Scalable pathways to net zero carbon in the UK Higher Education sector: A systematic review of smart energy systems in university campuses

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Abstract

The following literature review sets out the state-of-the-art research relating to smart building principles and smart energy systems in UK higher education university campuses. The paper begins by discussing the sector's carbon impact and the concept of 'smart campuses' in the context of decarbonisation. Opportunities and challenges associated with integrating smart energy systems at the university campus from a policy and technical perspective are then discussed. This is followed by a review of building and campus-scale frameworks supporting a transition to smart energy campuses using the BPIE' Smart Buildings' framework. The paper finds that the complexity of achieving net-zero carbon emissions for new and existing higher education buildings and energy systems can be addressed with the adoption of 'smart building principles' and integrating 'smartness' into their energy systems. Several universities in the UK and worldwide are integrating smart services and Information and Communication Technologies (ICT) in their operations following the smart campus premise. At the building level, existing frameworks often create conceptual roadmaps for the smart building premise or propose technical implementation and assessment methods. At university campus scale, implementation typically comes through single-vector interventions, and only few examples propose a multi-vector approach. Comparisons of the drivers and the decision-making process are made, with carbon and cost reduction being the most prominent from leveraging distributed energy generation. Therefore, this study identified the need for a comprehensive technical or policy framework to drive the uptake of the smart energy campus, aiming to bring together the holistic value of smart energy campuses

Highlights

- Systematic literature review of smart energy systems at university campus-scale
- UK Policy and technical pathways to smart energy integration
- A critical review of the existing building and university campus-scale frameworks
- A holistic decision-making framework for the integration of multi-vector smart energy system integration at university campus scale.

Keywords

Smart energy campus, smart campus, university campus, decarbonisation, renewable energy, framework, systematic literature review, United Kingdom

Abbreviations	
AI	Artificial Intelligence
AR	Augmented Reality
BACS	Building Automation and Control Systems
BEIS	Department for Business, Energy and Industrial Strategy
BEMS	Building Energy Management Systems
BPIE	Building Performance Institute for Europe
BRP	Building Renovation Passport
CDBB	Centre for Digital Britain
CHP	Combined Heat and Power
DEC	Display Energy Certificate
DER	Distributed Energy Sources
EAUC	Environmental Association for Universities and Colleges
EI	Energy Internet
EPBD	Energy Performance of Buildings Directive
EU	European Union
GHG	Greenhouse Gases
HE	Higher Education
HEBCoN	Higher Education Business Continuity
IAQ	Indoor Air Quality
ICT	Information and Communicatiaon Technologies
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
NZEB	Nearly Zero Energy Buildings
PCC	Point of Common Coupling
PEV	Plug-in Electric Vehicles
RES	Renewable Energy Sources
RFID	Radio Frequency Identification
SES	Smart Energy Systems
SLR	Systematic Literature Review
SRI	Smart Readiness Indicator
VPP	Virtual Power Plant

1. Introduction

Growing concerns around the impeding climate crisis [1] support urgent calls for action in how built environment assets are designed and operated. Electricity and heat generation and land-use changes amount to a total of 79% of global Greenhouse Gases (GHG) emissions, according to the Stern review [2]. In 2018, the European Parliament adopted the European Commission's legislative proposals calling for energy transition under the guidelines included in the "Clean Energy for All Europeans" package [3]. The legislation aims to provide European citizens with secure, affordable and climate-friendly energy and calls for the relevant energy transition to commence [2]. One of the key drivers of the policy is to transform buildings, which currently consume 40% of the European Union's (EU) final energy, into more intelligent and energy-efficient entities [4]. In this context, pathways to "net-zero carbon" buildings frame the operational and whole life carbon emission reduction required from the built environment as a step towards the 2015 Paris Agreement aims [5].

In the UK, 40% of energy consumption originates from building-related activities [6]; in the Higher Education (HE) sector, buildings are the most significant contributor to GHG emissions [7]. The sector is facing urgent calls for carbon reductions, a substantial amount of which originates from the continuously expanding infrastructure and activities [8]. Hawkins et al. reviewed Display Energy Certificates (DEC) to determine the end-use of non-residential buildings [9]. They found that for 'University Occupied Buildings', the building use type is the strongest influencer of electricity use compared to geometry and fabric parameters. The heating fuel type is the most influential factor for consumption of heating fuel. The activity type is the second most impactful. These findings suggest that the intensive servicing and equipment requirements of certain building use types, specific to university campuses, can increase electricity consumption significantly.
Similarly, rising summer temperatures can strongly influence electricity use [9]. Energy consumption within university campuses can not be considered in isolation but is interlinked with other domains like water and waste management. The study by Gu et al. [10] used a nexus approach combining environmental sectors like water and energy to understand ways to reduce the carbon footprint of universities. The digital convergence from the adoption of novel Information and Communication Technologies (ICT), like, for example, the pervasive and ubiquitous sensing through the Internet of Things (IoT) technologies, can support advanced and proactive monitoring that can bring about efficiencies from the integrated facility management [11].

Smart energy systems can help achieve carbon emission reductions through more intelligent utilisation of energy resources to meet operational objectives and respond to grid signals. More details on smart energy attributes and conceptual and technical models have been reviewed in detail elsewhere [12–17]. Several universities have reduced their carbon footprint by integrating smart energy monitoring and renewable energy generation [18]. Taking advantage of IoT devices to gather data and events, it is possible to use AI/ML technologies to generate predictive models that can support operational optimisation [19]. Additionally, various universities offer smart services for learning and campus operations and therefore, can be considered smart universities [20].
Nevertheless, deep integration of multiple energy vectors, renewable energy sources (RES) and distributed energy resources (DER) with the intelligence field [21] appear to be critical for the successful transition to smart energy systems for university campuses. To date, the transition to smart energy systems is not strongly regulated by policy and the value and complexities of such a transition are not fully understood, further challenging the smart energy system uptake [22]. Any changes need to address the delicate balance of the 'energy trilemma' between energy cost, security and carbon emissions, and importantly, the 'energy quadrilemma', which includes sustaining the energy economy [23,24].

In terms of the available research, there is a clear need for transformational research to accelerate the clean energy transition [25,26]. Academic research and industry practice interface is one example of knowledge generation driven by practical impacts [25]. This review paper is a synthesis of previous empirical observations and theoretical concepts [27,28]. A systematic literature analysis presents the main opportunities and challenges associated with the university campus-scale smart energy transition. Headline findings, methods and research gaps are explored together with suggestions for future research. Building upon the key literature review findings, the paper provides an in-depth analysis of the smart energy system implementation in the context of university campuses. Toward this aim, a systematic literature review (SLR) was undertaken with three research objectives:

1. Identify existing frameworks for smart energy system integration and smart campus development.
2. Understand the scalability of existing smart building frameworks from building- to campus- scale. The starting point for the investigation are existing frameworks and methods to assess smartness at the building level. Literature was mapped against

the key elements of these frameworks to understand their relevance and applicability to the university campus scale.

3. Identify the opportunities and challenges of integrating smart energy systems at a university-campus scale by capturing the current and emerging knowledge on smart energy systems and smart campuses. Extract the values of implementing such concepts from global climate change mitigation and a university entity perspective.

Section 1 introduces smart energy systems and smart university campuses and the underlying literature review methodology outline. In Section 2, the policy and technical pathways to net-zero carbon buildings and specifically university campuses are presented. Then in Section 3 by a review of existing building scale smart building frameworks and implementation case study analysis presented. Finally, Section 4 presents the final remarks based on the systematic literature review outcomes.

1.1. Methodology

The current study has adopted essential methods of conducting a Systematic Literature Review (SLR) in collecting and reporting the review outputs. A rigorous analysis of literature collected for this review was performed to maintain the transparency and auditability of the outputs. The PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) guideline was used as the methodological basis to ensure the quality of reporting of the literature review outcomes [29]. PRISMA is widely used in reporting health care intervention investigations but can be used for reporting other types of research like this study. A three-stage process was followed: (i) Identification, to select the databases to be used for this study; (ii) Screening, to identify papers for inclusion and further processing and; (iii) Eligibility based on well-defined criteria for inclusion and exclusion of papers on the analysis set. In Figure 1, the process followed in selecting the research papers to be considered in this literature review is shown using the PRISMA flow diagram. For the selected studies, the data extraction process was based on the Building Performance Institute Europe's (BPIE) 10 Smart Building Principles [30] which offers ten key guidelines for smart building integration. BPIE is further explained in section 3.1, and narrative synthesis was utilised [31,32] to record and critique the existing literature in the field.

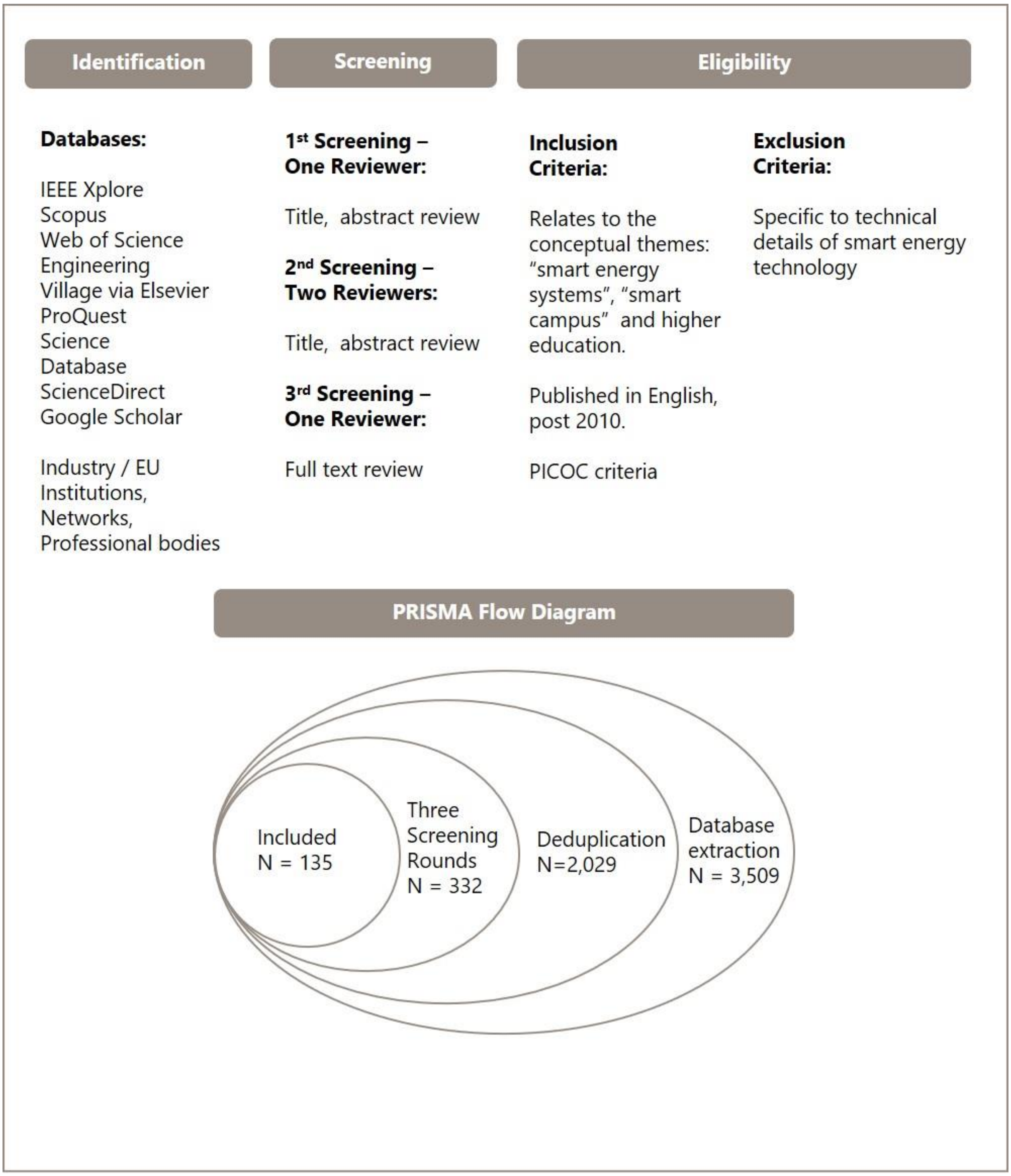

Figure 1: Systematic literature review protocol schematic through the different phases of the review, following the PRISMA flow diagram guidelines

2. Background

In various sectors and applications in everyday life, the word "smart" is used as a neologism and even a buzzword [20]. The use of the term can often be misleading, devoid of specific content and a priori suggesting that the introduction of ICT technology to standard processes can guarantee benefits like reduced energy demand, cost savings, increased productivity, or enhanced collaboration. Biresselioglu et al. [33] stated this dichotomy lucidly by stating that: 'Being smart should not be confused with being digital'.In this paper, we take a value-based perspective on what constitutes 'smart'. Digitisation, advanced and low-cost sensing technologies, cloud computing and ML/AI technologies to make sense of the wealth of data are all seen as Key Enabling Technologies. Instead, what defines smart is the value extracted from the data to support specific use cases and business scenarios. This definition focuses more on the value that can be extracted and how this can benefit working practices. A very relevant example can be smart building systems. Whilst we see modern systems being increasingly interconnected, supporting building-specific and IoT communication protocols, the value lies in the opportunities that linking and information exchange afford. For example, by being more aware of occupant-aware, system operation can contribute to more efficient user-centric operation contributing to improved productivity, health and well-being. Leveraging the big amount of data can help develop data-driven models that support more effective operation, whereas this is measured in carbon, cost, user experience or any other terms – of course, we have to admit that certain objectives can be conflicting and therefore a balance is required. The opportunities afforded by exploiting the insight are very significant, only constrained by our imagination and capabilities of existing technologies. Understanding the opportunities of change, and what constitutes value, is key to defining 'Smart Buildings' and subsequently 'Smart Campus'. The smart campus being a broad collection of buildings, often with varied characteristics such as use and age, which shares many similar principles to smart buildings. However, this increased diversity adds greater complexities and opportunities for a smart approach than at an individual building level. This has led to some authors considering campus scale smart systems a useful proxy for wider smart systems, such as city scale solutions [34]. Here we explore in more depths the attributes that define “smartness” focusing in energy applications in the context of energy systems and university campuses. The aim is to extract insights on the use of these terms in literature, their ascribed characteristics, barriers and motions for wider adoption, and the potential benefits.

2.1. Smart Energy Systems

Energy transition, referring to the decarbonisation of the energy sector and the sustainable response to growing energy needs [35–37], is integral to climate change mitigation. The idea of sustainable, low-carbon energy systems like 'Smart Grids' [22,33,38,39] has been studied extensively in that context to improve the monitoring and communication of the electricity grid with the consumer side with the use of ICT. The efforts to modernise the electricity grid [40], as captured in literature, are aiming to deliver clean, low-carbon, economical and resilient electricity supply [22,33,41,42]. The 'Smart Grid' evolution is referred to as 'Smart Energy System' [43,44]. It refers to integrating the intelligence field into the traditional energy system [21], focussing beyond the electricity network [22]. The lack of a universally accepted definition of the terms 'Smart Grid' and 'Smart Energy Systems' leads to these terms used interchangeably in the literature [33,43]. In the context of electricity networks, terms like The Energy Internet and Internet of Energy [45] and Transactive Energy Systems [46] refer to the Information and Communication Technologies (ICT) architecture of energy systems and the unidirectional selling and bidding of energy between prosumers.

Recent research refers to 'Smart Energy Systems' to refer to an integrated view that includes energy generation, management, transportation and consumption [6]. State-of-the-art paradigms and research for integrating renewable energy within the Smart Grid have been limited within these individual sub-sectors. These include nearly Zero-Energy Buildings (NZEB), transport and biomass fuels and power-to-heat sectors. Cross-sectoral research appeared later but overlooked heating and cooling and the industrial sectors [43,47]. Penetration of renewable energy sources, like wind and solar power sources, into smart energy systems poses specific challenges of accounting for the variability of these sources aiming for 100% renewable energy supply at the European level [48]. On the other hand, clean technologies like fuel cells, electric vehicles and batteries are in cost decline and could be utilised to manage the balancing of these dynamics [12,49].

At a national scale, smart grids are presenting substantial potential to enable the higher penetration of RES by providing the required flexibility and improving the quality and reliability of power distribution. The use of schemes like dynamic energy pricing can entice end-demand to pro-actively manage energy use for demand response, provide voltage regulation and load shifting opportunities, and provide an alternative to the power system expansion. The smart grid concept allows to depart from the concept of one central permitting for more decoupling and increase resilience. For example, by incentivising renewable distributed generation and intelligent management to better utilise flexible energy sources, introduce interesting possibilities. By relying on locally produced energy, better management and utilisation is possible on a local scale leading naturally to the concept of micro-grids and facilitating electricity network stability. Such approaches create opportunities for new participatory business models, like for example the aggregator business model. By balancing the demand and supply of energy, can lead to better utilisation of renewables, lower emissions and upgrades at building- and neighbourhood levels. Renewable energy production, together with energy storage can reduce reliance on external sources leading to concepts like grid islands. A shift in policy focus towards the district and local campus-scale is necessary to empower and enable a deeper energy system transition. The smart energy system model can be adopted to encapsulate distributed energy generation in microgrids and energy hubs devoid of the central electrical grid reference but including all elements that a multi-vector energy system contains [50].

More relevant to the university campus-scale, university smart energy systems connect and synchronise a group of buildings and university distributed energy resources with the energy system. They are part of the microgrid or energy-hub paradigms implementing various aspects of the microgrid architecture. Energy is produced, stored and consumed by the building efficiently, reducing the grid dependency and the grid stress through bidirectional communication and demand response techniques [51,52]. Thus, a single building or group of buildings can be a single DER node in the energy network and, at the same time a separate entity to the distribution network operating in island mode [53,54]. Within university campuses, the smart infrastructure adopted can be further developed to incorporate smart services related to the smart campus paradigm, as described below. The interactions of the smart energy and smart campus services are illustrated in Figure 2.

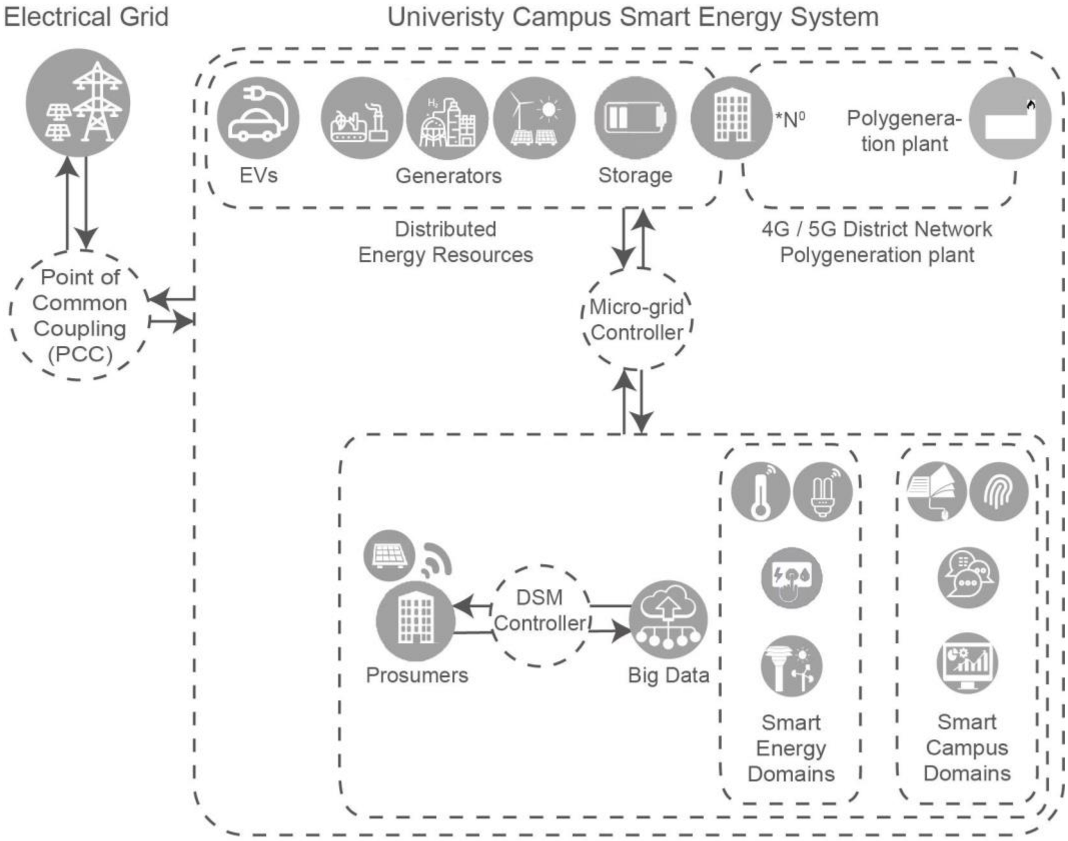

Figure 2: Smart energy system at university campus scale and interaction with the electrical Grid and district heat networks

Operations are managed through monitoring and automation. The data collected are used to optimise the performance based on the university campus value system like zero-carbon commitments, operations optimisation and user experience enhancement. An example of the smart energy system operation is load management in response to real time Grid prices, where price signals are communicated down to building level and demand-side response events ensure the optimised and coordinated control of loads within the campus buildings [55].

2.2. Smart Campuses

Like the Smart Grid and smart energy systems, the smart campus has been given a digital bias in the literature. Evolution from the traditional campus to a digital or e-campus has been through ICT adoption for material dissemination, online learning, internet-based teaching, and learning activities [9]. On top of these, the smart campus uses intelligence to adapt and react to changes to fulfil its users' needs, with campus buildings evolving from being an asset to becoming a service provider [16,56]. The building can be in dialogue with the user through agent-based social media participation, where it initiates communication with the students receiving feedback on building management [57]. The service, in this case being occupant health, comfort and well-being, and resilience against climate change impacts like heatwaves. The challenge, though, with the vastness of the data produced is the translation into the information available to operators, researchers and users, influences decision making and management and creates value for the university.

These smart services are categorised by Muhamad et al. [16] in six domains to include (1) technologies and systems for intelligent learning, (2) governance, (3) social networks, (4) campus management, (5) health and (6) green aspects. This conceptual clustering is based on the organisation of the university's values as an academic institution. This is to promote learning and research first and foremost. It is also to maintain efficient governance and management structures and to maintain a healthy economic standing. It is finally to encourage a healthy and environmentally sensitive 'ecosystem' for its community and wider context.

Key technologies related to the implementation of the smart campus are radio frequency identification (RFID), IoT, cloud computing, augmented reality (AR), sensor technology and mobile technology. These can bring about benefits like promoting energy efficiency by monitoring environmental conditions, automation and user engagement. Enhanced environmental comfort and good indoor air quality (IAQ) using smart sensors and HVAC system controls have been associated with enhanced cognitive performance during studies by Chatzidiakou et al. [58] on classroom environments. Cognitive buildings can learn from sensor subjective data and user objective data and can predict and respond to scenarios that enhance the user experience. Indoor environmental quality (IEQ) in educational buildings particularly is one key objective for educational activities [56]. As well as improved graduate performance, the smart campus enables further social interaction between the campus's users, wider attendance capabilities beyond the physical classroom, supports business processes, AR enabled way-finding, multi-media learning material and customised learning paths [16,20].

Opportunities and challenges associated with integrating smart energy systems at the university campus scale

2.3. Policy Pathways

Limiting the mean global temperature increase below 1.5°C is not without substantial socio-economic challenges like global cooperation, inequality, the growing population, resource consumption growth and uncertainties around land use emission control [59]. These are reflected in the several transformative mitigation policy pathways both internationally [36,59] and in the UK [35,49,60,61]. The National Grid [35] suggests that a high level of decentralisation and intense decarbonisation are required to meet 2050 targets. Achieving effective energy transitions requires transformative policy, investment in low-carbon technologies, research and development and integrated regulatory frameworks. The electricity sector share on GHG emissions and fossil fuel dependencies are major considerations for planning power systems expansion. RES diffusion plays a substantial role in GHG mitigation with respect to the incremental electricity demand growth and the inevitable nature of its consumption. The importance of the electric grid capacity in response to the electricity usage increase rate has been widely captured in literature [33].

Electricity infrastructure accounted for 45% of expenditure on new infrastructure in 2017 in the UK, amounting to £8.9bn, largely due to the construction of wind farms, of which 62.9% was private investment [62]. The Higher and Further education sector in the UK produced 1.6 million tonnes of CO_2 emissions during the 2017-2018 period, with energy consumption rising by 0.1 terawatt-hours in a year from 6.6 to 6.7 [63]. Despite a 2% rise in estate size in 2017/2018, CO_2 emissions have reduced by almost 20% in the same period. Wider UK trends in grid decarbonisation with renewable electricity supply supports this – with the carbon factor falling by 51% over the most recent 5 year period for which data is available [64]. In recent years increased renewable penetration has resulted in higher levels of price volatility in energy markets [65], from which smart energy systems can help protect campuses.

More than half of this energy cost comes from space heating, with lighting at around 20% of the total consumption [8]. Increased ICT requirements have also driven electricity consumption up, while ICT can also contribute to the problem when procurement and users are not fully aware of sustainable solutions and behaviours [66].
Similarly, an increase in temperatures and weather extremes in summer is also likely to increase cooling energy consumption [67]. Guerrieri et al. highlight the energy consumption associated with university campuses, attributed to the wide range of activities and use profiles of the campus buildings from teaching facilities, laboratories, administration offices, to student accommodation, catering, and sports facilities [68]. Other uses can include cultural participation within the campus, further extending the use profile beyond the standard working hours.

161 HE providers (including publicly funded Universities and HE Institutions, alternative HE course providers that do not receive public funding and Further Education Colleges in Wales [69]) are reporting their data to HESA, as presented in Figure 3. Institutions represented are mostly teaching universities, however, major research universities are also included in the list. The map indicates, renewable energy generation from on-site and off-site sources as a percentage of their total energy consumption. Suburban locations attract the largest proportions of renewable generation, although urban generation is present as well.

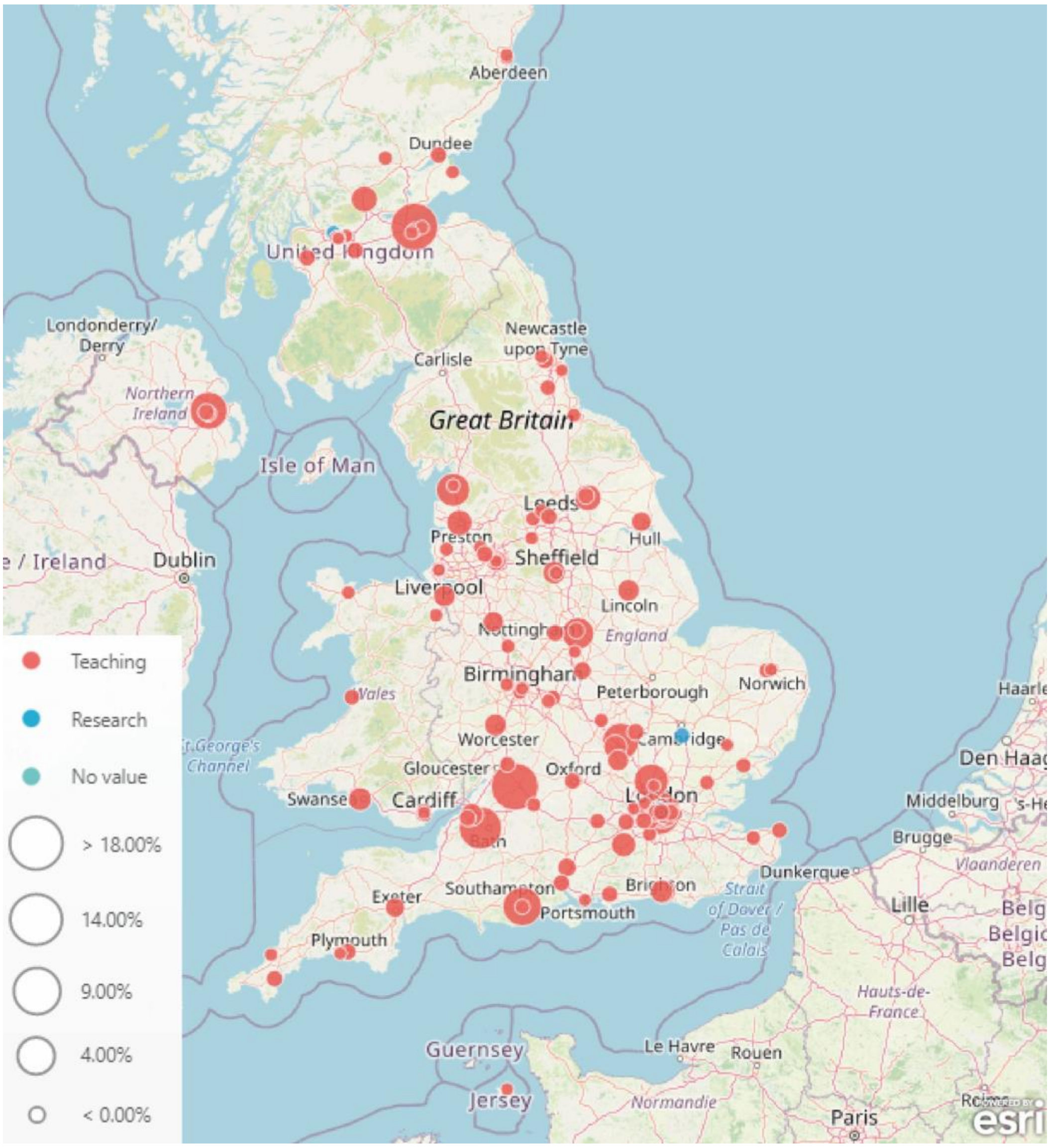

Figure 3: Higher education renewable energy generation as a percentage of total energy consumption, 2018/2019, Data source: HESA [63], *Map source: 'This map was created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. For more information about Esri® software, please visit www.esri.com.'*

Lack of climate resilience and climate change adaptation strategies can potentially create new ways of disruption to the education sector or exacerbate existing ones. Disruption to business continuity through electricity failures, flooding, and overheating may affect staff and student productivity, health, and well-being [62]. Existing regulation and policies related to smart energy systems are summarised in Figure 4. Several reviews have identified the policy gap between the need for smart energy system deployment and current regulations, policies and incentives [22,33,49]. The HE specific policy framework is obviously lacking as the only existing policy is currently voluntary without any linked financial incentives or regulatory requirements for existing university campuses which remain a key decarbonisation challenge.

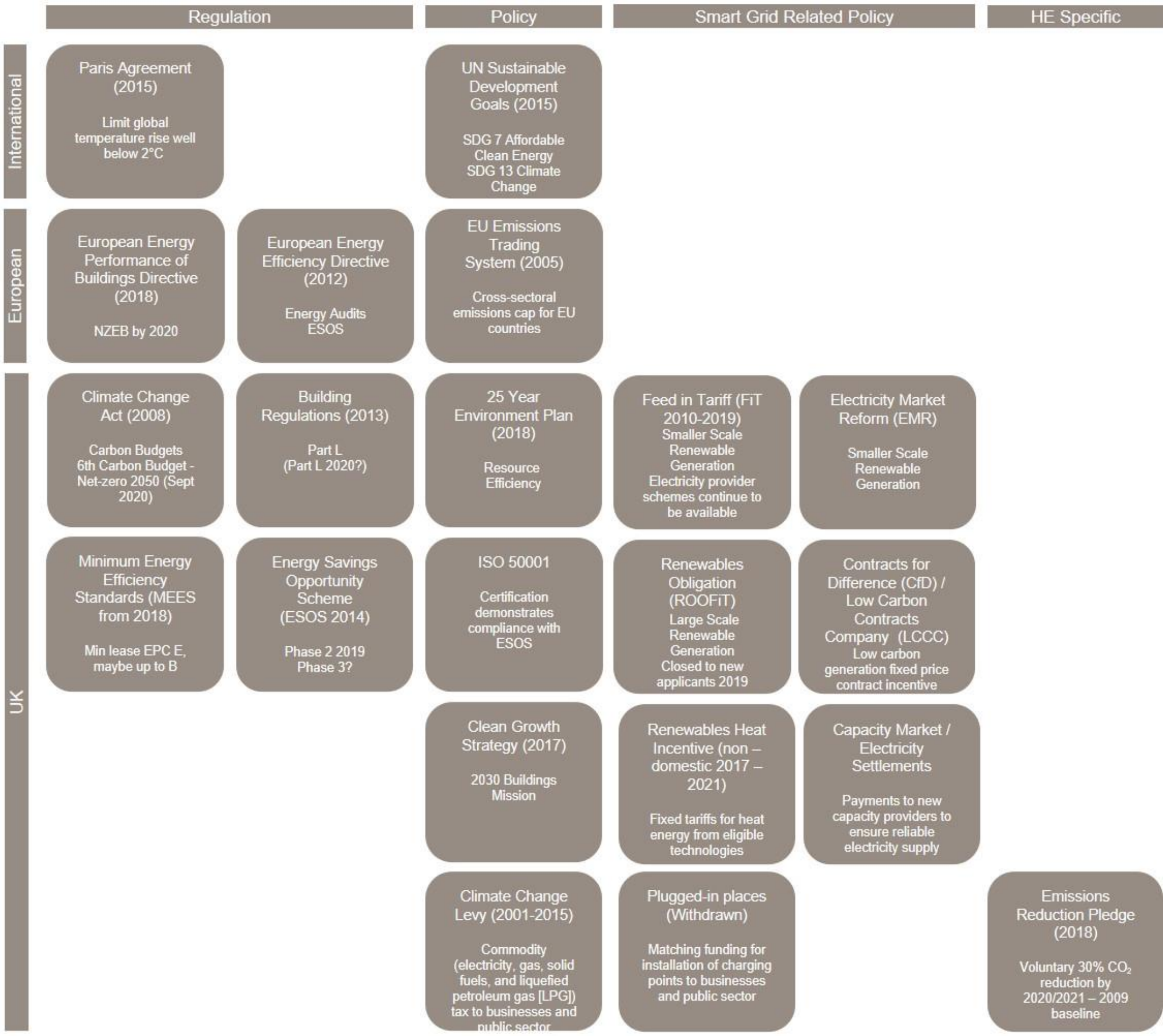

Figure 4: Key regulations and policies in the context of climate change, smart grid development and university campuses, adapted from Connor et al. and BEIS [22,70,71]

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 [33]. The smart energy system paradigm shift from energy consumers to prosumers should be also reinforced. This can be achieved with suitable incentives like dynamic pricing and with building trust by providing evidence on the benefits of smart technology integration and new business models [33]. Prompt development and smart energy technology installation could reduce required UK distribution networks investment by 2050 from £46bn to £23bn – £27bn, as calculated by SmartGrid GB and presented by Connor et al. [22].

Specific to the Higher Education sector, the UK Department for Business, Energy and Industrial strategy (BEIS) has introduced the 'Emissions Reduction Pledge'. This is a voluntary target for 30% carbon emissions reduction by 2020/2021 against a 2009/2010 baseline, aiming to support the UK's Climate Change Act commitments [72]. 91% of the institutions involved in the government Call for Evidence responded they would 'support and report against a voluntary emissions target' [73] for 30% reduction in GHG emissions by 2020/21 as is proposed in the Clean Growth Strategy [49]. A 'complex decision chain' [73] and lack of enforcement are identified as major barriers to university campus sustainability that is lost behind non-binding declarations instead of transformational commitments [74]. "Universities UK", GuildHE, the Association of Colleges and the Environmental Association for Universities and Colleges (EAUC) launched a Climate Commission for UK Higher Education and Further Education Students and Leaders to meet the desire for the Higher Education sector carbon emission reduction [71]. 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.

The current available energy efficiency and decarbonisation funding route for the UK education sector comes from Salix Finance [75] which is a government-funded company offering interest-free loans to the public sector for carbon reduction improvements. Between 2006 to 2017 Higher Education Institutions have received £130 million of funding through Salix Finance for a range of energy efficiency projects. These include fabric improvements, energy efficient lighting, heating and cooling system upgrades, while around £2 million has been received for controls and Building Energy Management Systems (BEMS), amounting to total of £35 million savings and 130,000 tonnes of carbon reduction annually [75]. Pre-brexit, universities also leveraged private funding from organisations like the European Investment Bank which is one of the largest climate finance providers and supports public sector entities in large investment [76]. For the post-Brexit UK, the UK Infrastructure Bank [77] could be another route to funding, should European resources seize to be available. Despite a £2 billion investment commitment from the UK Government to support decarbonisation across the economy, there was no direct commitment to the HE sector [71]. Other funding sources that Universities could leverage for developing smart energy system infrastructure include £500m for electric vehicle charging points [78], the 'Smart Export Guarantee' for up to 5MW of renewable generation exports to the Grid [79] and funding for smart energy system innovation and feasibility demonstrations [80].

2.4. Technical pathways

The decarbonisation potential across Europe through decarbonising the existing building stock is estimated to bring around 80% reduction in energy demand compared to 2005 [30]. The Energy Performance Buildings Directive recast calls for all Member States to ensure that "by 31 December 2020 all new buildings are nearly zero-energy buildings", which is further reinforced in the EU Directive 2018/884/EC [81]. The World Green Building Council has launched the 'Net Zero Carbon Buildings Commitment' in September 2018. The voluntary commitment encourages net zero carbon for operational energy (Scope 1 and 2 energy-related emissions) by 2030 for those organisations directly controlling their operations and for all others by 2050 [82]. The UK Green Building Council has adopted the campaign in the UK context by introducing the 'Advancing Net Zero' work programme in 2019, setting the highest priority in building energy demand reduction. A benefit of which is also the minimal infrastructure required for the future energy system. On-site renewables are prioritised over off-site [5].

University campuses typically aggregate several buildings in the same location, under the same owner. Therefore, operating under a single business strategy is connected to the same electrical network and sometimes heating network. Small distances between DER, varied load profiles and a single Point of Common Coupling (PCC) for the connection to the Grid render university campuses ideal for applying the smart energy system paradigm. Decentralised control within the local campus context also limits data and communication requirements with the central Grid [83]. University campuses are separate entities that can function disconnected from the Grid in island mode with sufficient resources to meet their energy demands [15] or as one aggregated entity with trading power to exchange power with the Grid at the price of the electricity market [54]. Besides, universities can obtain and trade green certificates for the renewable energy produced on-site [84]. This technical implementation pathway is also presented graphically in Figure 2.

The benefits of a campus smart energy system can be an amalgamation of the benefits of smart campuses and of smart energy systems. Benefits include: optimised electric and thermal power consumption, therefore operational cost reductions; reliable and flexible supply; integration of renewable energy sources with electric and thermal storage which provides clean energy to the university [85] and engagement of student and staff with innovation in the field based on interaction with smart technologies.

Universities as innovation hubs can be the frontrunners pushing the digital transformation and shift to smart campuses while, as small-scale city models [68] paving the way for the wider adoption of the smart city concept [86]. 'Educating for sustainability is a responsibility of universities, leveraging the access to cutting edge research and incorporating it into their curriculum. However, the power of universities lies in the ability to make education observable, serving as the evidence-based test models. A smart campus energy system paradigm can also be scalable to whole communities like neighbourhoods, cities and municipalities [74].

The integration of smart energy systems also comes with challenges, some of which were identified in a study by Shaffer et al. [12]. Technical transition and integration of new renewable or low-carbon infrastructure with existing systems can potentially disrupt business continuity and supply security. As the study highlights, a longer-term deeper adaptation plan likely has marginal financial returns. Commercial viability poses constraints in prioritising environmental and social long-term aspirations over investment towards a low-cost and quick return on investment interventions. Uncertainty about the actual energy savings [87] and lack of enforcement mechanisms are also prominent challenges for implementation of sustainability initiatives at university campuses [74]. These perceived risks could be counterbalanced by economies of scale achieved at the campus scale, where a range of activities and buildings are aggregated.

Therefore, a lack of a framework systematising the evidence base for the case of smart energy systems and regulatory enforcement remains one of the main barriers for their wider adoption.

3. Applicability of existing frameworks supporting a transition to smart energy campuses

The current literature review has identified a wealth of research and demonstrator initiatives around university campuses. The results are presented in Table 2, aiming to develop optimal techno-economic energy system performance often integrating CO_2 emission reduction targets, health and indoor environmental quality objectives, resilience and sustainability aspects. This type of action-oriented research is approaching system change not as an external problem but is tackling it from within the system studied, following the second-order, transformation research paradigm as described by Fazey et al. [25]. It is, however, narrowly focusing on the scalability of the proposals to the wider smart energy system. On the other hand, broader conceptual frameworks do not clearly set a path for the implementation of the proposed transition.

Industry networks [62] and universities [88] have responded to the climate change challenges with high-level 'readiness' and adaptation frameworks. With regards to climate change adaptation and resilience, the EAUC and the Higher Education Business Continuity Network (HEBCoN) have produced guidance and a high-level self-assessment framework for the climate-readiness of Further and Higher and Education Institutions [62]. The Centre for Digital Built Britain (CDBB) has published a roadmap to Information Management integration in the built environment [89].

3.1. Building scale frameworks

The Building Performance Institute Europe's (BPIE) 'Smart Buildings in a Decarbonised Energy System' is a conceptual framework for transforming the energy market through the existing building stock [30]. The proposed framework aims to leverage the potential untapped mitigation by reducing the climate impact of the three largest carbon emitting sectors – buildings, transport and the power sector combined [30]. The framework presents considerations for building smart integration opportunities like demand response, energy storage, dynamic tariffs and smart metering and primarily upgrade of the building energy performance to minimise energy demand and accommodate low-carbon heating and cooling technologies. The framework goes beyond building scale smart integration in bringing forward the value of building aggregation into micro energy hubs where on-site energy generation is maximised. The role of smart buildings within a district is also examined aiming to create interconnections between smart buildings and the local community. This can bring economic benefits through prosumer business models. Similarly, the concept can be applied to university campuses that interact with their local context as a group of buildings organised by a central entity.

Similarly, the Smart Readiness Indicator (SRI), introduced by the revised Energy Performance of Buildings Directive (EPBD) 2018/844/EU is aimed at promoting smart technologies with a focus on existing buildings with a tangible benefit to the building user, energy efficiency and flexibility. The SRI will form a common European Union scheme rating the smart readiness of buildings in terms of smart services and building-automation technologies in place as well as interconnectivity with the Grid and renewable energy integration [81]. The key principles and domains of these frameworks are being summarised in Table 1.

Table 1: BPIE 'Smart Buildings' 10 Principles and EPBD SRI domains

BPIE Smart Buildings Principles	EPBD SRI Domains
Principle 1: Maximise the building's energy efficiency first	1. Heating
Principle 2: Increase on-site or nearby RES production and self-consumption	2. Domestic hot water

BPIE Smart Buildings Principles	EPBD SRI Domains
Principle 3: Stimulate energy storage capacities in buildings	3. Cooling
Principle 4: Incorporate demand response capacity in building stock	4. Mechanical ventilation
Principle 5: Decarbonise the heating and cooling energy for buildings	5. Lighting
Principle 6: Empower end-users via smart meters and controls	6. Dynamic building envelope
Principle 7: Make dynamic price signals available for all consumers	7. Energy generation
Principle 8: Foster business models aggregating micro energy hubs	8. Demand side management
Principle 9: Build smart and interconnected districts	9. Electric vehicle charging
Principle 10: Build infrastructure to drive further market uptake of electric vehicles	10. Monitoring and control

Another building level framework specific to the drive towards building energy efficiency and NZEBs, the European Commission has introduced the Building Renovation Passport (BRP), which will provide homeowners with a roadmap to building energy efficiency renovation to nearly zero emissions standard. Clarity on how energy retrofits should be implemented is a key barrier to scaling up renovation rates apart from costs [87]. The benefits of Building Automation and Control Systems (BACS) are underpinned by the European standard BS EN 15232-1:2017 that forms the basis of the SRI [90]. From a list of control, automation and management options, the standard provides a method to assess the implementation requirements of such systems and two methods to quantify the impact of the systems on the building energy efficiency, a simple and detailed one. Additionally, the European Building, Automation, Controls Associate provides the eu.bac certification scheme for controls and building automation products. An ordinal system to evaluate smartness, is expected to drive energy efficiency in the operation of buildings by informing consumers about their choices of products [91].

These frameworks provide conceptual roadmaps or technology/equipment catalogues focused on specific domains within the system and the interactions between the building scale to the grid scale. The element of operational optimisation, energy management, integration with the Smart Grid, interactions between prosumers and the user beyond a single building focus could be explored to successfully implement the smart energy system to the university campus scale.

3.2. Campus scale frameworks

The BPIE framework's ten principles have been selected to follow conceptually and link challenges and opportunities related to Smart Energy within a university campus context.

A sample of key case studies included in this review is presented in Table 2 of this section to demonstrate that several universities worldwide adopt smart energy sectors. Examples like Stanford University and the University of California, Irvine campus demonstrate a whole system approach that takes advantage of their institution's research capabilities to testing and implementation. In most other cases otherwise, universities are adopting more than one of the principles. It is not through a strategic plan to develop a holistic smart energy system throughout their campus. Most case studies adopt some form of renewable energy generation source, and in most cases, solar panels, less common are wind power, fuel cells and waste-to-energy. Battery storage and smart energy management optimisation are common themes amongst case studies, while only five of these studies integrate demand response techniques. Smart energy management, monitoring, fault detection and predictive maintenance are widely mentioned at the building level. The user interface and engagement are missing as centralised supervisory control is typically utilised for HVAC controls. Dynamic pricing is only mentioned as part of a theoretical optimisation analysis for the University of Genoa, a long-standing microgrid demonstrator, since dynamic pricing is not yet regulated in most electricity markets worldwide. Similarly, integrating with the broader community and opportunities for multi-vector energy sharing are not prominent in these case studies. Six out of the twenty-six universities mentioned here are employing electric vehicles in their energy system strategy.

Table 2: University campuses integrating smart technologies and energy systems organised under the 10 Smart Building principles

	University Campus	*Ref.*	*Description/ KPI*	*Location*	*Study Type*	*Alignment to BPIE 10 Principles for Smart Buildings*									
						P.1	*P.2*	*P.3*	*P.4*	*P.5*	*P.6*	*P.7*	*P.8*	*P.9*	*P.10*
1.	Keele University	[10]	Smart Energy Network, energy water carbon emissions	Rural	Demonstrator	✓	✓			✓	✓				
2.	Birmingham City University	[92]	Smart Campus	Urban	Sustainability						✓				
3.	University of Sussex	[93]	Energy Efficiency, Renewables	Rural	Sustainability	✓	✓				✓				
4.	University of Brighton	[94]		Rural	Sustainability		✓			✓					
5.	Newcastle University	[57]	Energy system integration: Smart Grid Lab and Energy Storage Test bed, Urban Sciences Building as a Power Plant	Urban	Demonstrator	✓	✓	✓	✓	✓	✓				
6.	Agricultural University of Athens (AUA)	[95]	PV autonomous microgrid	Urban	Demonstrator		✓	✓		✓	✓				✓
7.	Aligarh Muslim University (AMU)	[96]	Microgrid	Urban	Demonstrator		✓	✓							
8.	Brookhaven National Laboratory (BNL) campus	[97]	Microgrid	Suburban	Case Study		✓	✓			✓				
9.	ETH Zurich Hönggerberg campus	[98]	Low carbon multi-energy system	Suburban	Demonstrator			✓		✓					
10.	Uka Tarsadia University, Bardoli, CGPIT, MALIBA CAMPUS	[99]	Load scheduling, cost reduction	Suburban	Case Study				✓						
11.	University of Denmark, Risø Campus	[100]	Microgrid control strategy, energy balance	Rural	Case study		✓	✓			✓				

	University Campus	*Ref.*	*Description/ KPI*	*Location*	*Study Type*	*Alignment to BPIE 10 Principles for Smart Buildings*									
						P.1	*P.2*	*P.3*	*P.4*	*P.5*	*P.6*	*P.7*	*P.8*	*P.9*	*P.10*
12.	University of Genoa, Savona Campus	[101–109]	Smart-polygeneration microgrid, operational optimisation	Urban	Pilot, several case studies			✓	✓	✓		✓			✓
13.	National University of Colombia-Bogotá Campus	[110]	Hybrid renewable energy system, Smart Grid	Urban	Test-bed, Pilot			✓	✓		✓			✓	✓
14.	Politecnico di Milano	[111]	Cognitive Renovation	Urban	Demonstrator	✓					✓				
15.	Shandong Normal University - Lishan College	[112]	Zero-carbon campus	Urban	Demonstrator		✓	✓		✓					
16.	Tennessee Tech University (TTU)	[83]	Cost, Resilience, Health	Urban	Demonstrator				✓		✓				
17.	University of Brescia	[113]	Smart Campus	Urban	Demonstrator						✓				
18.	University of California Berkeley Campus	[114]	Building to Grid (B2G)	Urban	Test-bed				✓						
19.	University of California Irvine Campus	[12]	Carbon neutrality by 2025 - Microgrid	Urban	Demonstrator	✓	✓	✓	✓	✓	✓		✓	✓	✓
20.	University of California San Diego Campus	[115]	Microgrid	Urban	Case study		✓	✓	✓			✓	✓	✓	
21.	University of California, Merced Campus	[116]	Savings to Sustainability (S2S), net-zero 2030	Urban	Case study	✓	✓				✓				
22.	Illinois Institute of Technology	[40]	Smart microgrid "Perfect Power" feasibility	Urban	Demonstrator Test-bed		✓	✓			✓				✓
23.	University of Novi Sad	[117]	Microgrid, Energy-Cost- CO_2	Urban	Case study		✓	✓		✓	✓				✓
24.	Austrian University	[118]	DER and EE		Case study	✓	✓	✓							
25.	Sapienza University	[119]	Smart Campus	Urban	Case study	✓	✓				✓				
26.	Stanford University	[120]	Stanford Energy System Innovations (SESI)	Urban	Demonstrator	✓	✓	✓		✓	✓				✓

	University Campus	Ref.	Description/ KPI	Location	Study Type	Alignment to BPIE 10 Principles for Smart Buildings									
						P.1	P.2	P.3	P.4	P.5	P.6	P.7	P.8	P.9	P.10
27.	Washington State University (WSU)	[121]	Transactive energy, Prosumer blockchain	Suburban	Demonstrator		✓			✓		✓		✓	

Figure 5, groups the characteristics of the twenty seven case studies under the ten BPIE principles. Principle 2, referring to the integration of renewable energy resources, and Principle 6, which refers to the use of smart meters and controls, were the most common amongst university campus demonstrators, often proposed as a combined strategy. Business models fostering aggregation of energy hubs, under Principle 8, were least prominent in the case studies reviewed.

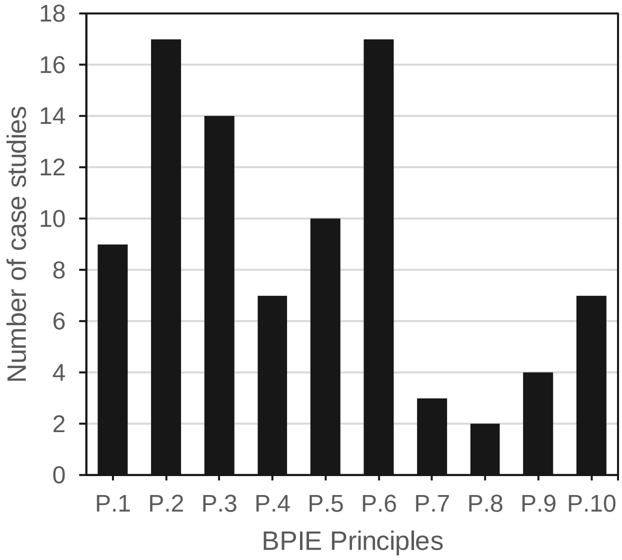

Figure 5: BPIE principles identified in 27 key case studies

Even though potential energy savings measures can vary amongst different climates. the common route identified in the case studies includes building envelope upgrade, replacing heating and cooling systems with more efficient low-carbon technologies, and often installing photovoltaics. The most common objective is cost reduction [110] and optimising cost and CO_2 emissions to nearly zero carbon standard [117,118,122,123]. The optimisation study of Stadler et al. [118] suggests that suboptimal retrofit interventions in the Austrian University campus reveal the complexity of interactions between passive interventions and DER and the need for a holistic cost and CO_2 optimisation approach. Embedding smart infrastructure at the renovation of the Politecnico di Milano enabled the digitisation of the construction process and was carried across the building's design life. Real-time operational data collected from the retrofitted plant and infrastructure allowed innovation with AI approaches on predictive maintenance and optimising energy efficiency and renewable resource management [111].

Guerrieri et al. [68] propose a multi-objective approach adding indoor comfort and financial incentives in the optimisation mix, although cost-optimality remains the overarching criterion.

The study by Xu et al. [112] proposes six design concepts for the transition to a zero-carbon campus based on the Shandong Normal University – Lishan College and highlights the fact that a zero-carbon campus can act as a test bed for innovation in low-carbon and sustainable development. The concepts involve:

1. Renewable energy application on a large scale for zero emissions;
2. Distributed energy for self-sufficient operation;
3. Low-grade heat utilisation;
4. Whole lifecycle design;
5. Minimum energy storage and seamless grid integration;
6. Closed-loop realisation based on the ecological cycle.

The study, however, identifies that the distributed energy generation is missing opportunities in operational optimisation and is proposing to adopt an 'Integrated Energy Management System', as defined, which coordinates the generation and load management.

The following studies reinforce the benefits of diversifying distributed energy resources to fully exploit RES within energy systems. In terms of distributed energy generation, self-consumption can: (i) empower end-users to control their energy consumption; (ii) provide cost savings to users under a grid parity scenario and; (iii) increase grid resilience by demand response and increasing use of storage and renewables. Electricity and thermal energy storage are essential in making renewable energy systems cost-effective [124]. Expensive energy consumption at peak load times can be avoided, balancing the intermittent supply and demand of renewable energy systems [30].

Much of the literature around higher renewable energy source penetration revolves around the Smart Grid and smart energy systems paradigms, representing the decentralised generation part within DER systems [14,21,53,115,125]. The potential of RES penetration to university campuses has been studied widely through case studies [68,95,126,127], others including energy storage [128,129] and demand response capability [55,100,130].

Solar and wind power are the most prominent RES in the case studies examined. Hybrid renewable systems consisting of more than one RES are also studied to mitigate the intermittency of RES and balance energy supply. Optimal self-consumption and utility power purchasing also benefit the local Grid, enhancing power quality, reliability and resilience [97].

The challenges around decarbonising existing heating and cooling systems in university campuses are not widely captured in the literature examined. Tuţică et al. [131] present the challenges in the University Politehnica of Bucharest's CHP heating system modernisation with the introduction of a waste heat cooling system decommissioning of the old steam turbines. The issue of excessive energy demand was addressed by double glazing installation and user behavioural education. A major UK demonstrator project based on the University of Keele, is trailing a 20% hydrogen blending into the gas grid [10] amongst others [12].

Overall, research focused on the savings potential from integrating such technologies to existing university campuses and the control and management methods for the optimal scheduling of energy vectors and planning of the system that is not necessarily captured at the smart building scale. Through a Virtual Power Plant (VPP) entity, energy management manages the production and demand balance in line with operation constraints [84]. Key objectives coming through are energy and investment cost optimisation, maximising self-consumption, net-zero drivers [132], demand forecasting and dispatch optimisation [133].

The architecture of a smart Energy Management System for the Tennessee Tech University has been described by Sulayman et al. in [83]. The system provides capabilities to monitor and troubleshoot the quality of power delivered and received; includes energy meters verifying and allocating bills to corresponding departments, areas or processes; allows to forecast demand, demand control events with load curtailment and preservation that improves system reliability. Overall, the systems reduces energy costs by identifying unused electricity capacity, monitors equipment and provides preventive maintenance and finally integrates utility meters aggregated and converted to energy units.

The study of Hau et al. [115] based on a California campus microgrid revealed that DER financial incentives like grants and tax benefits are essential to the profitability and commercial attractiveness of the project and to the effective design of the microgrid. As described by Hanna et al. [80] and focusing on the US landscape, the current policy environment makes investment in microgrids less attractive due to high inter-connection fees, long connection wait times and bans on-self generation. Other benefits identified are the potential reductions in energy cost, reliability, the value of the amenities involved with self-supply. In contrast, tariff rates, capital costs, natural gas prices and carbon emission cost remain as business case uncertainties.

Privacy-preserving transactive energy models have been demonstrated at Washington State University,. An energy-trading unidirectional framework was demonstrated, where blockchain technologies allowed to define and execute smart contracts [121]. Wang et al. [51] identified various examples of peer-to-peer cooperative microgrid trading moving from day-ahead to hour-ahead and real-time trading and from Smart Grids to Energy Internet (EI).

The interactions of university campus microgrids were not as prominent in the current literature review. However, several studies agree that Universities can resemble cities as independent entities within the energy system [68]. Electric vehicles represent one such interaction of universities with the wider community. They reduce traffic emissions, therefore enhancing local air quality and the potential to reduce primary energy consumption and fuel costs as described in the case of the University of Genoa, Savona campus by Foiadelli et al. [104]. Notably, plug-in electric vehicles (PEV) that can be part of the university's fleet and campus transportation represent both electricity demand and distributed generation with the ability to balance the RES fluctuating generation [53,134]

4.0 Discussion and Conclusions

Different reviews have already examined individual aspects of this paper's research objectives. The assessment demonstrated a lack of adopted definitions and adoption frameworks for smart campuses and smart energy systems. Although much of the literature around smart energy systems focuses on framing the concept and proposing conceptual models, implementation of services, required infrastructure and technologies around the smart energy system architecture and case studies based on those technologies and methods. Additionally, various reviews have identified operational university campus microgrids globally and have outlined architectures [40,135].

In terms of the existing policy scape, the current policy mainly drives the decarbonisation of the central electricity Grid and the decarbonisation of decentralised energy generation. The ongoing grid decarbonisation is not responding to the need to drive down the growing energy demands and integrate local renewable energy at the district scale. The issue is compounded at campus level by a notable lack of investment and regulation specific to smart energy integration for the UK HE sector. Similarly, a technical policy currently introduced is focusing on the decarbonisation of the building sector, for which energy systems play an integral role. However, there is no specific policy and regulation for the smart energy integration at the university campus scale. There is an evident lack of systematic approaches towards a transition pathway for the university campuses that are adopting the smart energy system. The leveraging of renewable energy generation and energy storage is not often holistically integrated with energy efficiency programmes, demand response schemes and bidirectional communication with the wider energy system. Overall, this review revealed a need for deep integration of multiple energy vectors, renewable energy sources (RES) and distributed energy resources (DER). Intelligent services for intersystem and user communications are needed to address the energy transition and the university campus services value offering. User engagement and enhanced environments conducive to learning are also key objectives of the paradigm.

In conclusion, case studies of smart energy or smart campus applications were often not critically challenging the conceptual framework. Therefore, they were not directly offering transformative value to future applications and research. As a result, the study has demonstrated the need to develop a framework that integrates the smart campus and smart energy system concepts to fulfil the university campus's fundamental values. This systematic literature review has identified the following three research gaps:

1. The evidence-base for the university campus-scale benefits of integrative, multi-vector smart energy system implementation, compared to standalone intervention benefits;
2. The evidence-base for the transferability of existing smart energy integration frameworks from building to campus, communities and cities scale;
3. A holistic decision-making framework for the development and integration of smart energy systems.

Declaration of competing interest

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

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References

[1] Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla PR, et al. Global warming of 1.5°C An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty Edited by Science Officer Science Assistant Graphics Officer Working Group I Technical Support Unit. 2019.

[2] The Economics of Climate Change: The Stern Review - Nicholas Stern, Nicholas Herbert Stern, Great Britain. Treasury - Google Books n.d. https://books.google.co.uk/books?hl=en&lr=&id=U-VmIrGGZgAC&oi=fnd&pg=PA1&dq=climate+change+stern+review&ots=9evU4xkpjf&sig=E8GtC5naDjOQ7j0OKHm0qE6YmFE&redir_esc=y#v=onepage&q=climate change stern review&f=false (accessed May 27, 2020).

[3] European Commission. Commission welcomes European Parliament adoption of key files of the Clean Energy for All Europeans package 2018. https://ec.europa.eu/commission/presscorner/detail/en/IP_18_6383 (accessed July 15, 2020).

[4] European Commission. Clean energy for all Europeans package | Energy 2019. https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en (accessed April 18, 2020).

[5] UKGBC. Net Zero Carbon Buildings: A Framework Definition Advancing Net Zero Programme Partners Lead Partner: Programme Partners. 2019.

[6] Cao X, Dai X, Liu J. Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. Energy Build 2016;128:198–213. https://doi.org/10.1016/j.enbuild.2016.06.089.

[7] Amber KP, Aslam MW, Mahmood A, Kousar A, Younis MY, Akbar B, et al. Energy consumption forecasting for university sector buildings. Energies 2017. https://doi.org/10.3390/en10101579.

[8] AUDE. AUDE's Higher Education Estates Management Report 2019 2019. https://www.aude.ac.uk/news/publications/ems-report/ (accessed April 22, 2020).

[9] Hawkins D, Hong SM, Raslan R, Mumovic D, Hanna S. Determinants of energy use in UK higher education buildings using statistical and artificial neural network methods. Int J Sustain Built Environ 2012;1:50–63. https://doi.org/10.1016/j.ijsbe.2012.05.002.

[10] Gu Y, Wang H, Xu J, Wang Y, Wang X, Robinson ZP, et al. Quantification of interlinked environmental footprints on a sustainable university campus: A nexus analysis perspective. Appl Energy 2019;246:65–76. https://doi.org/10.1016/j.apenergy.2019.04.015.

[11] Pecen R, Nayir A. Design and implementation of a 12 kW wind-solar distributed power and instrumentation system as an educational testbed for Electrical Engineering Technology students. n.d.

[12] Shaffer B, Flores R, Samuelsen S, Anderson M, Mizzi R, Kuitunen E. Urban Energy Systems and the Transition to Zero Carbon – Research and Case Studies from the USA and Europe. Energy Procedia 2018;149:25–38. https://doi.org/10.1016/j.egypro.2018.08.166.

[13] Bourdeau M, Zhai X qiang, Nefzaoui E, Guo X, Chatellier P. Modeling and forecasting building energy consumption: A review of data-driven techniques. Sustain Cities Soc 2019;48:101533. https://doi.org/https://doi.org/10.1016/j.scs.2019.101533.

[14] Soares N, Martins AG, Carvalho AL, Caldeira C, Du C, Castanheira É, et al. The challenging paradigm of interrelated energy systems towards a more sustainable future. Renew Sustain Energy Rev 2018;95:171–93. https://doi.org/https://doi.org/10.1016/j.rser.2018.07.023.

[15] Akindeji KT, Tiako R, Davidson IE. Use of Renewable Energy Sources in University Campus Microgrid – A Review. 2019 Int. Conf. Domest. Use Energy, 2019, p. 76–83.

[16] Muhamad W, Kurniawan NB, Suhardi, Yazid S. Smart campus features, technologies, and applications: A systematic literature review. 2017 Int. Conf. Inf. Technol. Syst. Innov., 2017, p. 384–91. https://doi.org/10.1109/ICITSI.2017.8267975.

[17] Hall LMH, Buckley AR. A review of energy systems models in the UK: Prevalent usage and categorisation. Appl Energy 2016;169:607–28. https://doi.org/10.1016/j.apenergy.2016.02.044.

[18] Jafary M, Wright M, Shephard L, Gomez J, Nair RU. Understanding Campus Energy Consumption -- People, Buildings and Technology. 2016 IEEE Green Technol. Conf., IEEE; 2016, p. 68–72. https://doi.org/10.1109/GreenTech.2016.20.

[19] Moreno MV, Dufour L, Skarmeta AF, Jara AJ, Genoud D, Ladevie B, et al. Big data: the key to energy efficiency in smart buildings. Soft Comput 2016;20:1749–62. https://doi.org/10.1007/s00500-015-1679-4.

[20] Coccoli M, Guercio A, Maresca P, Stanganelli L. Smarter universities: A vision for the fast changing digital era. J Vis Lang Comput 2014;25:1003–11. https://doi.org/10.1016/j.jvlc.2014.09.007.

[21] Haitao L, Yiming L, Ling W, Xijun G, Shouzhen Z, Jinghong Z, et al. Research on the conceptual model of smart energy system. 2017 IEEE Conf. Energy Internet Energy Syst. Integr. EI2 2017 - Proc., vol. 2018- Janua, Institute of Electrical and Electronics Engineers Inc.; 2017, p. 1–6. https://doi.org/10.1109/EI2.2017.8245690.

[22] Connor PM, Baker PE, Xenias D, Balta-Ozkan N, Axon CJ, Cipcigan L. Policy and regulation for smart grids in the United Kingdom. Renew Sustain Energy Rev 2014;40:269–86. https://doi.org/https://doi.org/10.1016/j.rser.2014.07.065.

[23] Good N, Martínez Ceseña EA, Mancarella P. Ten questions concerning smart districts. Build Environ 2017;118:362–76. https://doi.org/https://doi.org/10.1016/j.buildenv.2017.03.037.

[24] Olabi AG. Energy quadrilemma and the future of renewable energy. Energy 2016;108:1–6. https://doi.org/10.1016/j.energy.2016.07.145.

[25] Fazey I, Schäpke N, Caniglia G, Patterson J, Hultman J, van Mierlo B, et al. Ten essentials for action-oriented and second order energy transitions, transformations and climate change research. Energy Res Soc Sci 2018;40:54–70. https://doi.org/https://doi.org/10.1016/j.erss.2017.11.026.

[26] Khan N, Kalair E, Abas N, Kalair AR, Kalair AR. Energy transition from molecules to atoms and photons. Eng Sci Technol an Int J 2019;22:185–214. https://doi.org/https://doi.org/10.1016/j.jestch.2018.05.002.

[27] Moses I. Supervision of Higher Degree Students —Problem Areas and Possible Solutions. High Educ Res Dev 1984;3:153–65. https://doi.org/10.1080/0729436840030204.

[28] Phillips E. How to get a PhD : a handbook for students and their supervisors / Estelle M. Phillips and Derek S. Pugh. 5th ed. Maidenhead: Open University Press; 2010.

[29] Moher D, Liberati A, Tetzlaff J, Altman DG, Altman D, Antes G, et al. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. PLoS Med 2009;6. https://doi.org/10.1371/journal.pmed.1000097.

[30] BPIE. 10 Principles to deliver real benefits for Europe’s citizens. Smart buildings in a decarbonised energy system. 2016.

[31] Booth A, Sutton A, Papaioannou D. Systematic approaches to a successful literature review. Second. 2016.

[32] Thomas J, Harden A. Methods for the thematic synthesis of qualitative research in systematic reviews. BMC Med Res Methodol 2008. https://doi.org/10.1186/1471-2288-8-45.

[33] Biresselioglu ME, Nilsen M, Demir MH, Røyrvik J, Koksvik G. Examining the barriers and motivators affecting European decision-makers in the development of smart and green energy technologies. J Clean Prod 2018;198:417–29. https://doi.org/10.1016/j.jclepro.2018.06.308.

[34] Vasileva R, Rodrigues L, Hughes N, Greenhalgh C, Goulden M, Tennison J. What Smart Campuses Can Teach Us about Smart Cities: User Experiences and Open

Data. Information 2018;9:251. https://doi.org/10.3390/info9100251.
[35] National Grid ESO. Future Energy Scenarios. 2019.
[36] Renewable Energy Agency I. Global Renewables Outlook 2050 Energy Transformation Edition: 2020. 2020.
[37] Energy Transmitions Commision. Making Mission Possible Delivering a Net-Zero Economy. 2020.
[38] Siano P. Demand response and smart grids—A survey. Renew Sustain Energy Rev 2014;30:461–78. https://doi.org/https://doi.org/10.1016/j.rser.2013.10.022.
[39] Sharma A, Mathew M, Mitra I, Anwer N. Approaches Leading to Different Definitions of Smart Grid: A Review. n.d.
[40] Talei H, Zizi B, Abid MR, Essaaidi M, Benhaddou D, Khalil NLB-SPU. Smart campus microgrid: advantages and the main architectural components. 2015 3rd International Renewable and Sustainable Energy Conference (IRSEC): 2016.
[41] Xenias D, Axon CJ, Whitmarsh L, Connor PM, Balta-Ozkan N, Spence A. UK smart grid development: An expert assessment of the benefits, pitfalls and functions. Renew Energy 2015;81:89–102. https://doi.org/https://doi.org/10.1016/j.renene.2015.03.016.
[42] Kolokotsa D. The role of smart grids in the building sector. Energy Build 2016;116:703–8. https://doi.org/10.1016/j.enbuild.2015.12.033.
[43] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. https://doi.org/https://doi.org/10.1016/j.energy.2017.05.123.
[44] Xu Y, Yan C, Liu H, Wang J, Yang Z, Jiang Y. Smart energy systems: A critical review on design and operation optimization. Sustain Cities Soc 2020;62:102369. https://doi.org/10.1016/j.scs.2020.102369.
[45] Appelrath H-J, Terzidis O, Weinhardt C. Internet der Energie. Bus Inf Syst Eng 2012;54:1–2. https://doi.org/10.1007/s11576-011-0304-0.
[46] Ambrosio R. Transactive Energy Systems [Viewpoint]. IEEE Electrif Mag 2016;4:4–7. https://doi.org/10.1109/MELE.2016.2614234.
[47] Paardekooper S, Lund R, Lund H. Smart Energy Systems. Issues Environ Sci Technol 2019;2019-:228–60. https://doi.org/10.1039/9781788015530-00228.
[48] Connolly D, Lund H, Mathiesen B V. Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60:1634–53. https://doi.org/10.1016/j.rser.2016.02.025.
[49] BEIS. The Clean Growth Strategy Leading the way to a low carbon future. 2017.
[50] Phuangpornpitak N, Tia S. Opportunities and challenges of integrating renewable energy in smart grid system. Energy Procedia 2013;34:282–90. https://doi.org/10.1016/j.egypro.2013.06.756.
[51] Wang N, Xu W, Xu Z, Shao W. Peer-to-Peer Energy Trading among Microgrids with Multidimensional Willingness. Energies 2018;11:3312. https://doi.org/10.3390/en11123312.
[52] Pouttu A, Haapola J, Ahokangas P, Xu Y, Kopsakangas-Savolainen M, Porras E, et al. P2P model for distributed energy trading, grid control and ICT for local smart grids. 2017 Eur. Conf. Networks Commun., IEEE; 2017, p. 1–6. https://doi.org/10.1109/EuCNC.2017.7980652.
[53] Howell S, Rezgui Y, Hippolyte J-LL, Jayan B, Li H. Towards the next generation of smart grids: Semantic and holonic multi-agent management of distributed energy resources. Renew Sustain Energy Rev 2017;77:193–214. https://doi.org/10.1016/j.rser.2017.03.107.
[54] Benalcazar P, Suski A, Kamiński J. The Effects of Capital and Energy Subsidies on the Optimal Design of Microgrid Systems. Energies 2020;13:955. https://doi.org/10.3390/en13040955.
[55] Zhang X, Pipattanasomporn M, Kuzlu M, Rahman S. Conceptual framework for a multi-building peak load management system. 2016 IEEE PES Innov. Smart Grid Technol. Conf. Eur., IEEE; 2016, p. 1–5.

https://doi.org/10.1109/ISGTEurope.2016.7856238.

[56] Ciribini ALC, Pasini D, Tagliabue LC, Manfren M, Daniotti B, Rinaldi S, et al. Tracking Users' Behaviors through Real-time Information in BIMs: Workflow for Interconnection in the Brescia Smart Campus Demonstrator. Procedia Eng., vol. 180, Elsevier Ltd; 2017, p. 1484–94. https://doi.org/10.1016/j.proeng.2017.04.311.

[57] Mitchell Finnigan S, Olivier P, Clear AK. SpaceBot: Towards participatory evaluation of smart buildings. Conf. Hum. Factors Comput. Syst. - Proc., 2018. https://doi.org/10.1145/3170427.3188491.

[58] Chatzidiakou L, Mumovic D, Dockrell J. The Effects of Thermal Conditions and Indoor Air Quality on Health, Comfort and Cognitive Performance of Students. 2014.

[59] Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V, et al. 2018: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission. 2018.

[60] DEFRA. The National Adaptation Programme and the Third Strategy for Climate Adaptation Reporting Making the country resilient to a changing climate. 2018.

[61] Pye S, Price J, Cronin J, Butnar I, Welshby D. Modelling "leadership-driven" scenarios of the global mitigation effort. 2019.

[62] EAUC, HEBCoN, AECOM. Adapting universities and colleges to a changing climate 2019.

[63] HESA. Table 2 - Energy by HE provider, academic year 2018/19 | HESA 2019. https://www.hesa.ac.uk/data-and-analysis/estates/table-2 (accessed April 14, 2020).

[64] BEIS. Digest of UK Energy Statistics (DUKES): electricity - GOV.UK 2020. https://www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes (accessed May 10, 2021).

[65] Blazquez J, Fuentes-Bracamontes R, Bollino CA, Nezamuddin N. The renewable energy policy Paradox. Renew Sustain Energy Rev 2018;82:1–5. https://doi.org/10.1016/j.rser.2017.09.002.

[66] EAUC-Scotland. Sustainability Sharing Series: Lowering the carbon impact of ICT Guide | Sustainability Exchange. 2018.

[67] Carbon Trust. Further and higher education Training colleges and universities to be energy efficient CTV020 Sector Overview. 2007.

[68] Guerrieri M, La Gennusa M, Peri G, Rizzo G, Scaccianoce G, Gennusa M La, et al. University campuses as small-scale models of cities: Quantitative assessment of a low carbon transition path. Renew Sustain Energy Rev 2019;113:109263. https://doi.org/https://doi.org/10.1016/j.rser.2019.109263.

[69] HESA. Higher education providers | HESA 2020. https://www.hesa.ac.uk/support/providers (accessed July 21, 2020).

[70] BEIS. UK National Energy and Climate Plan (NECP). 2019.

[71] OfS. Reducing higher education carbon emissions. 2020.

[72] BEIS. Emissions Reduction Pledge 2020 - Potential Assessment. A high level assessment examining the potential to reduce carbon emissions across the wider public and higher education sectors in the UK. 2018.

[73] BEIS. An emissions reduction target for the wider Public and Higher Education Sectors. A summary of responses to the call for evidence. 2018.

[74] Mohammadalizadehkorde M, Weaver R. Universities as Models of Sustainable Energy-Consuming Communities? Review of Selected Literature. Sustainability 2018;10:3250. https://doi.org/10.3390/su10093250.

[75] BEIS. Salix Finance working with Higher Education Institutes. 2017.

[76] EIB. Who we are 2020. https://www.eib.org/en/about/index.htm (accessed September 21, 2020).

[77] HM Treasury. Policy Design of the UK Infrastructure Bank - GOV.UK 2021. https://www.gov.uk/government/publications/policy-design-of-the-uk-infrastructure-bank (accessed May 10, 2021).

[78] HM Goverment. Over £500m new investment in green technologies for a cleaner and healthier future - GOV.UK 2019. https://www.gov.uk/government/news/over-500m-new-investment-in-green-technologies-for-a-cleaner-and-healthier-future (accessed July 21, 2020).
[79] Ofgem. About the Smart Export Guarantee (SEG) | Ofgem 2020. https://www.ofgem.gov.uk/environmental-programmes/smart-export-guarantee-seg/about-smart-export-guarantee-seg (accessed July 21, 2020).
[80] BEIS. Funding for innovative smart energy systems - GOV.UK 2020. https://www.gov.uk/guidance/funding-for-innovative-smart-energy-systems#funding-for-non-domestic-smart-energy-management (accessed July 21, 2020).
[81] European Union. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency . Off J 2018. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.156.01.0075.01.ENG&toc=OJ:L:2018:156:TOC (accessed May 23, 2020).
[82] Council WGB. The Net Zero Carbon Buildings Commitment | World Green Building Council 2018. https://www.worldgbc.org/thecommitment (accessed May 23, 2020).
[83] Sulayman U, Alouani AT. Smart grid monitoring using local area sensor network. Real-time data acquisition, analysis and management. 2011 Proc. IEEE Southeastcon, IEEE; 2011, p. 444–9. https://doi.org/10.1109/SECON.2011.5752983.
[84] Lazaroiu GC, Dumbrava V, Costoiu M, Teliceanu M, Roscia M. Smart campus-an energy integrated approach. 2015 Int. Conf. Renew. Energy Res. Appl. ICRERA 2015, 2015. https://doi.org/10.1109/ICRERA.2015.7418657.
[85] Hanna R, Ghonima M, Kleissl J, Tynan G, Victor DG. Evaluating business models for microgrids: Interactions of technology and policy. Energy Policy 2017;103:47–61. https://doi.org/10.1016/j.enpol.2017.01.010.
[86] Zhuhadar L, Thrasher E, Marklin S, de Pablos PO. The next wave of innovation—Review of smart cities intelligent operation systems. Comput Human Behav 2017;66:273–81. https://doi.org/10.1016/j.chb.2016.09.030.
[87] Sesana MM, Salvalai G. A review on Building Renovation Passport: Potentialities and barriers on current initiatives. Energy Build 2018;173:195–205. https://doi.org/10.1016/j.enbuild.2018.05.027.
[88] University of London. University of London - Zero Carbon Estates Handbook | Sustainability Exchange 2019. https://www.sustainabilityexchange.ac.uk/university_of_london_zero_carbon_estates_handbo (accessed May 23, 2020).
[89] CDBB. Press Release: Roadmap from the DFTG and launch of Digital Twin Hub | Centre for Digital Built Britain 2019. https://www.cdbb.cam.ac.uk/news/2019April8RoadmapPressRelease (accessed May 23, 2020).
[90] British Standards Institution. BS EN 15232-1 2017: Energy performance of buildings. Impact of Building Automation, Controls and Building Management 2017.
[91] eu.bac. eu.bac- The European Product Certification for Energy Efficiency in the range of Home Controls and Building Automation 2020. https://www.eubac.org/product-certification-/index.html (accessed September 30, 2020).
[92] Hipwell S. Developing smart campuses: A working model. 2014 Int. Conf. Intell. Green Build. Smart Grid, IEEE; 2014, p. 1–6. https://doi.org/10.1109/IGBSG.2014.6835169.
[93] University of Sussex. Energy : Creating a sustainable university : About us : University of Sussex 2020. https://www.sussex.ac.uk/about/sustainable-university/energy (accessed July 22, 2020).
[94] University of Brighton. What we’re doing 2020. https://www.brighton.ac.uk/about-us/your-university/sustainability/what-we-do/index.aspx (accessed July 22, 2020).
[95] Karavas CS, Papadakis G. Integration of renewable energy technologies in the

community of the agricultural university of Athens. EU PVSEC, 2019, p. 2520–3.
[96] Ahmad F, Alam MS. Optimal Sizing and Analysis of Solar PV, Wind, and Energy Storage Hybrid System for Campus Microgrid. Smart Sci 2018;6:150–7. https://doi.org/10.1080/23080477.2017.1417005.
[97] Jung J, Villaran M. Optimal planning and design of hybrid renewable energy systems for microgrids. Renew Sustain Energy Rev 2017;75:180–91. https://doi.org/10.1016/j.rser.2016.10.061.
[98] Gabrielli P, Acquilino A, Siri S, Bracco S, Sansavini G, Mazzotti M. Optimization of low-carbon multi-energy systems with seasonal geothermal energy storage: The Anergy Grid of ETH Zurich. Energy Convers Manag X 2020;8:100052. https://doi.org/10.1016/j.ecmx.2020.100052.
[99] Solanki Z, Wani U, Patel J. Demand side management program for balancing load curve for CGPIT College, Bardoli. 2017 Int. Conf. Energy, Commun. Data Anal. Soft Comput., IEEE; 2017, p. 769–74. https://doi.org/10.1109/ICECDS.2017.8389542.
[100] Mantovani G, Costanzo GT, Marinelli M, Ferrarini L. Experimental Validation of Energy Resources Integration in Microgrids via Distributed Predictive Control. IEEE Trans Energy Convers 2014;29:1018–25. https://doi.org/10.1109/TEC.2014.2362887.
[101] Rivarolo M, Cuneo A, Traverso A, Massardo AF. Design optimisation of smart poly-generation energy districts through a model based approach. Appl Therm Eng 2016;99:291–301. https://doi.org/10.1016/j.applthermaleng.2015.12.108.
[102] R Nudell T, Brignone M, Robba M, Bonfiglio A, Delfino F, Annaswamy A. A Dynamic Market Mechanism for Combined Heat and Power Microgrid Energy Management. IFAC-PapersOnLine 2017;50:10033–9. https://doi.org/10.1016/j.ifacol.2017.08.2040.
[103] Labella A, Mestriner D, Procopio R, Delfino F. A simplified first harmonic model for the Savona Campus Smart Polygeneration Microgrid. 2017 IEEE Int. Conf. Environ. Electr. Eng. 2017 IEEE Ind. Commer. Power Syst. Eur. (EEEIC / I&CPS Eur., vol. 10, IEEE; 2017, p. 1–6. https://doi.org/10.1109/EEEIC.2017.7977491.
[104] Foiadelli F, Longo M, Delfino F, Bracco S, Spina D, Dhaene T. Electric vehicle use in public fleets: The case of the Genoa University. 2017 Int. Conf. ENERGY Environ., IEEE; 2017, p. 490–4. https://doi.org/10.1109/CIEM.2017.8120773.
[105] Brenna M, Foiadelli F, Longo M, Bracco S, Delfino F. Sustainable electric mobility analysis in the Savona Campus of the University of Genoa. 2016 IEEE 16th Int. Conf. Environ. Electr. Eng., IEEE; 2016, p. 1–5. https://doi.org/10.1109/EEEIC.2016.7555562.
[106] Bracco S, Delfino F, Pampararo F, Robba M, Rossi M. The University of Genoa smart polygeneration microgrid test-bed facility: The overall system, the technologies and the research challenges. Renew Sustain Energy Rev 2013;18:442–59. https://doi.org/10.1016/j.rser.2012.10.009.
[107] Bracco S, Delfino F, Pampararo F, Robba M, Rossi M. A dynamic optimization-based architecture for polygeneration microgrids with tri-generation, renewables, storage systems and electrical vehicles. Energy Convers Manag 2015;96:511–20. https://doi.org/10.1016/j.enconman.2015.03.013.
[108] Bracco S, Delfino F, Pampararo F, Robba M, Rossi M. Planning and management of sustainable microgrids: The test-bed facilities at the University of Genoa. 2013 Africon, IEEE; 2013, p. 1–5. https://doi.org/10.1109/AFRCON.2013.6757862.
[109] Bonfiglio A, Brignone M, Delfino F, Girdinio P, Pampararo F, Procopio R. A two-step procedure for the energy management in smart microgrids accounting for economical and power quality issues. 2015 IEEE 15th Int. Conf. Environ. Electr. Eng., IEEE; 2015, p. 395–400. https://doi.org/10.1109/EEEIC.2015.7165194.
[110] Tellez S, Alvarez D, Montano W, Vargas C, Cespedes R, Parra E, et al. National Laboratory of Smart Grids (LAB+i) at the National University of Colombia-Bogotá Campus. 2014 IEEE PES Transm. Distrib. Conf. Expo. - Lat. Am. (PES T&D-LA), vol. 2014- Octob, IEEE; 2014, p. 1–6. https://doi.org/10.1109/TDC-LA.2014.6955185.
[111] Rinaldi S, Bellagente P, Camillo Ciribini AL, Chiara Tagliabue L, Poli T, Giovanni Mainini A, et al. A cognitive-driven building renovation for improving energy effciency:

The experience of the elisir project. Electron 2020;9. https://doi.org/10.3390/electronics9040666.

[112] Xu P, Jin Z, Zhao Y, Wang X, Sun H. Design and operation experience of zero-carbon campus. E3S Web Conf 2018;48:03004. https://doi.org/10.1051/e3sconf/20184803004.

[113] Bellagente P, Ferrari P, Flammini A, Rinaldi S. Adopting IoT framework for Energy Management of Smart Building: A real test-case. 2015 IEEE 1st Int. Forum Res. Technol. Soc. Ind. Leveraging a better tomorrow, IEEE; 2015, p. 138–43. https://doi.org/10.1109/RTSI.2015.7325084.

[114] Tatro R, Vadhva S, Kaur P, Shahpatel N, Dixon J, Alzanoon K. Building to Grid (B2G) at the California Smart Grid Center. 2010 IEEE Int. Conf. Inf. Reuse Integr., IEEE; 2010, p. 382–7. https://doi.org/10.1109/IRI.2010.5558902.

[115] Hau V, Husein M, Chung I-Y, Won D-J, Torre W, Nguyen T. Analyzing the Impact of Renewable Energy Incentives and Parameter Uncertainties on Financial Feasibility of a Campus Microgrid. Energies 2018;11:2446. https://doi.org/10.3390/en11092446.

[116] Sanders M, Parrish K, Earni S. Savings to Sustainability: Application of a Novel Approach to Delivering a Sustainable Built Environment. J Archit Eng 2013;19:156–63. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000119.

[117] Savic NS, Katic VA, Katic NA, Dumnic B, Milicevic D, Corba Z. Techno-economic and environmental analysis of a microgrid concept in the university campus. 2018 Int. Symp. Ind. Electron., IEEE; 2018, p. 1–6. https://doi.org/10.1109/INDEL.2018.8637613.

[118] Stadler M, Groissböck M, Cardoso G, Marnay C. Optimizing Distributed Energy Resources and building retrofits with the strategic DER-CAModel. Appl Energy 2014;132:557–67. https://doi.org/10.1016/j.apenergy.2014.07.041.

[119] Pagliaro F, Mattoni B, Gugliermenti F, Bisegna F, Azzaro B, Tomei F, et al. A roadmap toward the development of Sapienza Smart Campus. 2016 IEEE 16th Int. Conf. Environ. Electr. Eng., IEEE; 2016, p. 1–6. https://doi.org/10.1109/EEEIC.2016.7555573.

[120] AASHE. Stanford University | Scorecard | Institutions | STARS Reports 2019. https://reports.aashe.org/institutions/stanford-university-ca/report/2019-02-22/ (accessed July 22, 2020).

[121] Hahn A, Singh R, Liu C-C, Chen S. Smart contract-based campus demonstration of decentralized transactive energy auctions. 2017 IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf., IEEE; 2017, p. 1–5. https://doi.org/10.1109/ISGT.2017.8086092.

[122] Ascione F, Bianco N, De Masi RF, Mauro GM, Vanoli GP. Energy retrofit of educational buildings: Transient energy simulations, model calibration and multi-objective optimization towards nearly zero-energy performance. Energy Build 2017;144:303–19. https://doi.org/https://doi.org/10.1016/j.enbuild.2017.03.056.

[123] Bellia L, Borrelli M, De Masi RF, Ruggiero S, Vanoli GP. University building: Energy diagnosis and refurbishment design with cost-optimal approach. Discussion about the effect of numerical modelling assumptions. J Build Eng 2018;18:1–18. https://doi.org/10.1016/j.jobe.2018.02.017.

[124] Powell KM, Kim JS, Cole WJ, Kapoor K, Mojica JL, Hedengren JD, et al. Thermal energy storage to minimize cost and improve efficiency of a polygeneration district energy system in a real-time electricity market. Energy 2016;113:52–63. https://doi.org/10.1016/j.energy.2016.07.009.

[125] Eid BM, Rahim NA, Selvaraj J, El Khateb AH. Control methods and objectives for electronically coupled distributed energy resources in microgrids: A review. IEEE Syst J 2016;10:446–58. https://doi.org/10.1109/JSYST.2013.2296075.

[126] Zhu Y, Wang F, Yan J. The Potential of Distributed Energy Resources in Building Sustainable Campus: The Case of Sichuan University. Energy Procedia 2018;145:582–5. https://doi.org/10.1016/j.egypro.2018.04.085.

[127] Melo M.G PWPA. Model and simulation of a microgrid based on a traditional electrical

infrastructure. n.d.

[128] Saritha KS, Sreedharan S, Nair U. A generalized setup of a campus microgrid — A case study. 2017 Int. Conf. Energy, Commun. Data Anal. Soft Comput., IEEE; 2017, p. 2182–8. https://doi.org/10.1109/ICECDS.2017.8389838.

[129] Hongbo R, Weijun G. Integrated plan of distributed energy systems taking into consideration energy storage. 2nd WSEAS/IASME Int. Conf. ENERGY PLANNING, ENERGY SAVING, Environ. Educ., 2008, p. 42–7.

[130] Xiongwei L, Chilvers I, Mokhtar M, Bedford A, Stitt K, Yazdani J. Microgrid development for properties. n.d.

[131] Tuţică D, Cenuşă V, Tudor P, Pătraşcu R, Minciuc E. Energy Management Solutions To Increase Performance Of A Supplier And Consumer System: Case Study For A University CHP. Int. Multidiscip. Sci. GeoConference, Sofia: 2018. https://doi.org/10.5593/sgem2018/4.1/S17.045.

[132] Damm CJ, Zloza WA, Stafl SJ, Radlinger BLB-SPM. Development of a web-based decision tool for selection of Distributed Energy Resources and Systems (DERS) for moving college and corporate campuses toward net-zero energy. 2017 ASEE Annu. Conf. Expo., vol. 2017- June, 2017.

[133] McLarty D, Civit Sabate C, Brouwer J, Jabbari F. Micro-grid energy dispatch optimization and predictive control algorithms; A UC Irvine case study. Int J Electr Power Energy Syst 2015;65:179–90. https://doi.org/10.1016/j.ijepes.2014.09.039.

[134] Brenna M, Foiadelli F, Longo M, Bracco S, Delfino F. Smart microgrids in smart campuses with electric vehicles and storage systems: Analysis of possible operating scenarios. 2016 IEEE Int. Smart Cities Conf., IEEE; 2016, p. 1–6. https://doi.org/10.1109/ISC2.2016.7580794.

[135] Hadjidemetriou L, Zacharia L, Kyriakides E, Azzopardi B, Azzopardi S, Mikalauskiene R, et al. Design factors for developing a university campus microgrid. 2018 IEEE Int. Energy Conf., 2018, p. 1–6. https://doi.org/10.1109/ENERGYCON.2018.8398791.