, heat, and cooling. The optimal design resulted in a reduction of carbon emissions to between 8% and 17% of the value in 2020. Table 1 presents the detail of the above-mentioned studies.

d) Combined RE sources

In terms of combined energy systems, REs are also investigated in conjunction with other clean energy system types. For example, Horan et al. [25] compared the performance of various REs, including building integrated PV panels, ground-mounted PV panels, biomass boilers, building interacted wind turbines, and electrifying the campus fleet with RE sources that are available in the Irish context, and showed that the combined effect of these strategies has the potential to lower total on-site carbon emissions by 25% (Fig. 8). In a similar study, a clean energy framework was deployed to provide preliminary estimations of the deployment potential of building integrated photovoltaics (PV), micro-wind turbines, rainwater harvesting, and ground mounted PV at UCs [47].

In other study, by switching the local CHP system to renewable fuels (biomethane) and installing a total of 720 kWp photovoltaics, 20% of the campus power consumption is fulfilled with a 95% self-consumption rate. Table 1 demonstrated the detailed reviewing of implementing RE sources in UCs.

Table 1
Reviewed studies on the topic of implementing RE in UCs.

Ref	Year	Country	RE source	Metric	Tool/software	Finding
[42]	2022	China	• Photo-voltaic panels	• Energy consumption • Carbon analysis	–	• Tsinghua University can achieve carbon neutrality by 2030 by deploying photovoltaic panels and growing building-mounted plants.
[34]	2022	O	• On-grid photovoltaic (PV) power system	• Energy generation • Cost	Web-based PV system design software (HelioScope)	• The energy payback period for a PV plant with a 20–25-year lifespan is 6.47–6.94 years. • Up to 25% of the existing system's electrical energy could be supplemented by a PV system.
[41]	2022	US – New York	• Earth source heat • Lake source cooling • On-site renewable electricity generation	• Carbon analysis • Cost • Seasonal operations	–	• Based on the existing electric power mix, scope 1 and 2 emissions are significantly decreased to 8%–17% of their value in 2020.
[39]	2021	Canada	• Gasification system from the campus waste	• Energy generation • Carbon analysis	HOMER simulation software	• Using the suggested standalone gasification system, it was determined that 400 kW of renewable electricity and 500 kW of clean heat could be generated daily using around 3500 tons of feedstock per year. • By avoiding landfill disposal of the waste feedstock, approximately 1130 tCO2-eq of annual GHG emissions might be reduced.
[37]	2021	Japan	• Biomass power generation from pruned branches	• Reduction in greenhouse gas (GHG) emissions • Cost	–	• Using clipped branches for heating on campus reduced GHG emissions by 70–180%. • For the planned wood stove and wood-chip heater systems, the expected payback periods were 2 and 4 years, respectively. • The total costs can be decreased by about 20% over the course of 20 years.
[32]	2020	Spain	• Solar photovoltaic systems	• Energy generation • Carbon analysis • Cost	A tool for solar radiation calculations at an urban scale developed by UPM's Solar Energy Institute + PVSyst	• Covering of approximately 40% of total electricity usage. • 30% reductions in emissions are possible. • A comprehensive economic analysis reveals that the project is extremely profitable.
[43]	2020	US - Ohio	• Geothermal heat pumps	• Carbon analysis • Lifecycle costs	–	• Switching from on-site natural gas combustion to geothermal heat pumps would lower greenhouse gas emissions by 15% while incurring a lifecycle costs a premium of $15.5 million.
[44]	2020	Saudi Arabia	• Roof-integrated solar panels	• Energy generation	The simulation software IDA-ICE	• Potentially large reductions in the use of non-renewable energy sources, along with the creation of both electrical energy and solar thermal cooling, may result in a high coverage fraction.
[25]	2019	Ireland	• Photovoltaics (PV) • Micro-wind turbines • Ground-mounted PV at Higher	• Carbon analysis • Energy generation	Google Earth imagery coupled with publicly available online HEC maps	• Informing city-scale decarbonisation transitions • There is a significant opportunity for the deployment of

(*continued on next page*)

Table 1 (*continued*)

Ref	Year	Country	RE source	Metric	Tool/software	Finding
			Education Campuses (HECs)			decarbonisation technologies on Irish campuses. • Carbon emissions related to the water supply were determined to have a large reduction potential. • The findings revealed a substantial correlation between HEC's gross interior area and roof area, but a weaker correlation between gross internal area and parking area, with urban form being a more significant component in determining carpark area at HEC.
[45]	2017	India	• Solar PV	• Energy consumption	NASA surface meteorology data and Google SketchUp	• The proposed captive plant is a solar photovoltaic power system with a 5 MW capacity. • Over its lifetime, this plant will be able to reduce 173318.0 tCO_2, which is a significant amount of GHG emissions.
[36]	2017	Germany	• CHP to renewable fuels (biomethane) • Photovoltaics on facade	• Energy efficiency • Carbon analysis •	DOE 2.1E + ZUB Helena + TRNSYS	• Yearly savings of 2424 t CO_2-eq. • The use of renewable gas in CHP-based DHS permits the system-scale offsetting of nonenergy-related emissions caused by the replacement of coal-fired power units.
[40]	2016	UK	• Micro-CHP power plant	• Energy efficiency	The simulink-based tool-box + simPowerSystem for the electrical generator	• In comparison to conventional power plants, the best total thermal efficiency of CHP power plants in winter is 83%. • For district energy supply, such as on university campuses, CHP is the best option because it saves energy and lowers carbon emissions.
[46]	2011	US	• Solar PV array	• Cost	RETScreen + PV Watts v.2.0	• The cost of power generated by solar PV is around 30% more expensive than electricity generated by fossil sources. • When prices fell to $3.00 per installed watt, the net present value of a net-zero energy solar PV array became zero.

4.1.3. Energy systems

UCs as complicated large-scale districts include a wide variety of building functions such as educational, commercial, residential, etc. Also, UCs locate buildings with special needs and requirements such as labs and data centres. These buildings need special mechanical, electrical and lighting systems which consume a significant share of the total energy of UCs. As a result, new trends such as integrated and hybrid energy systems are getting more attraction. In the following section, a number of studies which assessed these energy systems and their corresponding components and networks, their energy sources and storage devices (renewable and/or fossil energy sources) in UCs are reviewed.

Literature on integrated energy systems shows that different hybrid energy systems are implemented in UCs, such as hybrid RE systems integrated with stationary batteries and mobile hydrogen vehicle storage [48], a hybrid system of a solar photovoltaic panel, wind turbine, and a biomass gasifier [39], an integrated renewable power system consisting photovoltaic and hydrogen fuel cell system [49], a hybrid system of a micro gas turbine with combined heat and power module, thermal boilers, converters, photovoltaic panels, pumped hydro storage units, and a predictive controller [50], a Hybrid RE System (HRES) consisted of photovoltaic (PV), wind turbine, battery, diesel generator and inverter components [51], and integrated system of gas boilers, heat pump units, solar collectors, and

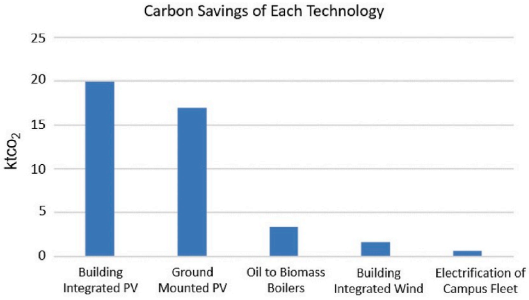

Fig. 8. Potential of each technology in carbon saving in the Irish campus [25].

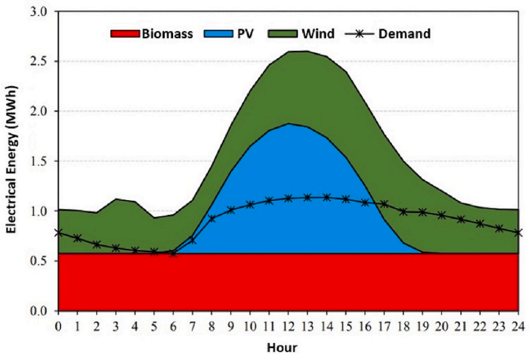

Fig. 9. The average hourly electricity generation of all days throughout the year from the components of the proposed hybrid system plus the mean hourly demand of campus [53].

circulation pumps [52].

For the development of efficient integrated energy systems, (i) the correct size of each technology and (ii) the formulation of optimal management techniques for each component are of paramount importance. The combination and size of measures and technologies utilized by the energy systems of various UCs depend on the UC's local resources and needs. In research by Al-Ghussain et al. [53], the optimal components' capacities of a proposed system, including a Photovoltaic (PV)/wind/biomass hybrid system in the Middle East Technical University Northern Cyprus Campus was investigated. They concluded that the integration of a hybrid energy storage system with the PV/wind/biomass system ensures very high autonomy approaching almost 99%, and as shown in Fig. 9, the electricity generation from the wind system meets a significant portion of the demand while the biomass model delivers the baseload.

Moreover, in Ref. [54], an analysis and optimization process was conducted to replace real-time power with constant power from the grid in order to reduce costs and the micro-impact grid's on the main grid, while simultaneously proposing the use of a grid-connected solar-plus-storage micro-grid to provide power. Ref. [55] analysed the likelihood of the University of California, Davies, pursuing a carbon-neutral energy pathway, focusing on the utilization of solar photovoltaic and thermal, biomass combined heat and power, biomass boiler, heat pump, and electric boiler replacement systems. Additionally, Ref. [56] developed a solar-based air conditioning system using Photovoltaic (PV) cells, which offers optimal cooling efficiency without requiring significant power consumption and is a RE source that can be used in a variety of climates. All of the aforementioned studies evaluated one or more performance metrics of energy systems, such as energy consumption, energy generation, carbon emissions, energy efficiency, cost efficiency, and optimization, areas shown in Table 2 in more detail along with the results.

4.1.4. Building envelope

Thermal envelope protects the inside environment and provides indoor comfort against the adverse environment, plays a crucial role in decreasing building energy consumption and, as a result, limiting the CO$_2$ imprint on the environment. The most effective energy-saving strategies are not only those linked to construction design but also those that take into account materials' characteristics as well. Passive solar design, insulation, high-performance windows, air sealing, and controlled ventilation are a few examples of building envelopes that can be integrated into energy systems to increase energy efficiency and lessen environmental impact. It can also be incorporated into renewable energy systems, such as those that use solar panels and wind turbines to produce power or provide heating and cooling for buildings. Additionally, ground-source heat pumps allow for the integration of the building envelope with geothermal systems. Therefore, energy savings at UCs can be achieved by the strategic design of the thermal properties of building envelopes, and the significant impact of building envelopes on energy consumption or carbon emission reduction makes it important to research their performance.

In this regard, Ref. [36] reported that the architecture and facade design at the University of Lüneburg greatly reduced cooling demand (2.5 kWh/m2a). Besides, the evaluation of passive systems, such as facade insulation and window replacement, to increase the

Table 2
Reviewed studies on the topic of implementing integrated energy systems in UCs.

Ref	Country/ Year	System Type		Metric						Tool/software	Finding
		Clean/green energy system	Renewable energy system	Energy consumption	Energy efficiency	Carbon analysis	Cost	Optimization	Thermal comfort•		
[51]	Turkey/ 2022	battery, diesel generator and inverter components	The HRESs consisted of photovoltaic (PV), wind turbine,	×			×	×		Harmony Search (HS) algorithm + HOMER, Ant Colony Optimizer and Jaya + MATLAB simulation package	• HS provided the optimum sizing among the other methods including HOMER, Ant Colony Optimizer and Jaya. • The time performances of the HS algorithm had better performance and convergence properties.
[56]	India/ 2021	Air Conditioning system	Solar power	×	×					The MPPT tracking algorithm + the CPG system	• Delivers minimal energy consumption and a high-performance coefficient. • Compatible with varying climate conditions
[48]	Hong Kong/ 2021	Stationary battery + mobile hydrogen vehicle storage	–	×	×	×	×			Coupled platform of TRNSYS and jEplus + EA	• The zero-energy community's self-consumption of RE, load coverage, hydrogen system efficiency, and grid integration are all enhanced by battery storage. • Reducing carbon emissions by 71.23%–90.93%.
[54]	Japan/ 2021	–	A grid-linked solar-plus-storage micro-grid	×	×	×	×			The non-dominated sorting genetic algorithm II (NSGA-II)	• While cutting expenses, the influence on large-scale electricity grids is diminished. • Enhancing the dependability of campus microgrids
[39]	Canada/ 2021	A biomass gasifier	Solar photovoltaic panels, wind turbine				×			HOMER simulation software	• University of Victoria will save 386 000 the total annualized cost in addition to 1039 tons of CO_2 emissions by implementing the suggested hybrid renewable energy system.
[49]	Nigeria/ 2021	Hydrogen fuel cell system	Solar Photovoltaic	×	×	×	×			The energy-balance procedures for electric renewables software tool	• CO_2 emissions are reduced by 95.2%, while the renewable fraction rises by 91.2%. • The grid electricity purchases decrease by 80.7%, resulting in a cost savings of 91.6%.

(*continued on next page*)

Table 2 (*continued*)

Ref	Country/ Year	System Type		Metric						Tool/software	Finding
		Clean/green energy system	Renewable energy system	Energy consumption	Energy efficiency	Carbon analysis	Cost	Optimization	Thermal comfort•		
[50]	Iran/ 2021	A micro gas turbine, thermal boilers, converters, pumped hydro storage units, and a predictive controller	photovoltaic panels	×		×				–	• In comparison to the Campus's use of the national energy grid, the proposed energy system results in an annual reduction of CO_2 emissions of 8000 megatons.
[52]	China/ 2019	NG boilers, HP units, and circulation pumps	solar collectors		×		×	×	×	Simplified decision-making process	• The operating cost of the energy system can be reduced by 38.9% without compromising the thermal comfort requirements of the building occupants. • The performance factor of the system can be increased by 2.24% by increasing the performance factor of the system compared to the current experience-based operation strategies.
[57]	Mexico/ 2014	–	a hybrid system (solar–electric–LPG)	×		×				–	• Incorporating a hybrid system might reduce energy usage by 7.5% and CO_2 emissions by 11.3% when compared to 2011.

energy efficiency of the buildings was studied in another study [58] and findings showed that even with significant retrofitting and adaptation efforts, it will be challenging to meet the European targets by 2050. Therefore, the use of RE sources must either be expanded or efforts to reduce energy usage must be increased. Using the Nondominated Sorting Genetic Algorithm-II (NSGA-II) in conjunction with Multilayer Perception Artificial Neural Network (MLPANN) metamodel, Ref [59] evaluated the most influential facade design factors, such as internal and external wall types, roof types, solar absorption, and window shading, to obtain the optimal trade-off results (Pareto front) between energy consumption and thermal comfort. According to the optimization results, reductions were made in both the normalized objectives and the sub-objectives, with up to 78.2% less heating energy, 71.3% less cooling energy in air conditioning seasons, up to 97.7% less heating degree-hours, and 99.2% less cooling degree-hours in naturally ventilated seasons when compared to the original configuration. In another study [60], the influence of passive energy efficiency measures (PEEMs) on the possible reduction of internal temperature and cooling energy demand of an architectural campus buildin in Karachi, Pakistan, was examined. PEEMs emphasize the design and construction of the building envelope, which is a significant role in a building's cooling energy requirement [60].

In a similar study in Amity UC [61], the implementation of green roofs and the corresponding cost were investigated. Results showed that the enhancement of thermal insulation of the building's walls, roof, and floor resulted in a 44% reduction in the building's energy consumption of a UC [62]. Furthermore, combining this intervention with the glazing improvement and replacing the oil boiler with a heat pump reduces the building's energy consumption by 57%. The usage of Trombe walls reduces energy consumption for heating (37%) and cooling (22%). In addition to installing Trombe walls in classrooms and offices, a PV plant on the roof satisfied 120% of the building's energy needs [62]. Finally, Bellia et al. [63] suggested a comprehensive method for energy diagnosis to create effective steps for the energy-oriented renovation of academic facilities. The paper uses a university building in southern Italy, where heating is more important than cooling, as a case study. The Cost-Optimal method was used to compare potential retrofit outcomes, and results showed a significant improvement as a result of thermal envelope retrofit actions.

4.1.5. Green transportation

Sustainability concept in UCs is comprised of a variety of components. According to the Green Metric, 18% of all these components are devoted to sustainable transportation [64]. Increasing the usage of bicycles, decreasing the number of private vehicles, using shuttle buses for staff and students, and boosting public transit are all issues that come to mind when looking at prior research and standards developed on the topic. These are fundamental environmentalist strategies for cutting carbon emissions, and they work well with the ecological design, which boosts sustainability even further. In this context, a number of studies on the scope of sustainability and ecological design criteria in UCs for the transportation network have been conducted.

In the case of the Izmir Katip Celebi University Cigli Campus in Turkey, in addition to the examination of the ecological design criteria for the transportation network, a pedestrian- and bicycle-oriented transportation network was also proposed [64]. The findings of this study led to the creation of a mobility strategy that will raise the bio-comfort level of campus residents through the use of an eco-friendly environment and a design strategy that improves human harmony with the environment. In another study which was focused on CO_2 emissions of transportation systems during a four-year period [65], the CO_2 emissions from the fleet of university cars utilized for public transportation, as well as the emissions produced by staff and student mobility, were measured at University Technology Malaysia (UTM). Results demonstrated that air travel by college students and staff contributed, respectively, to 34.74% and 19.37% of the carbon emissions at UC which highlights the important impact of GHG emissions from transportation systems at UCs [65].

Furthermore, one of the fundamental pillars of sustainable UCs, is the incorporation of electric mobility and Electric vehicles (EV) with energy systems based on RE sources. This reduces the UC environmental effect and contributes to the realization of more advanced and recent trends such as energy independency and microgrid. In Ref. [66], a mixed-integer linear programming model was proposed for an Italian UC, with the goal of defining and designing electric services for a local energy community that draws power from a microgrid through the use of RE sources and storage devices. Thus, the ideal configuration of the electric mobility system, consisting of shuttles, vehicles, and bicycles, as well as charging stations, was found. The optimization model also examined the possibility of updating the microgrid of the campus to which the electric mobility infrastructures would be connected. Another study [67] did a complete investigation of the use of EV charging stations at the University of Georgia in Athens. Three EV charging points at this university were utilized to collect data on each of the 3204 charging events that occurred between 10 April 2014 and 20 June 2017.

As part of an electric mobility living lab in the public transport system of the University of Campinas (Unicamp, Brazil), an optimization model was suggested to reduce the operational costs of a sustainable charging station under several charging types for an electric bus [68]. Comparison of the optimization model's charging schedule with the campus's actual charging schedule reveals a 52% reduction in monthly cost, demonstrating the model's efficacy. Also, a battery energy storage system can further reduce operational expenses made possible by the installation of solar panels. In another study, at the University of Technology, Sydney (Australia) [69], was shown that if half as many staffs and students made their daily commutes via walking and biking, energy consumption could be cut by 35%. Also, the effectiveness of a smartphone app-based technique to encourage commuter students to embrace more environmentally friendly means of transportation is evaluated in Ref. [70] at the university of Palermo (Italy). The daily and yearly distances commuters travelled with the new mobility modes were computed, and the corresponding energy and CO_2 emissions savings were estimated.

To determine CO_2 emissions per commuter trip at the Technical University of Madrid, a basic mobility survey with 2149 responses was done [71]. The data indicate that public transportation accounts for nearly 75% of all trips. However, private mode commuters are responsible for more than 55% of all CO_2 emissions. Besides, the novel geospatial approaches done by Ref. [72] include mapping individuals' journeys to campus and the establishment of Commute/Policy Zones—walk, bike, transit, and motorized. Annually, it is projected that personal auto-commuting costs $46.7 million, healthcare expenditures from non-GHG air pollutants cost $1.67 million, and car commutes to campus waste $81 million worth of time (5.4 million hours). Lastly, a recent study employed the Economic Input-Output Life Cycle Assessment (EIO-LCA) model to evaluate GHG emissions and specifically focused on the influence of COVID on campus emissions at Cornell University [73]. In general, 2019's greenhouse gas emissions (285,3 thousand metric tons CO_2e) were greater than those of 2020 (239.3 thousand metric tons CO_2e). In the first and second half of 2020, commute-related emissions were reduced by 51.9% and 82.3%, respectively. Similar to other industries, the greatest reductions in air travel emissions (97%) occurred in the second half of 2020 [73].

4.1.6. Management and control

In order to achieve sustainability goals, most studies considered two main strategies of energy consumption reduction and the implementation of renewable generation to achieve zero-energy buildings. However, in UCs, one major challenge is to ensure delivery of the energy services in different areas of campus, taking into account the variable schedule of activities, users and operation schedule. Another major challenge is the need to increase the matching between local generation and demand, in order to increase the self-consumption and energy independency of UCs. Therefore, monitoring and control algorithms within central management platforms have an important role in addressing these challenges including addressing the individual consumption of different buildings, the global electricity demand and generation, improving indoor quality indicators including thermal comfort and air quality as well as other relevant queries such as weather data changes and the presence of users.

In this regard, different UCs have adopted a wide variety of control techniques and algorithms including predictive and optimization algorithms to ensure energy efficiency measures and indoor quality indicators. These two algorithms are mostly implemented in the central management departments and facilities in UCs. These algorithms and management centres are reviewed in more detail in the following paragraphs:

In terms of optimization control algorithms, machine learning techniques have been used widely to identify the most optimised solution among different challenging and competitive objectives such as energy consumption and generation, thermal comfort, indoor quality, etc. Management scenarios as complex problems involve a wide variety of goals which requires advanced techniques to handle these multi objectives and problems. In this regard, a recent study developed a control algorithm for optimising energy consumption of HVAC systems and balance indoor air quality and thermal comfort through Deep Q-Learning in reinforcement learning in a UC. This study showed that by adopting this optimization algorithm, energy consumption and concentration of CO_2 were reduced by 15% and 13% [74]. In another study, two bio-inspired heuristic algorithms of Firefly Algorithm (FA) and the Lion Algorithm (LA) were applied to a UC to analyse the possibility of minimising the cost of energy and the waiting time of end users [75]. Another study in Romania developed an AI-based optimization algorithm based on the electricity generated by RE sources and energy storage systems to boost the profit obtained by the UCs in exchanging energy flows with the upstream grid [76]. Another study put forward a novel approach to tackle multi-objective optimization problems for building the performance of Qingdao University (QUT) Gymnasium using a Non-dominated Sorting Genetic Algorithm-II (NSGA-II) combined with Multilayer Perception Artificial Neural Network (MLPANN) metamode. The most influential design factors like internal and external wall types, roof types, solar absorptance, windows shading as well as night ventilation (NV) strategy and displacement ventilation (DV) air conditioning system of the gymnasium were considered in three cases of 4108 possibilities to obtain the optimal trade-off results (Pareto front) between energy consumption and thermal comfort [77].

In terms of predictive control algorithms, statistical and analytic techniques play an important role to analyse the performance of energy systems and predict future trends which will help the facility managers to design required responses. Also, prediction models give insight into which building factors remain essential and applicable to UC building policy and action plans. An example of a predictive model in UCs is a study developed building energy prediction models by using statistical analysis techniques of multivariate regression models, multiple linear regression (MLR) models, and relative importance analysis [78]. The outputs were electricity (ELC) and steam (STM) consumption, and the independent variables used as inputs were building characteristics, temporal variables, and meteorological variables [78]. In another study, a novel nonlinear predictive control framework was developed for climate control of buildings located on the Cornell University campus with RE systems to minimize electricity costs. The results showed the NMPC framework could efficiently minimize total electricity cost and constraint violation for thermal comfort to 12.9% with no more than 0.2 of violation on the predicted mean value index in different seasons [79].

These two predictive and optimization sets of algorithms are usually implemented in management frameworks and centres. In terms of management centres, a new study by Konis et al. developed TrojanSense, a participatory sensing management framework to collect, analyse and report user assessments of thermal preference at the campus scale with room-level spatial resolution. TrojanSense was developed with the goal of supporting initiatives to improve campus community engagement on issues of occupant thermal comfort, energy efficiency, and equity in the environmental control of university buildings [80]. In another project by Kolokotsa et al. an efficient web-based energy management system for UCs was presented which manages the UCs and their spaces of public use in an energy-efficient way monitors the energy load and performs energy analysis per building and for the campus as a whole, as well as interacting with each building's management system and each user through questionnaires, e-mails and forms. To guarantee the system's scalability and respect consolidated and diffused standards, the logical/architectural level of the whole campus energy management system is linked with the existing infrastructure based on Internet Protocol (IP) [81].

Appropriate real-time monitoring and management of RE systems play an important role, however, this issue is more important in HRES and integrated systems play an essential role in providing accurate information to enable the system operator to evaluate the overall performance and identify any abnormal conditions. Moura et al. in a recent project introduce the implementation of the concept of internet of things (IoT) based architecture for HRES, consisting of a wind turbine, a photovoltaic system, a battery storage system, and a diesel generator. To ensure the implementation of the desired monitoring and control, an IoT platform based on wireless sensor network (WSN) infrastructure was designed and installed. Such a platform supports a smart system to control the heating, ventilation, air conditioning (HVAC) and lighting systems in buildings [82].

4.1.7. Human-related performance

All sections above were focused on the decarbonisation strategies which targeted the systems, technologies and equipment in UCs however space users as an important player in the energy performance of UCs are neglected and as such limited studies have investigated human-related parameters. Challenges related to studying people's opinions and preferences and their interactions with their environment make this kind of study more difficult. To save energy, retrofitting solutions need to focus on significant changes to the building's envelope and energy systems, as well as implementing better management practices. However, these technical solutions tend to overlook the behavioural aspect of how people use these spaces, and there is a lack of models that understand energy consumption in UCs. In this section, human-centric studies are reviewed in two different sections of exploring people's behavioural aspects (opinion/preferences) and increasing awareness/willingness.

In terms of the importance of behavioural aspects of decarbonisation in UCs, a recent study investigated energy usage and influential behavioural factors in dormitory buildings, which are large apartment buildings with high occupancy levels. The study found significant differences in energy usage based on factors such as gender, floor level, and room orientation. Male students used more electricity due to their frequent computer usage, lower floors used more energy due to poorer environmental conditions, and south-facing rooms consumed more electricity in summer while north-facing rooms consumed more in winter [83]. A study in a UC in the United States looked at how occupants' behaviours and habits affect their thermal sensation, acceptability, and preferences when increasing cooling temperature setpoints in certain areas of the building during peak hours. The results showed that occupants could tolerate at least a 2 °C increase in cooling temperature setpoints during peak hours without compromising their thermal comfort temporarily [84].

Another study examined the differences and similarities in students' energy-related attitudes, reported behaviour and perceptions of their institution's energy-saving efforts across universities in the UK and Portugal. The results showed that there were differences in how students perceived their individual actions and their university's environmental practices, with stronger perceptions in the UK. However, students in Portugal had a stronger sense of collective agency and trust in the government and business [85]. In addition to considering behavioural models, thermal comfort is also an important aspect of understanding people's preferences [86,87]. A study by Allab et al. aimed to develop and implement an energy audit protocol that addressed both the issues of thermal comfort and energy efficiency in higher education buildings [88].

In addition to explore people's behavioural and perceptions, it is important to improve people's occupants' awareness of promoting energy efficiency, and decarbonisation and move towards green future concept. In a study by Nguyen et al. a human-centric study explored students' opinions and preferences towards a plastic-free UC and then prioritised the suggested strategies based on the students' preferences [89]. In another study, a questionnaire survey was conducted among three campus building occupants, namely the lecturer, staff and students toward energy efficiency strategies. Participants in the questionnaire suggested that the awareness improvement should be conducted to three critical variables of recognising the issue of electricity resource depletion, resource sharing to reduce the use of electrical energy consumption and understanding to make efforts and prepare for electricity resource depletion [90]. All these kinds of actions help improve people's awareness and encourage them to collaborate in a green and decarbonised future. Although, research related to people for both above-mentioned aspects of human-centric studies - exploring people's opinions/preferences and increasing awareness/willingness - has not been widely explored.

4.1.8. Smartness

Reviewing the literature shows that the trend of incorporating smart technology into UCs design and planning is gaining popularity. A smart campus is an intelligent infrastructure that utilizes smart sensors and actuators to gather information and communicate with machines, tools, and users. The move from a traditional campus to a digital or smart campus is spurred by the use of Information and Communication Technology (ICT) for distributing materials, conducting online learning, and delivering internet-based teaching activities. Additionally, the smart campus is adaptable and responsive to changes in order to better serve the needs of its users. Rather than just being an asset, UC buildings become service providers.

Integrating smart technology into universities can yield numerous advantages. By adopting "smart building principles" and implementing smart features into energy systems, universities can tackle the challenge of achieving net-zero carbon emissions for both new and existing buildings and energy systems [9]. Furthermore, smart UCs can function as a prototype for the smart city concept, which may not be practical to test on a large scale in urban areas. Smart UCs utilize technology to introduce novel services and experiences and enhance operational efficiency, providing a more manageable setting for experimenting with these ideas.

Research on the implementation of smart technology in UCs is limited, but the number of studies on the subject is growing rapidly. A recent study by da Silva et al. developed an ICT-based methodology and software toolchain to improve the management of a smart campus with a step-by-step process that covers local mini-grid EMS, IoT DMS, Mobility, real-time retrofitted efficiency, and institutional energy governance, following the policies set forth by the ISCN/GULF Sustainable Campus Chapter [91]. A different research project put forward a smart campus approach that focuses on merging building information modelling tools with wireless sensor networks based on the IoT for environmental monitoring. In addition, this study examined the use of emotion detection to evaluate comfort levels. It also delves into how UCs can participate in local sustainability efforts by fostering collaboration and knowledge-sharing across various disciplines [92].

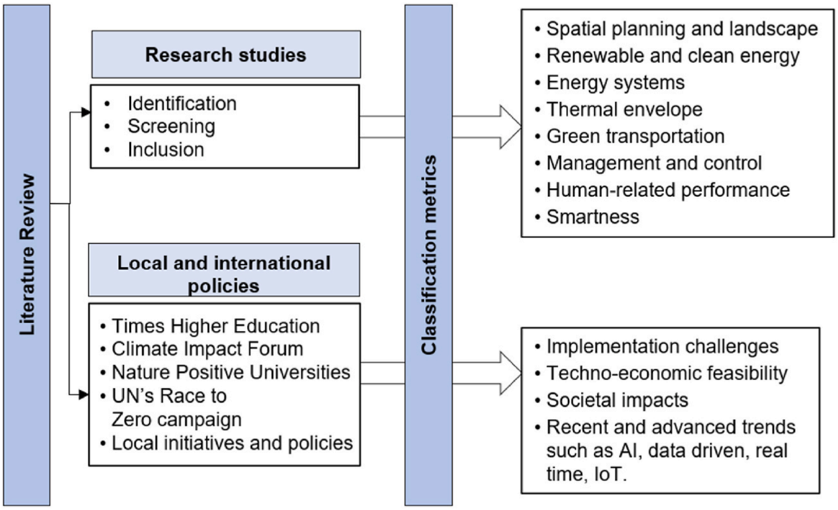

Fig. 10. An outline of the complete review plan in a flowchart.

Another application of smartness is for improving the users' experience and feedback. In this regard, If-This-Then-That paradigm has been proposed as a user-friendly programming approach with building automation systems for occupants to dynamically control and personalize indoor workplace environments [93]. Also, combining smartness with Artificial Intelligence (AI) and data-driven techniques provides a unique opportunity to develop prediction tools for energy consumption in different climate conditions. Looking beyond individual building levels, forecasting building energy performance can help UC mangers have a better understanding of their future energy needs, and plan for satisfying them more efficiently [94].

In addition to academic research, there are also real-life examples of the implementation of smart technology in UCs. One such example is the Smart Campus project, a European initiative located in four pilot sites in Helsinki (Metropolia University), Lisbon (Instituto Superior Técnico), Luleå (Technology University), and Milan (Politecnico di Milano) that has engaged 76 000 users since 2012 [95]. The main goal of the project was to highlight the central role of ICT-based services in energy management systems and demonstrate savings of almost 40% in some of the test locations. The results demonstrated that the level of energy savings varied across the test locations based on factors such as the type of space, occupancy and usage patterns, installed equipment, HVAC and lighting control systems, and user interaction. Such kinds of a project can facilitate the smart UC concept as this kind of project aims at the development of services and applications supported by a data gathering platform that integrates real-time information systems and intelligent energy management systems that drive a bi-directional learning process such that the user learns how to interact with the building and the building learns how to interact with the user in a more energy efficient.

Finally, Fig. 10 summarizes the policy outcomes of the research reviews and lists all the procedures and classification metrics used in the literature.

5. Conclusion

As UCs are growing rapidly worldwide and have a high share of energy consumption and carbon emissions, establishing decarbonisation and energy-saving measures are crucial. This paper reviewed the most highlighted studies regarding decarbonisation strategies in UCs. The studied aspects in the reviewed studies are divided into different topics of spatial planning and landscape, renewable and clean energy, energy systems, thermal envelope, green transportation, management and control, human-related performance and smartness. UCs are unique environments with their own social and economic identities. The activity in these places is diverse, embracing different activities and people who work, study or live with a wide variety of working and living conditions.

Energy consumption and carbon emission from UCs have increased due to sudden growth in UCs population due to the increases rate of international students seeking to continue their education at postgraduate and PhD levels. Also, improving indoor quality conditions (such as thermal comfort and air quality) in both educational and residential buildings has led to a significant increase in energy consumption. Some global circumstances such as COVID-19 significantly increased the need for fresh air in indoor spaces which increased energy consumption and carbon emission in the last two years. In conclusion, the causes are different though the consequences are the same, which are in large-scale energy and other resources consumption and thus continues exacerbation of the carbon emission in urban areas.

To add to this complexity, guidelines and policies in smart campus development, sustainability promotion and resiliency of UCs are not fully developed, and the strategies are cherrypicked on many occasions with paying minimal attention to the global scale challenges of UCs. Also, the nature of complicated and multi-functional identity, political challenges, and the presence of people with mixed social and behavioural characteristics, place a wide variety of challenges in front of governments and international agencies ahead of generating long-term agenda for sustainable development of UCs and decarbonisation of these places.

Also reviewing UCs policies shows that the UCs specific policy framework is obviously lacking as the existing policies are currently voluntary without any linked financial incentives or regulatory requirements for existing UCs which remain a key decarbonisation challenge. A key element that the current policy is lacking, is a shift in focus to technological innovation, instead, the focus is historically put on capacity and infrastructure expansion. Also, government support with a 'complex decision chain' on a large scale and lack of enforcement are identified as major barriers to UCs sustainability that are lost behind non-binding declarations instead of transformational commitments.

Yet, for those UCs with ambition in offering sustainable development and decarbonisation regulations, large-scale regulations such as decarbonisation and sustainable development are barely seen as a priority. Besides, one should add barriers in front of the retrofit and renovation activities of many poorly constructed buildings both residential and educational in UCs on a global scale.

Effective communication between policy-making entities and scientific institutions is not fully developed in the reviewed documents and papers. This results that UCs studies can neglect political, social and economic aspects of developing decarbonisation strategies which are mostly focused on technical aspects such as a series of simulations over RE modelling especially PV panels and retrofitting energy consumption of buildings. These technical aspects are generic and can be applied in other types of buildings while specific studies are required while considering all aspects and functions of campus buildings. As lacking in the current state-of-the-art and briefly addressed in this paper, it is up-most of importance that the other aspects of decarbonisation such as economic, societal and policies and regulations are taken into account to mitigate the carbon emissions from these large-scale carbon producers around the world. In this aspect, the commitment, and collaboration of UCs with governmental support to both national and international holistic plans and guidelines are significantly important for this type of building.

Also, reviewing the literature indicates that there is a growing trend of incorporating intelligent technology into the planning and design of universities. The shift from a conventional campus to a digital or intelligent campus is driven by the use of ICT. By integrating smart technology into UCs, there are several advantages that can be gained, such as addressing the challenge of achieving net-zero carbon emissions for both new and existing buildings, as well as serving as a prototype for the smart city concept, which may not be feasible to test on a large scale in urban areas. UCs can utilize predictive and optimization algorithms in the central management departments and facilities in order to achieve green future objectives. As a result, new advances in AI, IoT, and other data-driven techniques are being implemented.

With these great endeavours, an upgrade from an energy and resource-efficient campus to a green campus is in progress, which expands its scope to sustainable education and the initiative of low-carbon life on campus. Future studies can develop the scope of this work by looking at location-specific guidelines and incentives form different political contexts and investigating the success rate of decarbonisation strategies in UCs.

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

No data was used for the research described in the article.

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