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Cost-effective and optimal pathways to selecting building microgrid components – The resilient, reliable, and flexible energy system under changing climate conditions

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ABSTRACT

Amidst the changing climate conditions, electricity retailers-led demand response programs and the emergency backup power for possible grid outages are often discussed in isolation, although several underlying linkages exist, which are important for how the existing building stock evolves with the energy transition. This study navigates through the linkages while investigating the levelized cost of electricity (LCOE)-based building microgrid components and undertakes a comparative analysis of energy optimisation models with and without emergency diesel generators. It also examines the building energy system's resilience, reliability, and flexibility by using OpenStudio and HOMER Grid to develop energy simulation and optimisation models and other probabilistic models for a chosen building archetype in Sydney, Australia. This study finds that excluding the emergency diesel generator will require a larger battery storage system, increasing LCOE from A$0.17/kWh to A $0.20/kWh across climate scenarios. However, the larger battery storage system increases the probability of surviving outages (> 4 h) by around 10 % across climate scenarios. The LCOE increases up to 45 % for outages up to 8 h across climate scenarios and up to 85 % for outages up to 12 h. Additionally, for the building archetype, the probability of grid purchase (below the current average) is 0.78 in 2030, which drops to 0.55 in 2050. The probability of grid sales (above the current average) also drops from 0.69 to 0.46. Thus, while the narratives around the building energy system's flexibility overstate the electricity exchange between the building and the grid, this study finds that increasing the on-site production utilisation rate and larger battery throughput contributes to demand response application and flexibility.

1. Introduction

Renewable energy integration and the energy system's resilience, reliability, and flexibility are increasingly discussed together in literature focusing on microgrid application at various scales [18,103,108]. While the microgrid is discussed more in the context of community electrification and as an off-grid solution, their applications include grid-connected commercial, institutional, educational, and industrial facilities [96,102,103,45]. A building microgrid's capacity is usually around hundreds of kilowatts, and they have an active role in partial-to-full electricity supply to buildings via onsite energy supply components, such as solar PV, battery energy storage systems (BESS), and diesel generators (DG) [56]. Literature on building microgrids focuses primarily on grid-connected solar PV, with and without battery storage system, given that most office and commercial buildings have peak power demand during the daytime and in the context of net zero energy buildings [89,96]. Other advanced microgrid applications include electric road and rail transportation, maritime (e.g. shipboard microgrid) and aerospace [19,117,81].

A new strand of literature discussing the flexibility, reliability, and

Abbreviations: A$, Australian Dollar; BESS, Battery Energy Storage System; CDD, Cooling Degree Days; CL, Critical Load; DG, Diesel Generator; DOD, Depth of Discharge; DR, Demand Response; DREEF, Demand Response Events Effectiveness Factor; EV, Electric Vehicle; FCAS, Frequency Control Ancillary Services; FTS, Failure To Start; HVAC, Heating, Ventilation, and Air Conditioning System; kWh, kilowatt hours; LCOE, Levelized Cost of Electricity; MTTF, Mean Time To Failure; NCC, National Construction Code; NPC, Net Present Cost; OA, Operational Availability; PGp, Probability of purchasing electricity from the grid; PGs, Probability of supplying electricity to the grid; Ps, Probability of surviving outages; RCP, Representative Concentration Pathways; SOC, State of Charge; TMY, Typical Meteorological Year; ToU, Time-of-Use; V2G, Vehicle-to-Grid; VPP, Virtual Power Plant.

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resilience of solar PV-based and grid-connected building microgrids emphasises the integration of Vehicle-to-Grid (V2G) for their additional offering, such as demand response [72,110,125,126]. Some papers have gone beyond the concept of using Solar PV-plus-BESS and V2G by researching the integration of cutting-edge technologies, such as electrolyser, hydrogen storage and fuel cell stacks in the building microgrids [10,31,98]. However, electrolyser types and efficiency (e.g. proton exchange membrane and capillary-fed electrolysis cell), and green hydrogen production and storage pathways (e.g. catalytic ammonia cracking, photo electrolysis, and thermochemical pyrolysis) are still under development for commercialisation in the future [43,11,85,34,119].

Energy-flexible buildings pertain to matching and managing the building energy load profile and the energy supply profile (on-site energy dispatch and grid import), given that the profiles fluctuate depending on local climatic conditions, user consumption behaviour, and grid performance [107,87,125,82,78]. An energy-flexible building is expected to operate under frequently varying energy demand and supply profiles but are expected to be synchronised. While the BESS and DG can contribute significantly to synchronising energy demand and load profiles, the utility of V2G and bi-directional EV chargers is still an evolving research area and has limited practical examples [70,82,78,12].

Reliability is a key performance indicator often discussed in microgrid-related literature, usually presenting it as an added advantage of having an onsite storage system at a smaller scale and distributed generation at a relatively larger scale [90,77,112]. A reliable renewable energy integrated energy supply is expected to have zero energy demand shortfall, especially during multiple short-term grid power outages. Resilience, although initially used to define how the ecological system absorbs disruption without changing its state significantly, has found an application in electric power systems [97,92], including buildings' microgrids [39]. Microgrid application is often discussed as one of the solutions to any energy resilience and reliability-related issues that buildings may face following the increased integration of renewable energy resources in the grid [2]. While reliability is primarily discussed with short-term power outages and grid failures, resilience is mainly discussed with extended outages (ranging from a few hours to days) and external shocks (e.g. climate change and cyber-attacks). Resilience and reliability are sometimes discussed in the context of stabilising fluctuating energy load profiles. Recent advancements in energy load forecast methods (e.g. bidirectional Long Short-Term Memory (BiLSTM) neural network, have helped better understand reliability and resilience against highly fluctuating energy load profiles [86].

There is also a separate literature strand on microgrid application in buildings that assimilates the concept of net zero energy buildings amidst an increased share of renewable energy in the energy supply, either on-grid or off-grid [28,37]. The existing literature reveals various renewable energy options, their combination, and topology for building microgrids and their implications for resilience, reliability, and flexibility, including the effectiveness of demand response programs [70,82,78]. However, limited literature discusses the following three key aspects of building microgrids. First, the cost-effective microgrid design for the energy transition in the existing building stock, such as choosing the right combination of microgrid components and topology that considers the complex electricity tariff structure and the electricity retailers-led demand response programs. For example, the levelized cost of the electricity (LCOE)-based microgrid components and their performance amidst demand response events and demand-side energy efficiency. Green hydrogen, a positive prospect for an Australian off-grid microgrid with LCOE between A$0.42/kWh and A$0.44/kWh [41], may not be ideal for grid-connected building microgrids that would have an expected LCOE well below A$ 0.40/kWh. A green hydrogen and solar PV integrated microgrid in an urban apartment resulted in higher LCOE than without green hydrogen [79].

The state of New South Wales in Australia has a demand charge tariff [116], which is one of the key drivers for conceptualising demand response programs for office and commercial buildings for their potential to reduce peak demand and the associated cost. Demand-side efficiency measures, such as envelope insulation, adjusting the heating and cooling setpoint temperatures, and other passive strategies are found to reduce the peak load, although there is scarce evidence of a clear nexus between these efficiency measures and energy resilience under changing weather events [124].

Second, on-site energy production uncertainties under changing climate conditions, climate change-related power outages, and the dynamic attribute of the energy end-use structure receive limited focus in building microgrid design. Renewable energy resources (e.g. Solar PV and wind energy) are characterised by unpredictability, and so is the building energy demand, as both are dependent on external climatic and weather events [61]. Likewise, extreme climate events such as bushfires and heatwaves disrupted electricity transmission in Australia, resulting in power outages [111]. While extreme climate events can significantly change building heating and cooling energy demand, the energy end-use structure is also impacted by the energy transition in line with the net zero energy buildings objective. The electrification of gas-using loads (e.g. boilers, chillers, and water heaters) will entail additional electricity demand. As Zhang et al. [123] echoed, building energy flexibility and resilience analysis often ignore these inevitable micro changes within the building energy system.

Third, while the emergency diesel generator (DG) is found to be useful in enhancing the resilience and reliability of the building microgrid [74,97], existing literature lacks a comparative analysis of energy optimisation models, LCOE, and the building microgrid performance with and without DG. This paper addresses the three gaps and presents insights into LCOE changes across electric loads in different climate scenarios. Consequently, this paper contributes to the evolving literature on cost-effective and optimal pathways to selecting building microgrid components amidst objectives, such as achieving net zero energy building status and improving the building energy system's resilience, reliability and flexibility. Further, it contributes to creating LCOE data for various climate scenarios with and without DG, which could be useful for net zero energy buildings-related capital expenditure analysis. The rest of the paper is structured as follows. Section 2 provides a brief literature review and analytical foundations. Section 3 is the methodology. Section 4 presents the results and discussions. Finally, section 5 is the conclusion.

2. Brief literature review and analytical foundations

There are two aspects to how the energy transition manifests in buildings. First, renewable energy integration in buildings via grid-connected microgrids, especially amidst the increase in the share of renewable energy in the grid and anticipated electrification of the gas-using building service systems and plug loads [109,120]. Almost 40 % of electricity generation in Australia was from renewable energy sources in 2023, and this figure is projected to grow owing to the rapid growth in the share of solar and wind energy in total renewable electricity, which was around 85,000 GWh in 2022 [29,23]. The national electricity market in Australia is expected to operate with up to 90 % of renewable electricity by 2035 [9]. Second, grid services and flexibility the renewable energy integrated buildings can provide to a grid through demand response, V2G, grid-interactive features and by acting as the virtual power plant (VPP) [3,70,124].

The energy transition is inevitable for an existing building stock that relies largely on the grid. As such, the quantum of building energy transition, as demonstrated by adopting different traditional and emerging renewable energy technologies, transition period pertaining to net zero objectives, and building energy characteristics, such as flexibility, reliability, and resilience, are key considerations. However, existing energy transition literature often discusses it in a broader context, such as at the transnational, national, regional, sectoral, and community levels [55]. For buildings, energy transition discusses the shift from gas-using service systems (e.g. heating and cooling) to electrifying them, renewables in the energy supply system (both off-grid and grid-connected) and energy efficiency retrofits [84,121]. These technological changes are often envisioned together with an aspiration to achieve net zero energy building status [122]. Therefore, energy transitions in buildings are sometimes referred to as technological and demand-side transitions, noting that buildings operate on the demand side [20]. Nonetheless, the recent studies on building microgrids, grid-interactive buildings, and the VPP and V2G have substantially highlighted buildings' grid services, especially in the context of electricity retailers-led demand response programs [15,70,82,78,13,24].

The narratives around future climate change scenarios and net zero energy buildings are drivers of technological changes as part of the energy transition in buildings [121]. There is a well-developed body of literature on the future impacts of climate change on building energy demand, especially the changes in heating and cooling loads and how energy efficiency retrofits can partially or fully offset the increase in climate-related energy demand [14]. As such, forecasted weather scenarios for three representative concentration pathways (RCPs), RCP 2.6, RCP 4.5, and RCP8.5, are used to predict changes in the structure of heating and cooling energy demand for both short- and long-term futures [88]. However, the structural changes in the building energy demand are uncertain and complicated because of non-climatic factors, such as in realising the net zero energy building concept and cost implications. For example, the future electrification of gas-using service systems and individual appliances, demand response, and electricity tariff and rate fluctuations. These necessitate adjustments in design parameters for renewable energy integration [33,13]. Thus, the uncertainties with building microgrids, resulting from future climate scenarios and demand-side strategies, are often discussed in silos. Additionally, while studies on building microgrids have sufficiently covered energy flexibility and reliability, the impact on the overall resilience of the building energy system amidst demand-side and climate-related uncertainties and building energy transition is relatively less discussed.

Table 1
Recent literature on building microgrids discussing resilience, reliability, and flexibility.

References	Tools & methods	The focus of the study	Grid-connected?	Components combination	Back-up generators in analysis?	Building energy system's characteristics addressed
Tavakoli et al. [101].	Stochastic modelling	demand side control leveraging fluctuations in the electricity price	Yes	Wind power with Vehicle-to-Grid (V2G) supply	No	renewable energy integration, flexibility, reliability, and resilience
Elavarasan et al. [33].	MATLAB/SIMULINK	optimal load management strategy based on varying degrees of supply and demand	Yes	Wind power and solar PV with battery energy storage system (BESS)	Yes	renewable energy integration, flexibility, reliability, and resilience
Yamashita et al.[113].	Literature review	literature review of the main hierarchical control algorithms for building microgrids	Yes	Solar PV with V2G and BESS	No	renewable energy integration, flexibility, and reliability
Mannai et al. [68].	HOMER Pro	minimise the net present cost while enhancing the grid-microgrid interaction	Yes	Solar PV and wind power with BESS	No	renewable energy integration, flexibility, and reliability
Mokhtara et al. [80].	HOMER Pro	techno-economic analysis of grid-connected rooftop PV	Yes	Solar PV and wind power with BESS	No	renewable energy integration, flexibility, and reliability
Yamashita et al.[114].	Economic modelling	enhanced performance of building microgrids with hybrid energy storage	Yes	Solar PV with BESS and hydrogen fuel cell	No	renewable energy integration and reliability
Sambhi et al. [96]	HOMER Pro	Techno-economic analysis of the standalone hybrid power generation.	No	Solar PV, BESS, and DG	Yes	Renewable energy integration, flexibility, and resilience
Alzahrani et al. [6].	Lyapunov optimisationtechnique-based algorithms	random load-based real-time scheduling and energy optimisation	Yes	Solar PV and wind power with BESS and fuel cell	No	renewable energy integration, flexibility, and reliability
Liu et al.[65]	Scenario based TRANSYS simulation	renewable energy design and optimisation framework for a net-zero energy building	Yes	Solar PV with BESS and V2G	No	renewable energy integration, flexibility, and reliability
El Hassani et al. [32].	EnergyPlus and HOMER Pro	Building energy modelling with a rooftop solar PV system	Yes	Solar PV with BESS	No	renewable energy integration, flexibility, and reliability
Hwang et al. [48].	REopt	Transitioning from diesel backup generators to PV-plus-storage microgrids	Yes	Solar PV with BESS	Yes	renewable energy integration, flexibility, reliability, and resilience
Amin et al. [7].	REopt and HOMER Pro	Resilience and sustainability analysis of PV-battery microgrid	Yes	Solar PV with BESS	Yes	renewable energy integration, flexibility, reliability, and resilience
Yue et al. [118].	Mixed-integer linear programming via Python	evaluation of the grid-friendly attributes of buildings	Yes	Solar PV with BESS	Yes	renewable energy integration, flexibility, reliability, and resilience
Stamatellos et al. [99].	TRANSYS simulation	short-term and long-term energy storage options for buildings	Yes	Solar PV with V2G, BESS, and hydrogen electrolyser	Yes (hydrogen generator)	renewable energy integration, flexibility, reliability, and resilience
Bai et al.[13].	Python-based random forest algorithm	collaborative matching of supply and demand for multi-energy systems	Yes	Solar PV with V2G and BESS	No	renewable energy integration, flexibility, and reliability
Soyturk et al. [98].	Dynamic modelling, building simulation, and HOMER	examine the potential of solar PV and hydrogen-based microgrids for residential applications	Yes	Solar PV with BESS, hydrogen storage, and fuel cell	No	renewable energy integration, flexibility, and reliability

The building energy system's resilience is often discussed in a broader context, such as in relation to power disruption from terrorist and cyber-attacks, earthquakes, and climate-related hazards (e.g., flooding, heatwaves, bushfires, and storms). Table 1 lists some recent building microgrid-related studies that envision a connection to the grid but excludes emergency generators that would improve the building energy system's resilience to any power disruptions. Nonetheless, while Stamatellos et al. [99] discuss the provision of hydrogen-fuelled emergency generators that utilise PV-powered hydrogen electrolyser, Hwang et al. [48] and Amin et al. [7] use backup diesel generators to test the building microgrid's resilience. The resilience testing for buildings is done quantitatively, such as by using indicators and terminologies, such as 'survivability' [93], 'resilience cost index' [7], 'resilience benefit' [22], 'probability of surviving an outage' [97], and 'optimal backup electric system' [48]. Regardless, two common aspects bind these studies together: resilience against the power outage while sustaining the critical load throughout the range of power outage duration and the building microgrid's efficacy in fostering resilience and energy supply reliability during multiple short-term outages.

Buildings' energy reliability is often discussed together with resilience, especially when referring to the power backup components' (BESS, V2G, and emergency generators) ability to deliver energy to critical loads during outages. Marqusee et al. [74] used three metrics to analyse and compare the reliability – 1) probability of supporting 100 % of critical load, 2) fraction of expected lost critical load, and 3) probability of meeting highest priority critical loads. The related study [73] introduces another set of metrics that are more suited for individual components of the building microgrids. For example, the operational availability (OA), failure to start (FTS), and mean time to failure (MTTF). These are applied to the buildings' microgrid components, such as emergency diesel generators, Solar PV, and BESS. These metrics are relatively more insightful compared to the capacity shortage fraction, which is the ratio of the total capacity shortage to the total electrical load [80]. The capacity shortage fraction should be significantly less than 5 % for the building microgrid system to be labelled as reliable. Other advanced methods, such as the Markov chain and multi-state matrix approach, are also used for microgrid reliability assessment [5]. However, the advanced approaches are more suited for microgrids with complicated components.

In the building microgrids literature, energy flexibility, grid-interactive buildings, and demand response are discussed together because of the building's ability to ease pressures on the grid during peak demand, given proper control strategies and demand response programs [21,3,100]. Zou et al. [127] highlight the electric load characteristics to explain the building energy flexibility, noting that some loads are flexible (elastic) and some are not (inelastic). The flexible loads (e.g. lighting, HVAC, and electric water heaters), dispatchable loads (e.g. BESS and backup generators), and V2G and deferrable EV chargers are enablers for demand response programs that would enhance energy flexibility and the grid-interactive property [70,69,127,40,78,82].

Building energy flexibility is quantified via load match indicators, grid interaction indicators, modified Hooke's law, and various optimisation functions [3,118]. Most of these methods and indicators underscore the stochastic nature of microgrid components (e.g. Solar PV and BESS) and demand response strategies. For example, the 'building energy flexibility capacity' [118]considers solar generation and energy storage as key variables, and the 'grid interaction index' and 'absolute grid support coefficient' [3]use generation and available capacity of the microgrid. Demand response-based energy flexibility metrics include 'demand decrease intensity', 'demand decrease', 'demand decrease percentage', and 'demand shift from peak hours' [63,66]. With these indicators in the backdrop, the underlying factor determining the building energy system's flexibility and the ability to deliver the grid services hinges on the building's reaction to demand response events. In essence, buildings should react to the electricity retailers' demand response programs by reducing the peak demand by lowering non-critical consumption, drawing less from the grid during demand, and relying on the onsite generation and energy storage components during response events.

3. Methodology

3.1. Study area and the representative building archetype

The study area for this research is Sydney, Australia. Sydney lies within the New South Wales (NSW) state of Australia and belongs to the region with a Köppen Climate Classification 'Cfa', which is a humid subtropical climate with warm, sometimes hot summers and cool winters. Fig. 1 shows the location of Sydney in Australia. Sydney is the largest city in Australia, with more than 5 million people living and working across the city. Recently, it has been exposed to increasing urban overheating and heat waves [57], meaning microclimatic and global climate change-induced additional building energy demand and increased pressure on the electricity grid. An increase in the number of hot days is one of the key variables that act as a risk to the effective functionality of electricity infrastructure in NSW and Australia [75,67].

A building archetype (Fig. 2), which is a three-storey office building, is chosen to represent the existing office building stock in Sydney. Most of the existing office buildings are yet to fully electrify their service system, realise the energy efficiency potential (both active and passive strategies) and are gradually adopting various microgrid components, such as solar PV, BESS, and EV charging infrastructures. Table 2 shows the key characteristics of the building archetype (e.g. construction set, HVAC system, and insulation) that align with certain requirements of the National Construction Code [1].

3.2. Weather files and electrical loads

Current and future weather files are basic inputs to estimating future building energy use [42]. Usually, the weather files containing typical or extreme conditions, such as the typical meteorological year (TMY) and projected weather files for three representative concentration pathways (RCPs) – RCP 2.6, RCP 4.5, and RCP 8.5 are used in building simulations [42,27]. This study uses Sydney's TMY and future weather files (RCP 2.6, RCP 4.5, and RCP 8.5) for future years 2030 and 2050, and these data are drawn from CSIRO's AgData shop that stores the projected weather files for building energy modelling [91]. Two future years, 2030 and 2050, are selected for comparative analysis of short- and long-term implications of building microgrids on the building's energy system amidst changing climate conditions and aspirations to achieve the net zero energy buildings status by 2050. The TMY data is built on the historical weather information drawn from the period between 1990 and 2015. The weather files are in the EnergyPlus (.epw) format and are compatible with building simulation software such as EnergyPlus and Openstudio.

OpenStudio software is the preferred tool for estimating the electrical loads in 2030 and 2050 for the building archetype (Fig. 2) with certain building characteristics (Table 2). Openstudio was chosen because it uses EnergyPlus as a simulation engine, and previous research has validated its results by comparing them with the monthly utility data and load monitoring [36]. Likewise, the multiple experimental energy simulations done via Openstudio were compared with the measured data to find an acceptable level of overlapping between predicted and measured energy consumption [58]. Openstudio uses TMY and future weather files in the EnergyPlus format for energy modelling [49]. We use a two-stage approach for the electrical load calculation and energy end-use decomposition. First, the building characteristics (Table 2) and TMY weather file are used to build a model '(Base Model TMY) $_{\text{Reference}}$'. This is followed by six additional models – three each for 2030 and 2050 – that consider the future climate scenarios (e.g. RCP 2.6, RCP 4.5, and RCP 8.5) but no electrification of gas-using building services and demand-side efficiency. These are labelled as '(2030 RCP 2.6) $_{\text{Reference}}$',

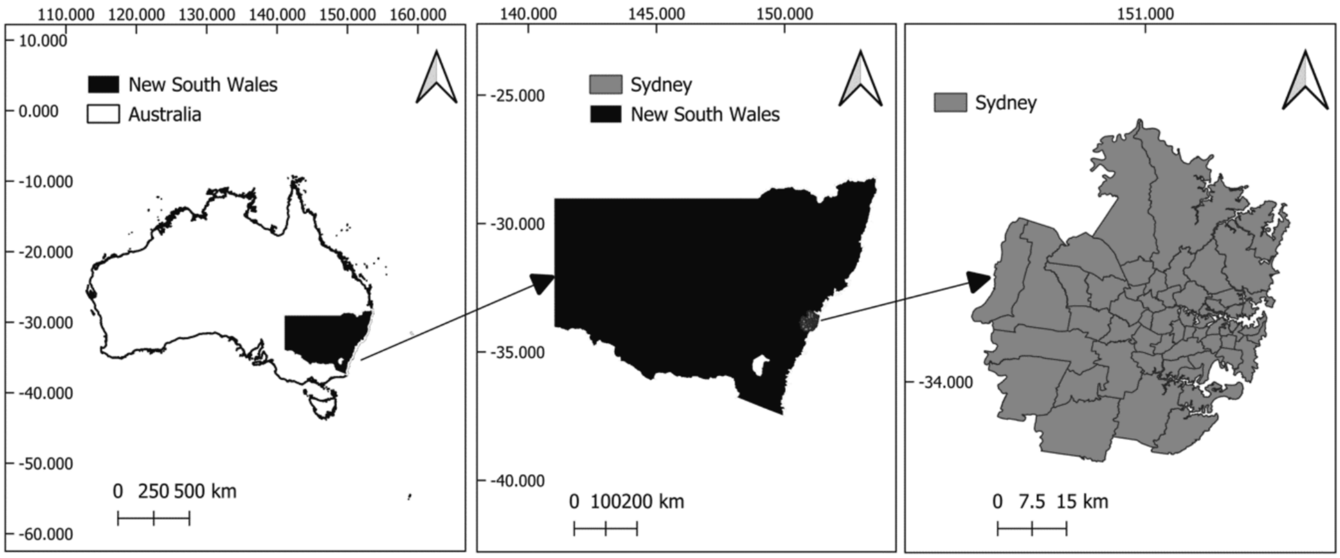

Fig. 1. Location of Sydney, Australia (study area).

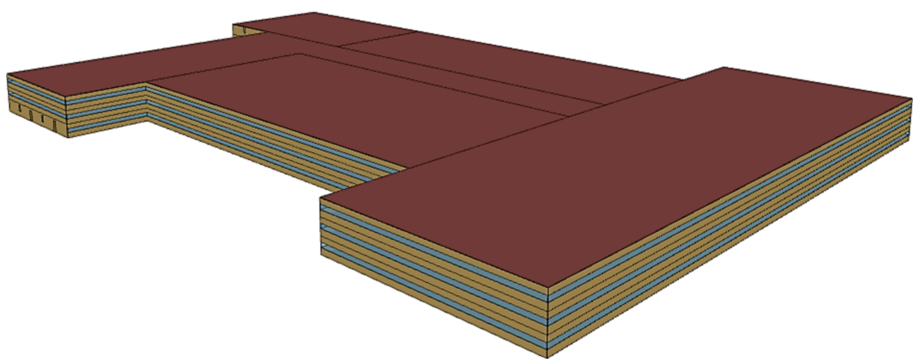

Fig. 2. Building archetype representing existing building stock.

'(2030 RCP 4.5) $_{\text{Reference}}$', '(2030 RCP 8.6) $_{\text{Reference}}$', '(2050 RCP 2.6) $_{\text{Reference}}$', '(2050 RCP 4.5) $_{\text{Reference}}$', and '(2050 RCP 8.5) $_{\text{Reference}}$'. These are reference models against which the impact of electrification and demand-side efficiency on future electric loads can be compared.

The second stage considers the electrification and demand-side efficiency measures, meaning certain changes in key building characteristics (Table 2). The gas-fired furnace (part of the HVAC system) is replaced by an electric heat pump (auto sizing), and the gas-fuelled water heater is replaced by an electric water heater (2,000 L capacity). Additionally, the lighting density is adjusted from 9 W per floor area to 7 W per floor area as commercial and office buildings in Australia are rapidly switching from fluorescent to LED lights. While the lighting power density fell from 14 W/m^2 to marginally less than 10 W/m^2 between 2011 and 2020 in Australia [30], the Australian Building Codes Board in its National Construction Code (NCC) recommends a lighting power density of 7 W/m^2 for office buildings [1]. The share of lighting in Australian buildings' total energy demand is around 10 % [30]. The second stage base model and future energy models are labelled as '(Base model TMY)', '(2030 RCP 2.6)', '(2030 RCP 4.5)', '(2030 RCP 8.6)', '(2050 RCP 2.6)', '(2050 RCP 4.5)', and '(2050 RCP 8.5)'. These energy models provide future electricity loads for different climate scenarios with a certain level of demand-side efficiency incorporated together with electrification. These electric loads are inputs in designing, configuring, and sizing the building's microgrid components.

3.3. Microgrid system architecture and optimisation models

The office building microgrid includes solar PV, battery storage, converter, and deferrable electric vehicle chargers, plus an emergency diesel generator (DG). An emergency DG is added to evaluate the resilience, reliability, and generator's role during demand response events. Thus, there are two grid-connected microgrid configurations – one with DG and another without DG. Fig. 3 shows the system architecture adopted for the levelized cost of electricity (LCOE)-based optimization models. Although cutting-edge technologies, such as hydrogen-fuelled generators and hydrogen fuel cells, have been discussed in the building microgrid studies [31,98,99], higher LCOE of green hydrogen, and ongoing research on electrolyser's efficiency undermine their commercial relevance [41]. Therefore, hydrogen-based technologies are excluded, noting that they can be integrated with the existing building microgrids when deemed commercially viable. The deferrable electrical vehicle charger is unidirectional, allowing users to optimise charging during non-peak hours while the solar PV production is on. The Australian Renewable Energy Agency (ARENA) recently trialled the V2G services to find that it can improve the buildings' grid services while generating revenue for EV owners[12]. This study was conducted to understand the V2G's utility to supply Frequency Control Ancillary Services (FCAS) to the National Electricity Market (NEM). While the trial vehicles were found to discharge only 1 % of the total capacity to provide FCAS services (0.146MWh compared to 18.4MWh of energy imported during 2022), V2G's utility in the building microgrids can be more attractive for future demand response events, especially

Table 2
Key characteristics of the building archetype.

Type	Office building
Stories	3
Area	6,000 m^2
Floor-to-Floor height	3 *m*
Thermal Zones	Closed office with two zones (one for shared spaces and another for office spaces)
Schedules	• Office activity/working hours (8 AM – 7 PM) • Cooling HVAC, Heating HVAC, building equipment, and building light.
Window-to-Wall Ratio (WWR)	• 0.25 • window type 1 – repeating window (H 1 m, W 0.7 m, sill height 1 m, and spacing 0.7 m). • window type 2, 14 single windows with the same dimensions as window type 1
Construction set	• exterior roof with roof membrane, roof insulation, and metal decking. • exterior concrete wall with wall insulation and gypsum board. • exterior glass window. • interior floors and internal ceilings with acoustic tiles, ceiling air and lightweight concrete.
Insulation	• Roof insulation's thermal conductivity = 0.042 W/m.K • Wall insulation's thermal conductivity = 0.0393 W/m.K • Window glass thermal conductivity = 0.075 W/m.K
Infiltration rate	• Flow per exterior surface area of 0.000226568 m/sec at 50 Pa for the chosen construction set.
HVAC system	• one gas-fired furnace with a heating coil. • packaged rooftop heat pump with both heating and cooling DX coils. • Heating setpoint temperature – 18 °C • Cooling setpoint temperature – 24 °C
Lights (lighting density)	10 Watts per space floor area (average for all spaces)
Electric equipment (plug load density)	15 Watts per space floor area (average for all spaces)
Hot water system	Gas fuelled water heater (temperature at outlets < 50 °C)

when the DGs are fully replaced by BESS. Buildings with dual-power backup systems add to the reliability and resilience of the whole building microgrid system.

The preferred microgrid components can have multi-fold combinations. Thus, the combination that has the lowest LCOE is preferred – one with DG and another without DG (Fig. 3). HOMER Grid calculates the LCOE and estimates the optimal sizing of the solar PV, BESS, and DG. Other similar tools, such as REopt [48,7], DER-CAM [35], GridLAB-D [16], PVSyst [17], TRNSYS [65], MATLAB [33], and SAM [50], are also useful in designing the microgrid system. However, HOMER Grid was chosen for its ability to allow customised electricity tariff structure as in Australia, modelling of multiple demand response events, functionality to conduct resilience and reliability assessment, and it is less tedious to run models that render multiple combinations as possible microgrid options. However, unlike other tools (e.g. GridLAB-D and MATLAB) that use complex numerical modelling (e.g. mixed-integer linear programming), HOMER Grid uses optimisation models based on heuristic formulations. Nonetheless, the HOMER Grid is appropriate for the building microgrid system design. In comparison, tools that use complex numerical modelling are appropriate for analysing distributed energy resources at a larger scale. Results from HOMER were checked for accuracy by comparing the predicted energy flow, costs, and payback with the real data to find an acceptable level of discrepancy. For example, load and PV production variation is around 5 % [105].

The LCOE-based optimisation models that use electric loads across climate scenarios (refer to section 3.2) and customised Australian electricity tariff structure as inputs are based on three underlying assumptions. First, the critical load attribution, which is 50 % of the total electric load. Second, defining the DG's dispatch strategy during power outages to ensure the emergency DG is operational only during power outages. Additionally, the BESS's minimum state of charge (SOC) is kept at 10 % without reserving any during outages, as the DG is configured to run only during outages. For optimisation models without DG, the size of the BESS is optimised by the HOMER Grid to operate during outages. Third, consideration of possible random demand response events (5 no's 4 h each).

3.4. Electricity tariff structure, model inputs and assumptions

The electricity tariff structure for business customers in NSW (Australia) has retail charges (peak, off-peak, and shoulder), environmental schemes charges, network charges (peak, off-peak, shoulder), market operator charges, and metering charges. While the time-of-use applies to the retail and network charges, the demand charge applies to network charges only. Table 3 shows the electricity tariff structure

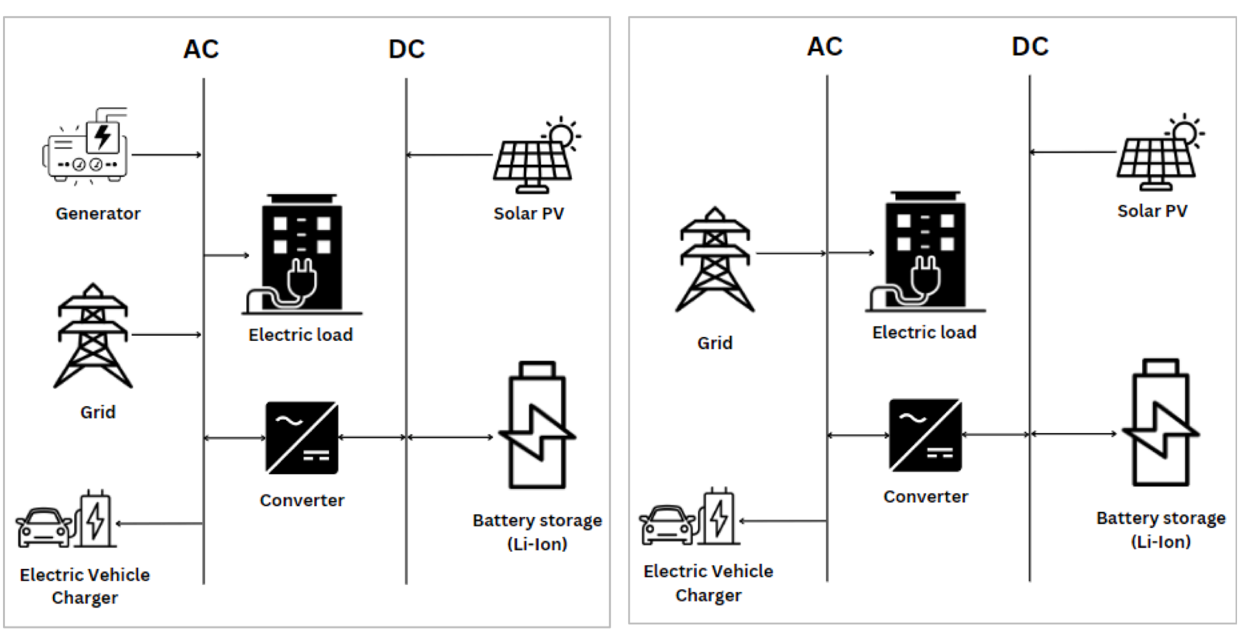

Fig. 3. Microgrid components and the system architecture with and without diesel generator (left with diesel generator and right without diesel generator).

and rates, which is an input for all the optimization models in the HOMER Grid software.

Table 4 shows the model inputs and assumptions related to the microgrid components. These techno-economic figures are reasonable estimates based on market research, although the market-derived figures are subjected to caveats such as cost variation across different suppliers, brands, quality, and size of the individual components. The project lifetime (analysis period) is 25 years, the discount rate is 6.5 %, and the inflation rate is 3 %. The electricity cost escalation rate was not considered because of the complicated electricity tariff structure, especially the uncertainties around the future rates of environmental schemes and demand charges. While the analysis period is 25 years, certain components, such as BESS and converters, may have an expected life of around 10 years, which the optimization models consider. Nonetheless, the payback period is expected to be less than 10 years in most cases.

3.5. Building energy system's resilience, reliability, and flexibility evaluation metrics

The building energy system's resilience and reliability metrics and models are grounded in the notion of survivability during unforeseen power outages and grid failures. Previous studies [54,93,97] using survivability as a measure of resilience estimate the probability of having electricity during power outages for a range of durations. This research builds on the same principle to estimate the probability of surviving the outages during (t = 4, 8, and 12 h) using the LCOE-based optimal combination of the building microgrid components. Thus, as part of the outage duration-based sensitivity analysis, the optimal sizes of the Solar PV, BESS, and DG are fixed to estimate the probability of surviving the outages using the Critical Load (50 % of the total electric load), top priority Critical Load (25 % of the Critical Load), and capacity shortage factors. The following equations (1) & (2) estimate the probability of survivability during power outages.

Table 3
Electricity tariff structure.

Charges	Categories	Type
Retail charges	NSW peak (12.5c/kWh)	Time-of-Use and consumption-related
	NSW off-peak (9c/kWh)	Time-of-Use and consumption-related
	NSW shoulder (12.5c/kWh)	Time-of-Use and consumption-related
Environmental Schemes	NSW Energy Savings Certificate (NESC) (0.30c/kWh)	Consumption-related
	Large-scale Renewable Energy Certificate (LREC) (0.47c/kWh)	Consumption-related
	Small-scale Renewable Energy Certificate (SREC) (0.85c/kWh)	Consumption-related
	GreenPower (0.28c/kWh)	Consumption-related
	Peak Demand Reduction Scheme (PDRS) (0.04c/kWh)	Consumption-related
Network charges	Peak (4.85c/kWh)	Time-of-Use and consumption-related
	Shoulder (3.90c/kWh)	Time-of-Use and consumption-related
	off-peak (2.53c/kWh)	Time-of-Use and consumption-related
	demand peak (10.95 $/kVA/month)	demand-based, Time-of-Use and consumption-related
	demand off-peak (2.60 $/kVA/month)	demand-based, Time-of-Use and consumption-related
	demand shoulder (9.92 $/kVA/month)	demand-based, Time-of-Use and consumption-related
	supply charge (17.75 $/day)	Fixed price (per day cost)
Market operator charges	market fee (0.04c/kWh)	Consumption-related
	market fee (2.20c/kWh)	Fixed price (per day cost)
	Ancillary fee (0.04c/kWh)	Consumption-related
Meter charges	meter charge (350 $/meter/annum)	Fixed price (per meter per annum)

Table 4
Model inputs and assumptions.

	Solar PV	Converter	BESS	Diesel Generator	EV charger
Capacity	1 kW	1 kW	1 kWh	1 kW	
Capital cost	$780	$450	$850	$800	$8000 per charger
Replacement	$700	$400	$750	$800	$7500 per charger
O&M	$250 per year	$50 per year	$100 per year	$250 per year	$250 per charger per year
Fuel cost	–-			$2.10 per litre	–-
Charger type	–-				deferrable office EV charger
Vehicle type	–-				Small/ medium EVs (> 40kWh capacity)
Charger output power (maximum)	–-				22 kW
No. of chargers	–-				6 (three-phase AC chargers)

$$Ps(CL) = \{1 - (CLcapacityshortage/CLtotal)\}{*}100\% \tag{1}$$

$$Ps(CLtoppriority) = \{1 - (CLtopprioritycapacityshortage/CLtotal)\}{*}100\% \tag{2}$$

The dispatch algorithm has advanced knowledge of the outage, which is modelled as four outages per year. The mean repair time is also four hours, given the office building archetype is located within the Sydney metro, meaning a fast response to restore supply from the grid. Nonetheless, the sensitivity analysis done for eight and 12 h evaluates the impact of extended power outages.

For buildings with on-site electricity production (e.g. Solar PV) and energy storage options (e.g. BESS), the energy flexibility evaluation accounts for the grid-friendly nature of the buildings, given that the grid and buildings exchange electricity and the effectiveness of the demand response programs. Various load match indicators (e.g. load cover factor, mismatch compensation factor, and on-site energy ratio) and grid interaction indicators (e.g. absolute and relative grid support coefficient, one per cent power peak, and grid interaction index) exist to evaluate the building's energy flexibility with and without demand response programs [3,118]. Building on these indicators, this paper uses Monte Carlo simulation to estimate the probability of supplying a certain fraction of the on-site electricity production to the grid ($P(G_s)$) and the fraction of the grid purchase for building consumption ($P(G_p)$). This is to factor in the stochastic nature of the on-site electricity production, storage, and consumption. While this method ignores the time-specific supply and demand balance that deterministic models consider, the Monte Carlo-based probabilistic model provides insights into the building-grid interaction. Additionally, this probabilistic method aligns with the load match indicator, such as the on-site energy ratio [4,3], and grid interaction indicators, such as no grid interaction probability, connection capacity credit and capacity factor [95,122]. The common aspects of these indicators are that they investigate the energy exchange between the building and the grid, on-site energy generation and the effect of demand response events. The following equations (3) & (4) are used to operationalise the Monte Carlo simulation.

$$P(G_P) = \left\{ \frac{(n < \overline{x})}{(N)} \right\} * 100\% \quad (3)$$

$$P(G_s) = \left\{ \frac{(n' > \overline{x'})}{(N)} \right\} * 100\% \quad (4)$$

Where n is the number of simulated results with the grid purchase less than average, and n' is the number of simulated results with grid sales more than average. N is the total no. of simulated results.

The demand response events effectiveness factor (DREEF) used by this paper is consistent with the 'flexibility factor' [60], both of which indicate the ability to shift energy use during periods with high energy demand and price. Likewise, the demand response effectiveness factor aligns with the 'grid interaction index' [95] and the 'One per cent peak power' [106]as they quantify the reduction in the grid stress by reducing the peak power. For 'n' demand response events and at T = 0, 1, ……t, the yearly DREEF is expressed below.

$$YearlyDREEF = [(PLi)DR/\{\sum_{i=1}^{n}[(PLi) - (PL_i)_{DR}]\}]*100\% \quad (5)$$

Where PLi is the peak load for an 'i' event without the impact of demand response event and $(PL_i)DR$ is the observed peak load during the 'i^{th}' demand response event. DREEF is useful for comparative analysis of the demand response events and it aligns with other flexibility indicators, such as 'demand decrease percentage', and 'demand shift from peak hours' [66].

4. Results and discussion

4.1. Electric loads and end-use decomposition across different climate scenarios

In the reference scenario, with no electrification of gas-using service systems and demand-side efficiency measures as in the building archetype, Fig. 4 shows the electricity end-use categorised into HVAC (heating and cooling), lighting, and other electric loads. The gas demand is mainly for the HVAC system (gas-fired heater) and for the hot water system. The share of electricity end use in non-residential buildings in the NSW jurisdiction of Australia is around 85 % as of 2022 [30], which corresponds to the numbers in Fig. 4. Unlike HVAC's share (65 %) in the total electric load [30] of the typical Australian office buildings in the financial year between 2014 and 2018, Fig. 4 shows that the HVAC system of the building archetype's contribution is around 45 %-55 % across climate scenarios. However, the share of HVAC gas demand and hot water system corresponds to the findings of DCCEEW [30]. The energy end-use intensity ranges between 105 kWh/m^2 to 130 kWh/m^2, which corresponds to 3.5 Stars to 4 Stars NABERS Rating [38].

Fig. 5 shows the electric loads in kWh/day with and without electrification of gas-using service systems and demand-side efficiency measures across RCPs. The electric loads (with electrification and demand-side efficiency) are inputs to designing the microgrid system. With electrification by 2030, gas demand is nil for both space heating (HVAC system) and the domestic hot water system, meaning an increase in the electric load. Across all RCPs, the electrification adds around 15 %- 20 % of kWh/day, and this is despite load reduction from demand-side efficiency measures. Fig. 6 shows the changes in electricity end-uses, mainly resulting from electrification and after adjusting the lighting power density from 10 Watts/m^2 to 7 Watts/m^2. The electricity savings from lighting efficiency are offset by electrification of the gas-using building service systems. The energy resource transition within space heating (e.g. gas to electricity) and additional climate-related cooling highlight the critical role of resilient and reliable building energy systems. Ahmed et al. (2018) stated that buildings in Sydney, Australia, will experience cooling energy demand because of changes in future cooling degree days (CDDs) and that the additional building electricity demand could be over 6 % by 2030, which this study corresponds (Fig. 6). Likewise, Khourchid et al. (2022) found that buildings in Australian cities (e.g. Brisbane and Canberra) may experience climate-related increases in cooling energy demand by over 20 %. The higher percentage of heating electricity is because of the replacement of a gas-fired heating furnace with an electric heat pump.

4.2. Levelized cost-based optimal combination of the building microgrid components

Table 5 shows the building microgrid component sizes, levelized cost of electricity (LCOE), and net present cost (NPC) across climate scenarios in 2030 and 2050. These techno-economic parameters vary depending on whether the emergency DG is included or excluded from the microgrid system. The LCOE and NPC increase when the DG is excluded from the microgrid, as the LCOE-based optimisation models significantly increase the size of the BESS while the solar PV size sees incremental changes. For electric loads across all climate scenarios, the lowest LCOE is around A$0.17 per kWh, while the highest is around A $0.2 per kWh. For a grid-connected and solar PV-integrated office building microgrid, the LCOE was around €0.07 per kWh [52]and US $0.07 – 0.10 per kWh [62]. These are around Australian $0.11–0.13 per kWh. A hydrogen fuel cell integrated commercial building microgrid (with Solar PV, BESS, and DG) and HOMER as an optimisation tool showed higher LCOE, US$0.3–0.6 per kWh (Tribioli & Cozzolino, 2019). Another study by Mayyas et al. [76] found that the combination of solar PV, BESS, and fuel cells applied in the commercial building microgrid showed an LCOE of around US$0.30 per kWh. Adding DG in the building microgrids decreases the NPC and the LCOE [97]. Likewise, Sambhi

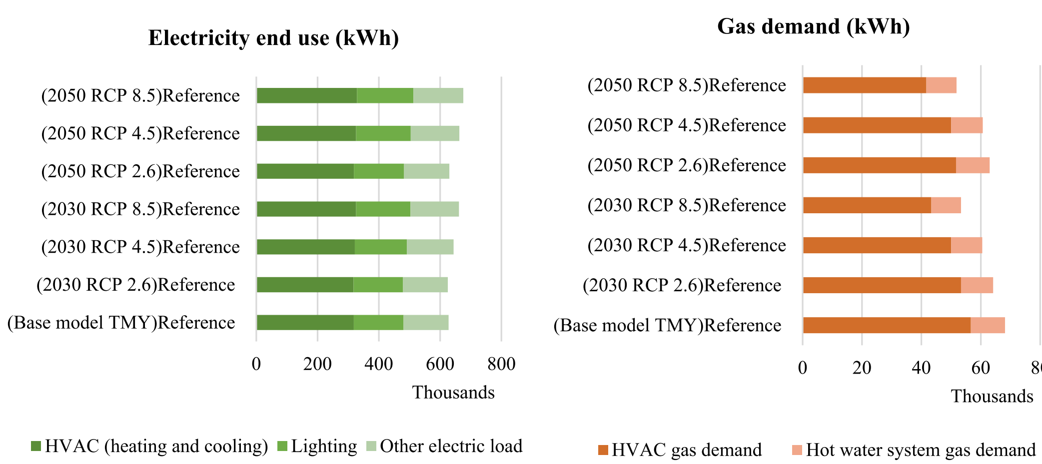

Fig. 4. Electric loads across climate scenarios.

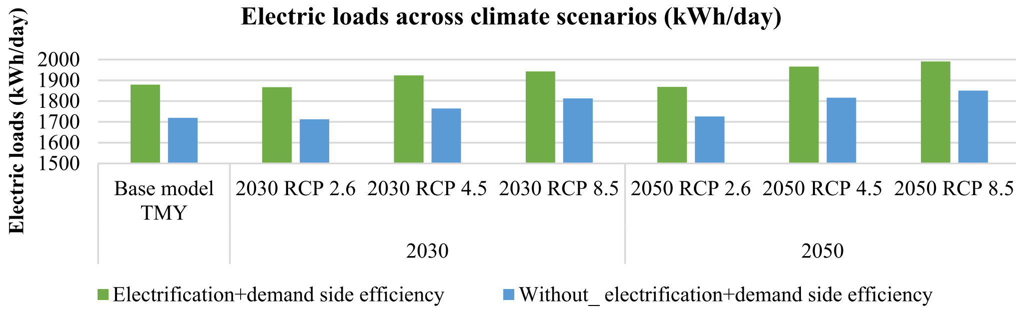

Fig. 5. Percentage change in the end-use electric loads compared to the reference scenario.

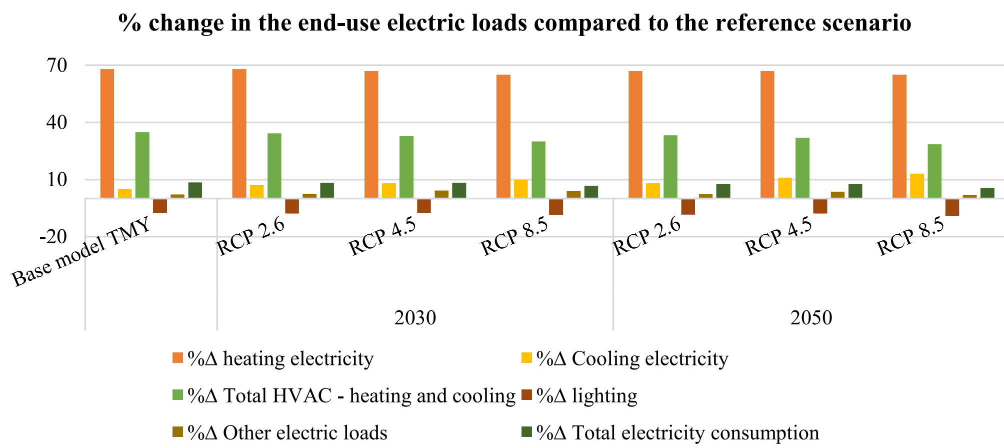

Fig. 6. Electricity supply and demand across climate scenarios.

Table 5
Microgrid components' sizes and levelized cost across climate scenarios (2030 and 2050).

		Diesel Generator (kW)	Solar PV (kW)	battery storage (kWh)	Converter (kW)	LCOE ($/kWh)	NPC ($ million)
Base model TMY	Base model TMY (with DG)	430	452	50	236	0.172	1.63
	Base model TMY (without DG)	–	492	348	199	0.198	1.77
2030	2030 RCP 2.6 (with DG)	430	455	48	233	0.172	1.63
	2030 RCP 2.6 (without DG)	–	489	346	198	0.198	1.76
	2030 RCP 4.5 (with DG)	440	437	60	240	0.174	1.67
	2030 RCP 4.5 (without DG)	–	503	354	236	0.190	1.81
	2030 RCP 8.5 (with DG)	440	486	60	249	0.178	1.69
	2030 RCP 8.5 (without DG)	–	562	346	267	0.181	1.82
2050	2050 RCP 2.6 (with DG)	430	460	48	241	0.172	1.63
	2050 RCP 2.6 (without DG)	–	489	346	198	0.196	1.79
	2050 RCP 4.5 (with DG)	440	495	62	258	0.174	1.71
	2050 RCP 4.5 (without DG)	–	568	350	269	0.198	1.85
	2050 RCP 8.5 (with DG)	450	493	64	245	0.176	1.73
	2050 RCP 8.5 (without DG)	–	572	352	271	0.199	1.86

et al. [96] found the LCOE to be around US$ 0.30 to US$0.6 per kWh for solar PV, BESS, and DG-integrated building microgrids. The findings of previous studies align with this study's findings, as 'without DG' optimisation models result in relatively higher LCOE and NPC.

Although marginally higher LCOE, the 'without DG' combination have an environmental benefit, such as CO_2 emissions reduction. For example, the base model TMY has additional CO_2 emissions savings of around 1.1 tons/yr. The CO_2 emissions savings for other 'without DG' combinations are 2030 RCP 2.6 (0.3 tons/yr), 2030 RCP 4.5 (36.1 tons/yr), 2030 RCP 8.5 (41 tons/yr), 2050 RCP 2.6 (7.4 tons/yr), 2050 RCP 4.5 (45.5 tons/yr), and 2050 RCP 8.5 (58.2 tons/yr). The nominal CO_2 emissions savings are because the DG is an emergency generator and is configured to auto-run only during power outages. Across all climate scenarios, the annual diesel consumption ranges between 400 and 550 L per year. The size of the BESS is around 6–7 times more across climate scenarios in the absence of DG to allow electrochemical storage for any unforeseen power outages, as the building microgrid system is configured for increased resilience and reliability. Thus, even with DG, the balance of energy-in (via solar PV, BESS throughput, and grid purchase) caters to most of the AC primary load and EV chargers across climate scenarios. DGs contribute to less than 0.2 % of the total production for all climate scenarios (Fig. 7). The DG as an emergency backup system, is normally used in supplying critical load during power outages[74]. In fact, compared to the stand-alone building-tied emergency DG, the DG as a microgrid component enhances the building energy system's resilience and reliability [94]. The marginal environmental benefit versus enhanced resilience and reliability necessitates a tough balancing act in designing the building microgrids.

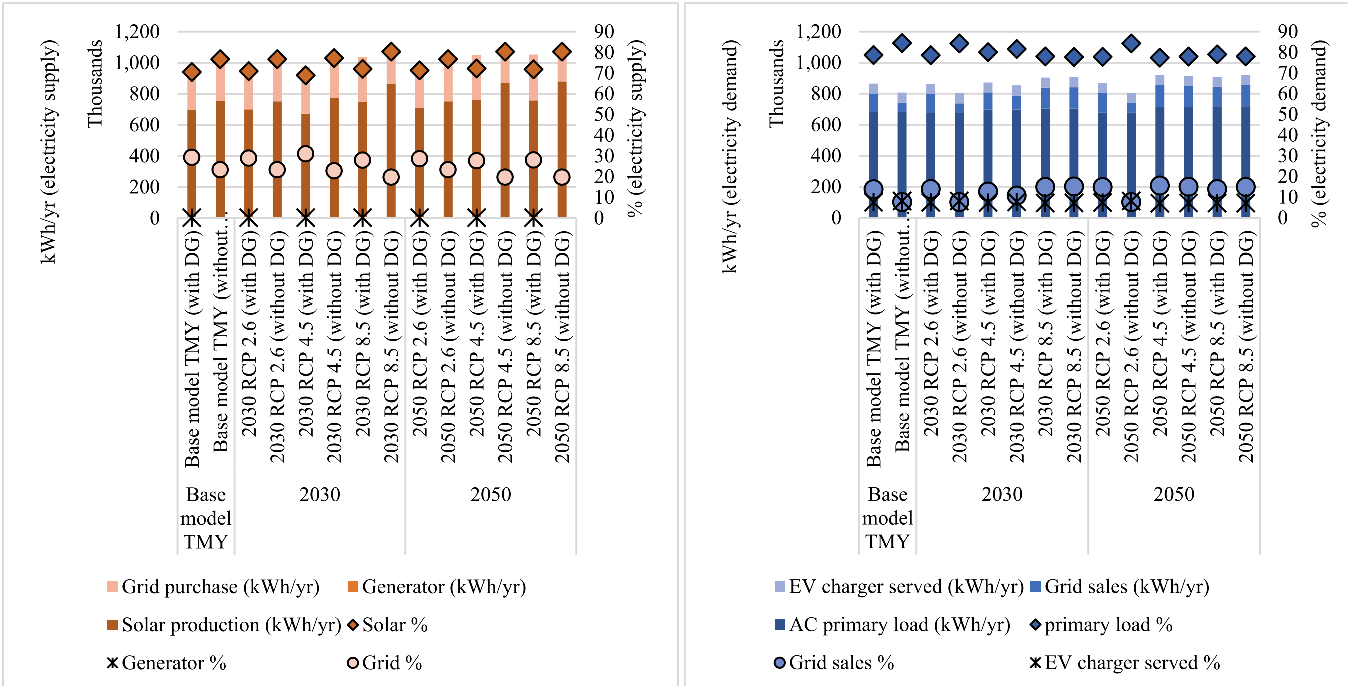

Fig. 7. LCOE vs battery energy discharge, solar + Grid purchase, and EV chargers served with and without DG.

Solar PV contributes most to the total electricity supply, with almost 70 % in base model TMY and around 70–80 % across climate scenarios in 2030 and 2050 (Fig. 7). This is followed by the grid purchase that covers the rest of the electricity supply (approximately 20–30 %). In 'without DG' combinations, the size of the solar PV and its share in the supply increases as it needs to charge the relatively large capacity BESS. The BESS throughput in 'without DG' combinations is around 3–5 times more compared to 'with DG' combinations. The grid purchase share falls in 'without DG' combinations as the battery throughput increases exponentially because the BESS is also configured to dispatch during 'no power outage'. Thus, despite additional cents (¢) per kWh as in 'without DG' combinations, the reduced share of grid purchase adds to the nominal CO_2 emissions savings as key benefits in building microgrids without DG. The reduced share of grid purchase is one of a few proxies used to explain the grid interaction traits and the net zero energy building concept [121]. Thus, it may be reasonable to say that the building's microgrids without DG and higher capacity BESS are relatively more grid-interactive. The grid interaction concept is paradoxical as Huang et al. [46] state that it is ideal to have zero electricity exchange between the grid and buildings if the net zero energy buildings are to be independent of the grid, given that the grid is subjected to failures. Nonetheless, the Solar PV-integrated buildings are expected to create feed-in-energy during peak production but low demand periods, and therefore, the grid interaction is natural.

The primary load contributes most to the energy demand with more than 80 % across all scenarios. The grid sale is around 7–15 %, and it is noteworthy that the grid sale is almost twice in 'with DG' combinations compared to 'without DG' models. This is because of the electrochemical storage (via BESS) for later use during no solar PV production or during power outages. A correlation between the LCOE and the kWh yielded by BESS, Solar PV + Grid Purchase, and EV chargers served showed the utility of DG, especially in relation to minimising the LCOE across climate scenarios (Fig. 8). Also, although marginal, the fewer the EV chargers served in 'with DG' combinations, the lower the LCOE is. The EV chargers are deferrable, meaning they are elastic and are configured to serve during high Solar PV production and low energy price durations. The deferrable EV chargers enhance the utility of Solar PV by absorbing the potential low-tariff 'feed-in-energy'. In the NSW state of Australia, the solar feed-in tariff is benchmarked at around 4.9 to 6.3 ¢/kWh for 2024–25 [51]. This is significantly low compared to the desirable solar feed-in tariff of around 20 ¢/kWh to 28 ¢/kWh in Australia for rooftop solar PV investors to feel better off [64].

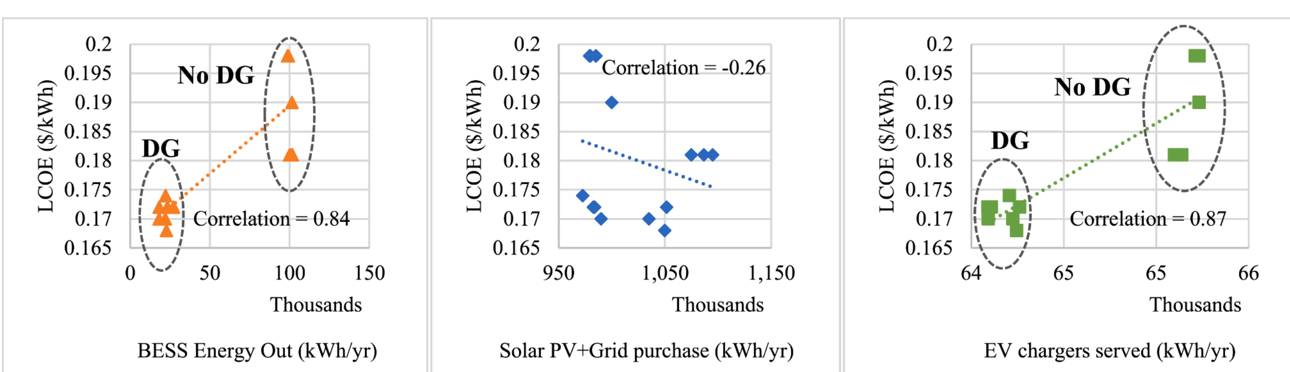

Fig. 8. Battery throughput during 'outage' and 'no outage'.

The higher the EV chargers served in 'without DG' combinations, the lower the share of grid sales (Fig. 7). This implies that the higher the penetration of EVs across office buildings, the lower the ability of buildings to export electricity and grid services the building may offer because of the higher PV self-utilisation. In solar PV-integrated buildings, smart control strategies for EV chargers are prerequisites for improving the PV self-utilization rates, especially amidst growing concern around power balance in an environment where EV charging loads are constantly increasing [47]. While this study uses the unidirectional chargers that do not necessarily improve the grid services, as evident from the results (Fig. 7), bidirectional chargers with V2G functionality can address the grid service and peak shaving elements that are often discussed together with microgrids [104]. The V2G concept is still a fledging idea in Australia [12]. Nevertheless, it is heading in the right direction with anticipation that bidirectional EV chargers and V2G-enabled vehicles will become more prevalent across residential, office and commercial buildings.

4.3. The building energy system's resilience, reliability, and flexibility in changing climate conditions

The battery throughput sees little changes across climate scenarios if we are to compare 'with DG' and 'without DG' combinations separately (Fig. 9). The sizing and configuration of the BESS are such that the depth of discharge (DOD) is 90 % for all scenarios regardless of the 'with DG' and 'without DG' combinations. However, notably, the battery throughput during 'outage' in 'with DG' combinations is always more than the battery throughput during 'no outage', and this is the opposite for the 'without DG' combinations. During 'outages', in the 'with DG' combinations, the DG works together with the BESS to act as a backup power. However, since the BESS size is smaller in 'with DG' combinations, it delivers its maximum capacity during 'outages' compared to 'no outages'.

In 'without DG' combinations, the larger size of BESS caters to the need even during 'no outages', in fact, much more than during 'outages' as only critical loads need to be serviced during 'outages', meaning only half of the total load must be covered by BESS. Hwang et al. [48] found that the combination of solar PV and BESS, if sized properly, can eliminate DGs with little effect on the building's energy system resilience. The average DG run time for all climate scenarios is around 16 h per year, with around 3.5 h long sessions each. Contrary to the findings of Hwang et al. [48], eliminating DG from building microgrids presents reliability challenges, especially when the power outage is for a longer period (> 4 h). For longer period power outages, reliability comes at higher LCOE.

Fig. 10 shows the probability of surviving the critical and priority critical loads for 4, 8, and 12 h. With the optimised DG size, the probability of surviving the critical and top-priority critical loads drops significantly when the outage duration is more than 4 h. A sensitivity analysis conducted to survive the critical load for 8 h (100 %) showed that the LCOE would increase by 35–45 % across climate scenarios because of the larger size of BESS, Solar PV, and DG. In 'without DG' combinations, the increase is around 43–55 %. Likewise, the probability of surviving an outage for 12 h (100 %) causes an almost 62–69 % increase in LCOE in the 'with DG' combination across climate scenarios and an almost 75–84 % increase in LCOE in 'without DG' combinations. To achieve a 100 % probability of surviving the top priority critical load for up to 12 h, the maximum LCOE is around 35–45 % increase compared to optimal combinations (Table 5). These results are similar to those of Rosales-Asensio et al. [94] and Marqusee et al. [74], who found that the combination of solar PV and electrochemical storage (e.g. BESS) could sustain power outages for up to 24 h. However, the survivability probability tends to decrease over time, the rate of which is dependent on the DG and BESS capacities. Anderson et al. [8] and Laws et al. [59] use the value of lost load (VOLL) concept to indicate that, during power outages, while the life cycle cost may increase, the probability of surviving extended outages (e.g. > 4 h) increases. Sepúlveda-Mora et al. [97] calculated the probability of surviving the critical load (50 % of the total electric load) to find that the effect of VOLL is insignificant for 'with DG' combinations. While this study does not calculate the VOLL, the findings – increase in LCOE cost for extended outages, concur with the notion of resilience and reliability-related costs.

While Sepúlveda-Mora et al. [97] state that the probability of surviving outages depends on the building load patterns, this study emphasises the critical role of demand-side efficiency measures in improving the probability of surviving outages. For example, elastic

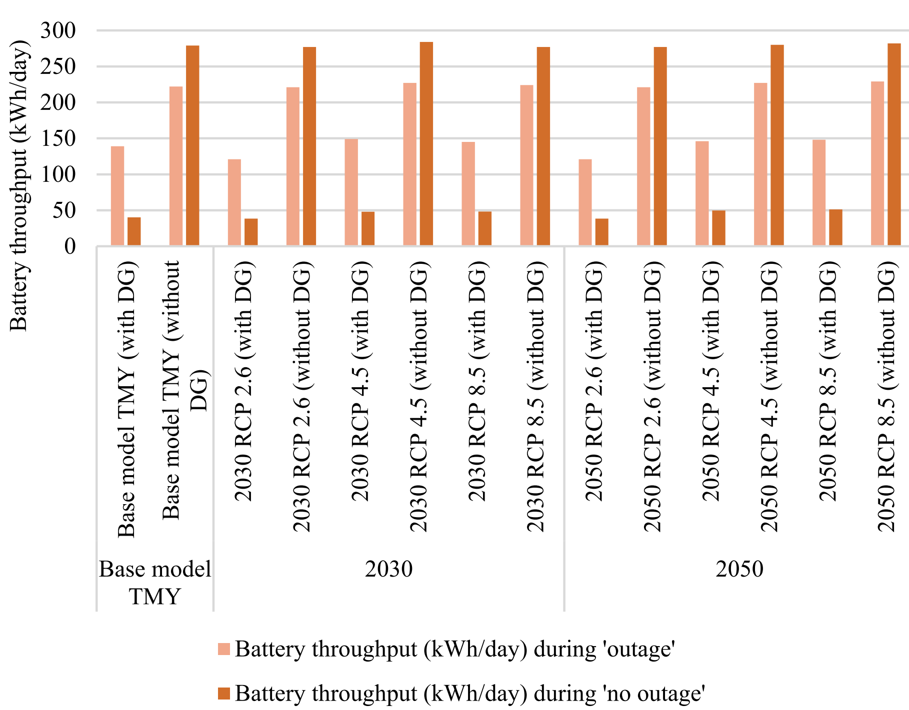

Fig. 9. Probability to survive critical load and highest priority critical load.

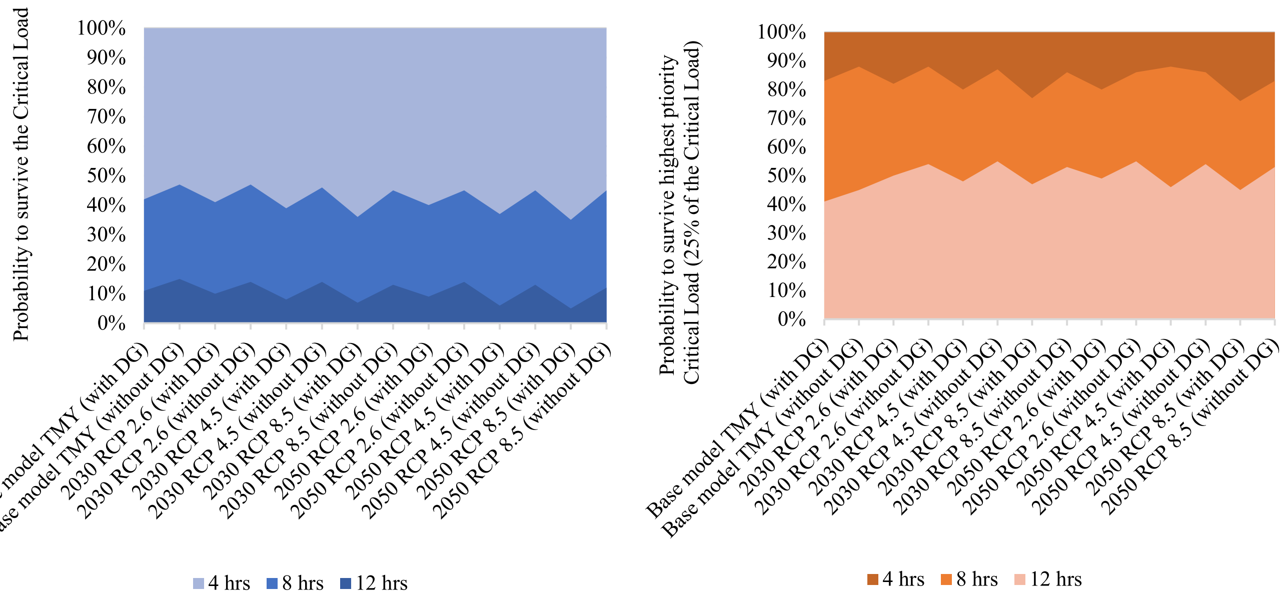

Fig. 10. Reduction in peak loads' grid purchase during demand response events.

loads, such as the deferrable EV chargers, plug loads and HVAC systems, all of which can contribute to up to 75 % of the total load can be controlled to reduce the scale of the critical load, which is usually 40–50 % of the electric load. An additional value proposition of the demand-side efficiency measures and lower critical load is enhanced flexibility, especially during demand response events. Fig. 11 shows the demand reduction during five demand reduction events (per year), which is in a range between 124 kW and 292 kW across climate scenarios and 'with DG' and 'without DG' combinations. While the peak load may not necessarily be reduced from a consumption perspective during demand response events, grid purchase should have demand reduction, which is achieved by utilising solar PV and BESS. Thus, the effect of the demand response is more in 'without DG' combinations across climate scenarios (2030 and 2050), as larger BESS means a higher solar PV utilisation rate (Fig. 7).

The demand response event (DR2) has the least reduction and lower DREEF because of the timing (5 pm) when BESS becomes the primary source during time-of-use peak demand hours (2 pm – 8 pm) in NSW, Australia. In DR1 (12 pm), DR3 (12 pm), DR4 (10 am), and DR5 (7 am) that last 4 h each, the demand reduction during grid purchase is more than DR2 across climate scenarios because they do not fully cover the time-of-use peak demand hours. Consequently, the demand charges savings are higher in DR2 compared to others. The cumulative demand charge savings range between A$ 7,000 and A$ 11,000 per year, including incentives such as through the peak demand reduction scheme in NSW, Australia. These DRs contribute to the buildings' supply-side flexibility by better utilizing the onsite production and BESS discharging. Better utilization of solar PV production implies improved flexibility [115]. Collectively, the supply-side flexibility and the demand-side flexibility [21] that leverage the elastic electric loads' potential contribute to the overall flexibility. While the deferrable unidirectional EV chargers used in this study do not provide V2G and vehicle-to-

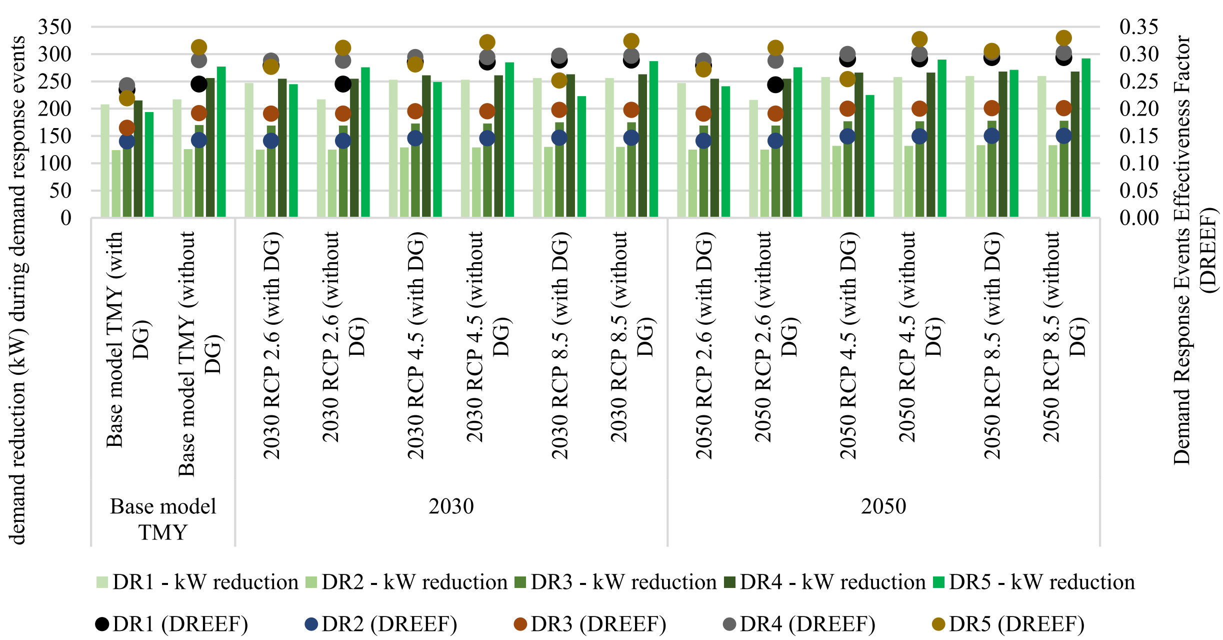

Fig. 11. Monte Carlo simulation results for the grid purchase and sales probability (2030 and 2050).

building (V2B) functionality that is considered ideal for demand response [26,71], it does allow the buildings to optimise the electricity use via charging stations to have some flexibility in load shifting.

Fig. 12 shows the probability of grid purchases and sales in 2030 and 2050. Contrary to the established notion about enhancing the building-grid interaction, the findings indicate lower grid purchases and sales in the future, especially in the context of an absolute replacement of DG by BESS and future impacts of climate change. In 2030 and across all climate scenarios, the probability of grid purchase below the average is 0.78 in 2030, which drops to 0.55 in 2050. The probability of grid sales above the average also drops from 0.69 to 0.46. This implies a relatively higher grid purchase and higher utilisation of solar PV because of the additional climate-related energy demand and the electrification impact (refer to Fig. 5). The reduced probability of grid sales implies the building's flexibility, considering the impact it has on the effectiveness of the demand response programs.

Net zero energy buildings are supposed to have stronger grid interaction [53,44], which in the future is likely to subside marginally in absolute terms. Another notion about flexibility that contradicts the increased grid interaction calls for a better alignment between onsite production and consumption to increase onsite utilisation, such as by using load-shifting approaches and load matching [124,83]. For example, the use of deferrable EV chargers and leveraging the elastic load capabilities, especially given electric heat pumps, will likely become a dominant heating and cooling system. Together with the results in Fig. 11, there is sufficient evidence of demand-side efficiency [25]contributing to the building's flexibility. The demand response-related building flexibility is, however, distinct from the grid interaction-related flexibility in a way that the emphasis is not solely on enhancing the onsite utilisation via load matching. It is on demand reduction during peak hours for the buildings to provide essential grid services when needed and as agreed with the electricity retailer.

5. Conclusions

This study investigated the LCOE-based microgrid component combinations across different climate scenarios and assessed their resilience, reliability, and flexibility. Additionally, it undertook a comparative analysis of the microgrid combinations and energy optimization models with and without DG to gain the following insights. First, while the LCOE can be minimised from A$0.20/kWh to A$0.17/kWh across climate scenarios by including a diesel generator as backup power for critical loads, it reduces the probability of surviving outages (> 4 h) by around 10 % across climate scenarios. It is possible to replace the diesel generator with battery energy storage. However, the LCOE increases by up to 45 % (A$0.29/kWh) across climate scenarios for outages up to 8 h and almost 85 % (A$0.37/kWh) for outages up to 12 h. The increase in LCOE and the corresponding NPC are the resilience and reliability-related costs in enhancing the building energy system's resilience against unforeseen power outages. Thus, a tough balancing act is necessary if buildings are to transition from relying on emergency backup generators to adopting large-size BESS to improve resilience and reliability.

Second, in extreme climate scenarios in the future, such as in the RCP 4.5 and RCP 8.5 models, the LCOE does not show significant change, such as in the comparison between 'with DG' and 'without DG' combinations, but the NPC does (almost 5 % to 9 %) because of larger-size Solar PV and BESS. While the marginal increase in the NPC can be attributed to the climate-related capital expenditure, the co-benefit includes realising the net zero energy building concept because of the energy asset transition from using diesel generators to BESS as a backup power system. Thus, this study adds to the recent progress on building

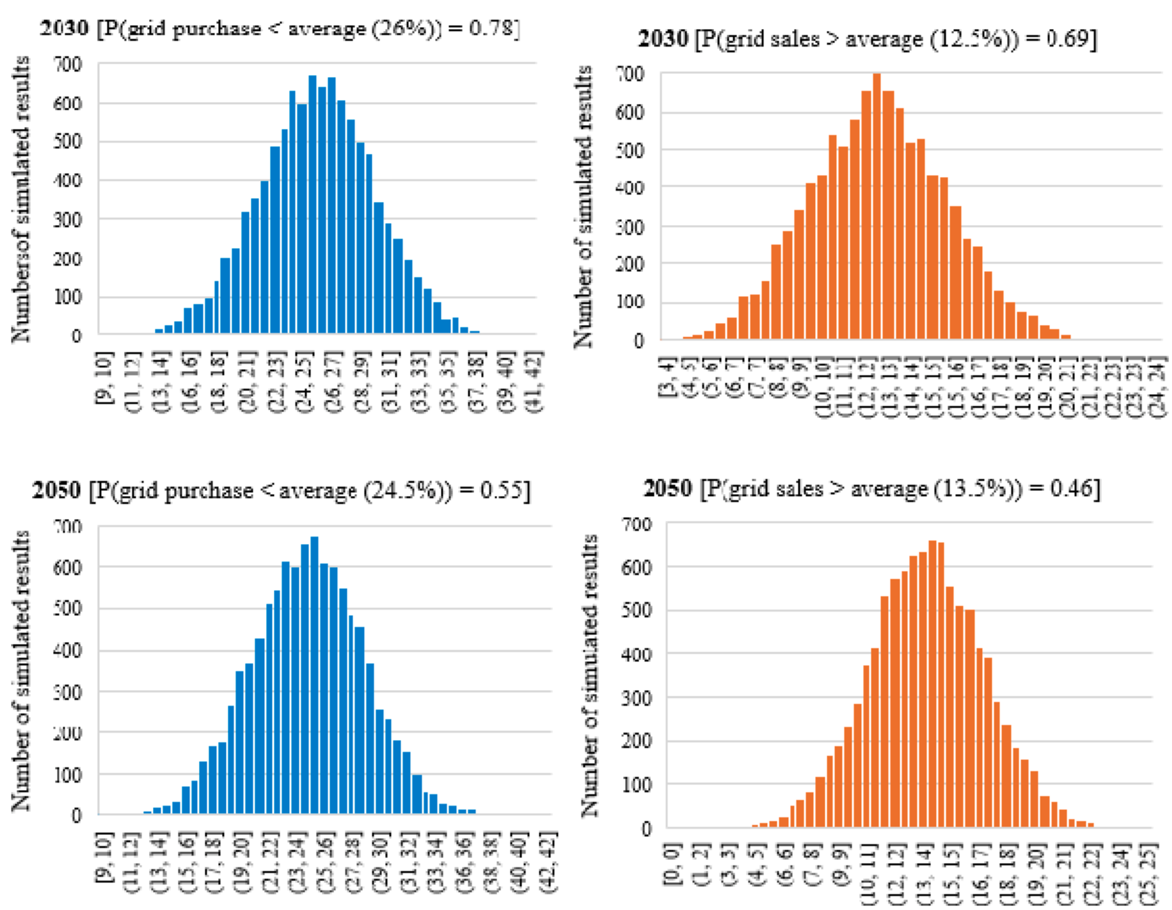

Fig. 12. Monte Carlo simulation results for the grid purchase and sales probability (2030 and 2050).

energy transition literature by providing insights into building energy performances (resilience and reliability) under changing climate conditions and the environmental and financial value propositions of greening the on-site backup power system.

Third, while the building energy system's flexibility to provide grid service is improved with onsite solar PV and BESS, two underlying aspects explain the notion of flexibility – grid sales and demand response. While the grid sales reductions intend to limit the building-grid interaction, this improves the onsite utilisation, implying more resilience against grid failures. Likewise, the demand response allows the buildings to provide the grid services when the grid is subjected to increased stress. The grid purchase and sales are dependent on the future electric load and especially the climate-related incremental changes in the electric load, which appears to impact the probability of a certain fraction of grid purchase and sales. These insights add to the debate about whether building energy systems should be designed and operated in a way to provide grid services when required or should it aim to increase on-site energy production utilisation rate focusing on self-sufficiency, resilience, and reliability. Further, the findings, such as the reduced probability of grid electricity exchange in the future, add to the demand side energy efficiency literature by highlighting their role in envisioning energy-flexible buildings.

Although this paper contributes to multiple building energy-related literature strands, there are some caveats and limitations. It uses a building archetype and simulated results. A similar method can be replicated for a real building, and the results can be cross-checked against the real monitored data. Nonetheless, the LCOE and NPV data for various climate scenarios and comparative analysis of building microgrid components with and without diesel generator cases contribute to understanding the inevitable building energy transition and implications on the building energy system's resilience, reliability, and flexibility.

CRediT authorship contribution statement

Bishal Baniya: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Damien Giurco:** Supervision, Writing – review & editing.

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

Data will be made available on request.

References

[1] ABCB. (2020). National Construction Code, Volume Two, Building Code of Australia 2019 Amendment 1.
[2] A.G. Abo-Khalil, M. Abdalla, R.C. Bansal, N.T. Mbungu, A critical assessment of islanding detection methods of solar photovoltaic systems, Case Stud. Therm. Eng. 52 (2023) 103681.
[3] G. Airò Farulla, G. Tumminia, F. Sergi, D. Aloisio, M. Cellura, V. Antonucci, M. Ferraro, A review of key performance indicators for building flexibility quantification to support the clean energy transition, Energies 14 (18) (2021) 5676.
[4] M. Ala-Juusela, T. Crosbie, M. Hukkalainen, Defining and operationalising the concept of an energy positive neighbourhood, Energ. Conver. Manage. 125 (2016) 133–140.
[5] B. Aluisio, M. Dicorato, I. Ferrini, G. Forte, R. Sbrizzai, M. Trovato, Planning and reliability of DC microgrid configurations for Electric Vehicle Supply Infrastructure, Int. J. Electr. Power Energy Syst. 131 (2021) 107104.
[6] A. Alzahrani, K. Sajjad, G. Hafeez, S. Murawwat, S. Khan, F.A. Khan, Real-time energy optimization and scheduling of buildings integrated with renewable microgrid, Appl. Energy 335 (2023) 120640.
[7] S.M. Amin, N. Hossain, M.S.H. Lipu, S. Urooj, A. Akter, Development of a PV/battery micro-grid for a data center in Bangladesh: Resilience and sustainability analysis, Sustainability 15 (22) (2023) 15691.
[8] K. Anderson, N.D. Laws, S. Marr, L. Lisell, T. Jimenez, T. Case, D. Cutler, Quantifying and monetizing renewable energy resiliency, Sustainability 10 (4) (2018) 933.
[9] F. Arraño-Vargas, Z. Shen, S. Jiang, J. Fletcher, G. Konstantinou, Challenges and mitigation measures in power systems with high share of renewables—the Australian experience, Energies 15 (2) (2022) 429.
[10] A. Arsalis, G.E. Georghiou, P. Papanastasiou, Recent research progress in hybrid photovoltaic-regenerative hydrogen fuel cell microgrid systems, Energies 15 (10) (2022) 3512.
[11] M. Asif, S.S. Bibi, S. Ahmed, M. Irshad, M.S. Hussain, H. Zeb, J. Kim, Recent advances in green hydrogen production, storage and commercial-scale use via catalytic ammonia cracking, Chem. Eng. J. (2023) 145381.
[12] Australian Renewable Energy Agency (ARENA). (2024). Insights from the Realising Electric Vehicle-to-Grid Services Project. Prepared by Energia on ARENA's behalf. Sydney, Australia.
[13] Y. Bai, W. Zhang, X. Hu, A collaborative matching method for multi-energy supply systems in office buildings considering the random characteristics of electric vehicles, Energ. Build. 303 (2024) 113809.
[14] B. Bass, J. New, How will United States commercial building energy use be impacted by IPCC climate scenarios? Energy 263 (2023) 125945.
[15] C.J. Bay, R. Chintala, V. Chinde, J. King, Distributed model predictive control for coordinated, grid-interactive buildings, Appl. Energy 312 (2022) 118612.
[16] B. Bhattarai, L. Marinovici, P.S. Sarker, A. Orrell, MIRACL Co-Simulation platform for control and operation of distributed wind in microgrid, IET Smart Grid 5 (2) (2022) 90–100.
[17] M.Z.A. Bhatti, A. Siddique, W. Aslam, S. Atiq, Design and analysis of a hybrid stand-alone microgrid, Energies 17 (1) (2023) 200.
[18] A. Boche, C. Foucher, L.F.L. Villa, Understanding microgrid sustainability: A systemic and comprehensive review, Energies 15 (8) (2022) 2906.
[19] G. Buticchi, S. Bozhko, M. Liserre, P. Wheeler, K. Al-Haddad, On-board microgrids for the more electric aircraft—Technology review, IEEE Trans. Ind. Electron. 66 (7) (2018) 5588–5599.
[20] L.F. Cabeza, D. Ürge-Vorsatz, The role of buildings in the energy transition in the context of the climate change challenge, Global Transitions 2 (2020) 257–260.
[21] Y. Chen, P. Xu, J. Gu, F. Schmidt, W. Li, Measures to improve energy demand flexibility in buildings for demand response (DR): A review, Energ. Build. 177 (2018) 125–139.
[22] T. Chowdhury, H. Chowdhury, K.S. Islam, A. Sharifi, R. Corkish, S.M. Sait, Resilience analysis of a PV/battery system of health care centres in Rohingya refugee camp, Energy 263 (2023) 125634.
[23] Clean Energy Council (CEC), (2024), New report: Almost 40 per cent of Australia's electricity supplied by renewables, https://www.cleanenergycouncil.org.au/news/new-report-almost-40-per-cent-of-australias-electricity-supplied-by-renewables, accessed on 30 May 2024.
[24] X. Cui, S. Liu, G. Ruan, Y. Wang, Data-driven aggregation of thermal dynamics within building virtual power plants, Appl. Energy 353 (2024) 122126.
[25] M. Curtis, J. Torriti, S.T. Smith, A comparative analysis of building energy estimation methods in the context of demand response, Energ. Build. 174 (2018) 13–25.
[26] H. Dagdougui, A. Ouammi, L.A. Dessaint, Peak load reduction in a smart building integrating microgrid and V2B-based demand response scheme, IEEE Syst. J. 13 (3) (2018) 3274–3282.
[27] D. D'Agostino, D. Parker, I. Epifani, D. Crawley, L. Lawrie, How will future climate impact the design and performance of nearly zero energy buildings (NZEBs)? Energy 240 (2022) 122479.
[28] R.S. de Oliveira, M.J.L. de Oliveira, E.G.S. Nascimento, R. Sampaio, A. S. Nascimento Filho, H. Saba, Renewable energy generation technologies for decarbonizing urban vertical buildings: A path towards net zero, Sustainability 15 (17) (2023) 13030.
[29] Department of Climate Change, Energy, the Environment and Water (DCCEEW), Australian Government, (2024), Renewables, https://www.energy.gov.au/energy-data/australian-energy-statistics/renewables, accessed on 30 May 2024.
[30] Department of Climate Change, Energy, the Environment and Water (DCCEEW). (2022). Commercial Building Baseline Study 2022 - Final Report, prepared by Strategy Policy Research, Australia.
[31] L.I. Dulău, Power cost and CO2 emissions for a microgrid with hydrogen storage and electric vehicles, Sustainability 15 (22) (2023) 15750.
[32] S. El Hassani, M. Charai, M.A. Moussaoui, A. Mezrhab, Towards rural net-zero energy buildings through integration of photovoltaic systems within bio-based earth houses: Case study in Eastern Morocco, Sol. Energy 259 (2023) 15–29.
[33] Elavarasan, M.R., Ghosh, A., K. Mallick, T., Krishnamurthy, A., & Saravanan, M. (2019). Investigations on performance enhancement measures of the bidirectional converter in PV–wind interconnected microgrid system. Energies, 12(14), 2672.
[34] A.S. Emam, M.O. Hamdan, B.A. Abu-Nabah, E. Elnajjar, A review on recent trends, challenges, and innovations in alkaline water electrolysis, Int. J. Hydrogen Energy 64 (2024) 599–625.
[35] M.M. Eskander, C.A. Silva, Techno-economic and environmental comparative analysis for DC microgrids in households: Portuguese and French household case study, Appl. Energy 349 (2023) 121495.
[36] G.M. Flechas, OpenStudio validation of a CLT building in Colorado, ASHRAE Trans. 127 (2021) 37–39.

[37] Forrousso, S., Kaitouni, S. I., Mana, A., Wakil, M., Jamil, A., Brigui, J., & Azzouzi, H. (2024). Optimal sizing of off-grid microgrid Building-Integrated-Photovoltaic system with battery for a Net Zero Energy Residential Building in different climates of Morocco. Results in Engineering, 102288.

[38] X. Gui, Z. Gou, Understanding green building energy performance in the context of commercial estates: A multi-year and cross-region analysis using the Australian commercial building disclosure database, Energy 222 (2021) 119988.

[39] A.K. Hamid, N.T. Mbungu, A. Elnady, R.C. Bansal, A.A. Ismail, M.A. AlShabi, A systematic review of grid-connected photovoltaic and photovoltaic/thermal systems: Benefits, challenges and mitigation, Energy Environ. 34 (7) (2023) 2775–2814.

[40] Y. Han, J. Wu, H. Chen, F. Si, Z. Cao, Q. Zhao, Enhancing grid-interactive buildings demand response: sequential update-based multi-agent deep reinforcement learning approach, IEEE Internet Things J. (2024).

[41] T. Hasan, N.M.S. Hassan, R. Shah, K. Emami, J. Anderson, A hydrogen supply-chain model powering Australian isolated communities, Energy Rep. 9 (2023) 209–214.

[42] M. Herrera, S. Natarajan, D.A. Coley, T. Kershaw, A.P. Ramallo-González, M. Eames, M. Wood, A review of current and future weather data for building simulation, Build. Serv. Eng. Res. Technol. 38 (5) (2017) 602–627.

[43] A. Hodges, A.L. Hoang, G. Tsekouras, K. Wagner, C.Y. Lee, G.F. Swiegers, G. G. Wallace, A high-performance capillary-fed electrolysis cell promises more cost-competitive renewable hydrogen, Nat. Commun. 13 (1) (2022) 1304.

[44] K. Hu, C. Yan, C. Xu, W. Li, J. Ye, Y. Gong, Y. Xu, Strategies for grid-friendly and uncertainty-adaptive design in zero energy buildings, Energ. Buildings 307 (2024) 113967.

[45] L. Huang, W. Sun, Q. Li, W. Li, Distributed real-time economic dispatch for islanded microgrids with dynamic power demand, Appl. Energy 342 (2023) 121156.

[46] P. Huang, G. Huang, Y. Sun, Uncertainty-based life-cycle analysis of near-zero energy buildings for performance improvements, Appl. Energy 213 (2018) 486–498.

[47] P. Huang, J. Munkhammar, R. Fachrizal, M. Lovati, X. Zhang, Y. Sun, Comparative studies of EV fleet smart charging approaches for demand response in solar-powered building communities, Sustain. Cities Soc. 85 (2022) 104094.

[48] S. Hwang, S. Tongsopit, N. Kittner, Transitioning from diesel backup generators to PV-plus-storage microgrids in California public buildings, Sustain. Prod. Consumption 38 (2023) 252–265.

[49] Im, P., New, J. R., & Bae, Y. (2019). Updated OpenStudio small and medium office prototype models. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States).

[50] A.A. Imam, Y.A. Al-Turki, Techno-economic feasibility assessment of grid-connected PV systems for residential buildings in Saudi Arabia—A case study, Sustainability 12 (1) (2019) 262.

[51] Independent Pricing and Regulatory Tribunal (IPART). 2024. Solar feed-in-tariff, https://www.ipart.nsw.gov.au/Home/Industries/Energy/Retail-prices/Solar-Energy, accessed on 27-06-2024.

[52] M.S. Islam, A techno-economic feasibility analysis of hybrid renewable energy supply options for a grid-connected large office building in southeastern part of France, Sustain. Cities Soc. 38 (2018) 492–508.

[53] S. Jia, K. Sheng, D. Huang, K. Hu, Y. Xu, C. Yan, Design optimization of energy systems for zero energy buildings based on grid-friendly interaction with smart grid, Energy 284 (2023) 129298.

[54] M.R. Jongerden, J. Hüls, A. Remke, B.R. Haverkort, Does your domestic photovoltaic energy system survive grid outages? Energies 9 (9) (2016) 736.

[55] L. Kanger, When the types do not make sense: Seven lessons to improve typology-building for energy transitions research, Energy Res. Soc. Sci. 107 (2024) 103360.

[56] M. Kermani, B. Adelmanesh, E. Shirdare, C.A. Sima, D.L. Carnì, L. Martirano, Intelligent energy management based on SCADA system in a real Microgrid for smart building applications, Renew. Energy 171 (2021) 1115–1127.

[57] H.S. Khan, R. Paolini, P. Caccetta, M. Santamouris, On the combined impact of local, regional, and global climatic changes on the urban energy performance and indoor thermal comfort—The energy potential of adaptation measures, Energ. Build. 267 (2022) 112152.

[58] J. Kim, S. Frank, P. Im, J.E. Braun, D. Goldwasser, M. Leach, Representing small commercial building faults in EnergyPlus, part II: Model validation, Buildings 9 (12) (2019) 239.

[59] N.D. Laws, K. Anderson, N.A. DiOrio, X. Li, J. McLaren, Impacts of valuing resilience on cost-optimal PV and storage systems for commercial buildings, Renew. Energy 127 (2018) 896–909.

[60] J. Le Dréau, P. Heiselberg, Energy flexibility of residential buildings using short term heat storage in the thermal mass, Energy 111 (2016) 991–1002.

[61] T. Levin, A. Botterud, W.N. Mann, et al., Extreme weather and electricity markets: Key lessons from the February 2021 Texas crisis, Joule 6 (2022) 1–7.

[62] C. Li, D. Zhou, Y. Zheng, Techno-economic comparative study of grid-connected PV power systems in five climate zones, China, Energy 165 (2018) 1352–1369.

[63] H.X. Li, Y. Zhang, Y. Li, J. Huang, G. Costin, P. Zhang, Exploring payback-year based feed-in tariff mechanisms in Australia, Energy Policy 150 (2021) 112133.

[64] H. Li, Z. Wang, T. Hong, M.A. Piette, Energy flexibility of residential buildings: A systematic review of characterization and quantification methods and applications, Adv. Appl. Energy 3 (2021) 100054.

[65] J. Liu, H. Wu, H. Huang, H. Yang, Renewable energy design and optimization for a net-zero energy building integrating electric vehicles and battery storage considering grid flexibility, Energ. Conver. Manage. 298 (2023) 117768.

[66] J. Liu, R. Yin, L. Yu, M.A. Piette, M. Pritoni, A. Casillas, P. Schwartz, Defining and applying an electricity demand flexibility benchmarking metrics framework for grid-interactive efficient commercial buildings, Adv. Appl. Energy 8 (2022) 100107.

[67] Lyster, R., Farber, D. A., & Verchick, R. R. (2022). Climate-induced disasters and electricity infrastructure. In Research Handbook on Climate Change Adaptation Law (pp. 358-391). Edward Elgar Publishing.

[68] Mannai, H., Oueslati, H., & Mabrouk, S. B. (2020, September). Homer-based optimization of pv-wind-grid connected hybrid system in administrative building. In 2020 6th IEEE International Energy Conference (ENERGYCon) (pp. 830-835). IEEE.

[69] S.A. Mansouri, S. Maroufi, A. Ahmarinejad, A tri-layer stochastic framework to manage electricity market within a smart community in the presence of energy storage systems, J. Storage Mater. 71 (2023) 108130.

[70] S.A. Mansouri, E. Nematbakhsh, A.R. Jordehi, M. Marzband, M. Tostado-Véliz, F. Jurado, An interval-based nested optimization framework for deriving flexibility from smart buildings and electric vehicle fleets in the TSO-DSO coordination, Appl. Energy 341 (2023) 121062.

[71] S.A. Mansouri, Á. Paredes, J.M. González, J.A. Aguado, A three-layer game theoretic-based strategy for optimal scheduling of microgrids by leveraging a dynamic demand response program designer to unlock the potential of smart buildings and electric vehicle fleets, Appl. Energy 347 (2023) 121440.

[72] Mansouri, S. A., Paredes, Á., González, J. M., & Aguado, J. A. (2023a). A three-layer game theoretic-based strategy for optimal scheduling of microgrids by leveraging a dynamic demand response program designer to unlock the potential of smart buildings and electric vehicle fleets. Applied Energy, 347, 121440.

[73] J. Marqusee, W. Becker, S. Ericson, Resilience and economics of microgrids with PV, battery storage, and networked diesel generators, Adv. Appl. Energy 3 (2021) 100049.

[74] J. Marqusee, S. Ericson, D. Jenket, Impact of emergency diesel generator reliability on microgrids and building-tied systems, Appl. Energy 285 (2021) 116437.

[75] N. Martin, J. Rice, Power outages, climate events and renewable energy: Reviewing energy storage policy and regulatory options for Australia, Renew. Sustain. Energy Rev. 137 (2021) 110617.

[76] A. Mayyas, A.A. Chadly, I. Khaleel, M. Maalouf, Techno-economic analysis of the Li-ion batteries and reversible fuel cells as energy-storage systems used in green and energy-efficient buildings, Clean Energy 5 (2) (2021) 273–287.

[77] P.S. Meera, S. Hemamalini, Reliability assessment and enhancement of distribution networks integrated with renewable distributed generators: A review, Sustainable Energy Technol. Assess. 54 (2022) 102812.

[78] Y. Meng, S.A. Mansouri, A.R. Jordehi, M. Tostado-Véliz, Eco-environmental scheduling of multi-energy communities in local electricity and natural gas markets considering carbon taxes: A decentralized bi-level strategy, J. Clean. Prod. 440 (2024) 140902.

[79] S.S. Mohammad, S.J. Iqbal, Hydrogen technology supported solar photovoltaic-based microgrid for urban apartment buildings: Techno-economic analysis and optimal design, Energ. Conver. Manage. 302 (2024) 118146.

[80] C. Mokhtara, B. Negrou, N. Settou, A. Bouferrouk, Y. Yao, Optimal design of grid-connected rooftop PV systems: An overview and a new approach with application to educational buildings in arid climates, Sustainable Energy Technol. Assess. 47 (2021) 101468.

[81] M.U. Mutarraf, Y. Guan, L. Xu, C.L. Su, J.C. Vasquez, J.M. Guerrero, Electric cars, ships, and their charging infrastructure–A comprehensive review, Sustainable Energy Technol. Assess. 52 (2022) 102177.

[82] X. Nie, S.A. Mansouri, A.R. Jordehi, M. Tostado-Véliz, A two-stage optimal mechanism for managing energy and ancillary services markets in renewable-based transmission and distribution networks by participating electric vehicle and demand response aggregators, Int. J. Electr. Power Energy Syst. 158 (2024) 109917.

[83] Y. Noh, S. Jafarinejad, P. Anand, A review on harnessing renewable energy synergies for achieving urban net-zero energy buildings: Technologies, performance evaluation, policies, challenges, and future direction, Sustainability 16 (8) (2024) 3444.

[84] S. Paardekooper, H. Lund, J.Z. Thellufsen, N. Bertelsen, B.V. Mathiesen, Heat Roadmap Europe: Strategic heating transition typology as a basis for policy recommendations, Energ. Effi. 15 (5) (2022) 32.

[85] S.R. Patlolla, K. Katsu, A. Sharafian, K. Wei, O.E. Herrera, W. Mérida, A review of methane pyrolysis technologies for hydrogen production, Renew. Sustain. Energy Rev. 181 (2023) 113323.

[86] C. Pavlatos, E. Makris, G. Fotis, V. Vita, V. Mladenov, Enhancing electrical load prediction using a bidirectional LSTM neural network, Electronics 12 (22) (2023) 4652.

[87] O. Pedram, E. Asadi, B. Chenari, P. Moura, M. Gameiro da Silva, A review of methodologies for managing energy flexibility resources in buildings, Energies 16 (17) (2023) 6111.

[88] Pulkkinen, J., Louis, J. N., Debusschere, V., & Pongrácz, E. (2024). Near-, medium-and long-term impacts of climate change on the thermal energy consumption of buildings in Finland under RCP climate scenarios. Energy, 131636.

[89] Radeva, T., & Mateev, V. (2022). Photovoltaic Energy Usage for Public Educational Building: A Case Study. In 2022 22nd International Symposium on Electrical Apparatus and Technologies (SIELA) (pp. 1-4). IEEE.

[90] S.S. Raghuwanshi, R. Arya, Reliability evaluation of stand-alone hybrid photovoltaic energy system for rural healthcare centre, Sustainable Energy Technol. Assess. 37 (2020) 100624.

[91] Ren, Z., Tang, Z., & James, M. (2021). Predictive weather files for building energy modelling.

[92] Rodriguez, R., Osma, G., Bouquain, D., Ordoñez, G., Paire, D., Solano, J., ... & Hissel, D. (2024). Electrical resilience assessment of a building operating at low voltage. Energy and Buildings, 114217.

[93] E. Rosales-Asensio, M. de Simón-Martín, D. Borge-Diez, J.J. Blanes-Peiró, A. Colmenar-Santos, Microgrids with energy storage systems as a means to increase power resilience: An application to office buildings, Energy 172 (2019) 1005–1015.

[94] E. Rosales-Asensio, D. Icaza, N. González-Cobos, D. Borge-Diez, Peak load reduction and resilience benefits through optimized dispatch, heating and cooling strategies in buildings with critical microgrids, J. Build. Eng. 68 (2023) 106096.

[95] Salom, J., Widén, J., Candanedo, J., Sartori, I., Voss, K., & Marszal, A. (2011, November). Understanding net zero energy buildings: evaluation of load matching and grid interaction indicators. In Proceedings of building simulation (Vol. 6, pp. 2514-2521).

[96] Sambhi, S., Sharma, H., Kumar, P., Fotis, G., Vita, V., & Ekonomou, L. (2022). Techno-economic optimization of an off-grid hybrid power generation for SRM IST, Delhi-NCR campus. Energies, 15(21), 7880.

[97] S.B. Sepúlveda-Mora, S. Hegedus, Resilience analysis of renewable microgrids for commercial buildings with different usage patterns and weather conditions, Renew. Energy 192 (2022) 731–744.

[98] G. Soyturk, S.A. Cetinkaya, M.A. Yekta, M.M.K. Joghan, H. Mohebi, O. Kizilkan, S. Ghandehariun, Dynamic analysis and multi-objective optimization of solar and hydrogen energy-based systems for residential applications: A review, Int. J. Hydrogen Energy (2024).

[99] G. Stamatellos, A.M. Stamatellou, The interaction between short-and long-term energy storage in an nZEB office building, Energies 17 (6) (2024) 1441.

[100] H. Tang, S. Wang, H. Li, Flexibility categorization, sources, capabilities and technologies for energy-flexible and grid-responsive buildings: State-of-the-art and future perspective, Energy 219 (2021) 119598.

[101] M. Tavakoli, F. Shokridehaki, M. Marzband, R. Godina, E. Pouresmaeil, A two stage hierarchical control approach for the optimal energy management in commercial building microgrids based on local wind power and PEVs, Sustain. Cities Soc. 41 (2018) 332–340.

[102] R. Trivedi, S. Patra, Y. Sidqi, B. Bowler, F. Zimmermann, G. Deconinck, S. Khadem, Community-based microgrids: Literature review and pathways to decarbonise the local electricity network, Energies 15 (3) (2022) 918.

[103] M. Uddin, H. Mo, D. Dong, S. Elsawah, J. Zhu, J.M. Guerrero, Microgrids: A review, outstanding issues and future trends, Energ. Strat. Rev. 49 (2023) 101127.

[104] G. Van Kriekinge, C. De Cauwer, N. Sapountzoglou, T. Coosemans, M. Messagie, Peak shaving and cost minimization using model predictive control for uni-and bi-directional charging of electric vehicles, Energy Rep. 7 (2021) 8760–8771.

[105] C. Vargas-Salgado, D. Díaz-Bello, D. Alfonso-Solar, F. Lara-Vargas, Validations of HOMER and SAM tools in predicting energy flows and economic analysis for renewable systems: Comparison to a real-world system result, Sustainable Energy Technol. Assess. 69 (2024) 103896.

[106] B. Verbruggen, J. Driesen, Grid impact indicators for active building simulations, IEEE Trans. Sustainable Energy 6 (1) (2014) 43–50.

[107] I. Vigna, R. Pernetti, W. Pasut, R. Lollini, New domain for promoting energy efficiency: Energy Flexible Building Cluster, Sustain. Cities Soc. 38 (2018) 526–533.

[108] V. Vita, G. Fotis, C. Pavlatos, V. Mladenov, A new restoration strategy in microgrids after a blackout with priority in critical loads, Sustainability 15 (3) (2023) 1974.

[109] R. Wallsgrove, J. Woo, J.H. Lee, L. Akiba, The emerging potential of microgrids in the transition to 100% renewable energy systems, Energies 14 (6) (2021) 1687.

[110] M. Wan, H. Yu, Y. Huo, K. Yu, Q. Jiang, G. Geng, Feasibility and challenges for vehicle-to-grid in electricity market: A review, Energies 17 (3) (2024) 679.

[111] Wang, C. H. (2021). Bushfire and Climate Change Risks to Electricity Transmission Networks. In Engineering for Extremes: Decision-Making in an Uncertain World (pp. 413-427). Cham: Springer International Publishing.

[112] H. Wang, H. Lu, K. Sun, X. Wu, Y. He, X. Du, Reliability evaluation method for distribution network with distributed generations considering feeder fault recovery and network reconfiguration, IET Renew. Power Gener. 17 (14) (2023) 3484–3495.

[113] D.Y. Yamashita, I. Vechiu, J.P. Gaubert, A review of hierarchical control for building microgrids, Renew. Sustain. Energy Rev. 118 (2020) 109523.

[114] D.Y. Yamashita, I. Vechiu, J.P. Gaubert, Two-level hierarchical model predictive control with an optimised cost function for energy management in building microgrids, Appl. Energy 285 (2021) 116420.

[115] X. Yang, Y. Zhang, F. Zhang, C. Xu, B. Yi, Enhancing utilization of PV energy in building microgrids via autonomous demand response, IEEE Access 9 (2021) 23554–23564.

[116] S. Young, A. Bruce, I. MacGill, Potential impacts of residential PV and battery storage on Australia's electricity networks under different tariffs, Energy Policy 128 (2019) 616–627.

[117] Y. Yuan, J. Wang, X. Yan, B. Shen, T. Long, A review of multi-energy hybrid power system for ships, Renew. Sustain. Energy Rev. 132 (2020) 110081.

[118] L. Yue, J. Niu, Z. Tian, Q. Lin, Y. Lu, A simplified assessment method based on Hooke's law to estimate the grid-friendly ability of buildings, Renew. Energy 223 (2024) 119931.

[119] B.S. Zainal, P.J. Ker, H. Mohamed, H.C. Ong, I.M.R. Fattah, S.A. Rahman, T. I. Mahlia, Recent advancement and assessment of green hydrogen production technologies, Renew. Sustain. Energy Rev. 189 (2024) 113941.

[120] K. Zhang, E. Saloux, J.A. Candanedo, Enhancing energy flexibility of building clusters via supervisory room temperature control: Quantification and evaluation of benefits, Energ. Build. 302 (2024) 113750.

[121] S. Zhang, P. Ocłoń, J.J. Klemeš, P. Michorczyk, K. Pielichowska, K. Pielichowski, Renewable energy systems for building heating, cooling and electricity production with thermal energy storage, Renew. Sustain. Energy Rev. 165 (2022) 112560.

[122] W. Zhang, C. Yan, Y. Xu, J. Fang, Y. Pan, A critical review of the performance evaluation and optimization of grid interactions between zero-energy buildings and power grids, Sustain. Cities Soc. 86 (2022) 104123.

[123] X. Zhang, F. Xiao, Y. Li, et al., Energy flexibility and resilience analysis of demand-side energy efficiency measures within existing residential houses during cold wave event, Build. Simul. (2024), https://doi.org/10.1007/s12273-024-1127-4.

[124] X. Zhang, F. Xiao, Y. Li, Y. Ran, W. Gao, Flexible coupling and grid-responsive scheduling assessments of distributed energy resources within existing zero energy houses, J. Build. Eng. 87 (2024) 109047.

[125] X. Zhou, S.A. Mansouri, A.R. Jordehi, M. Tostado-Véliz, F. Jurado, A three-stage mechanism for flexibility-oriented energy management of renewable-based community microgrids with high penetration of smart homes and electric vehicles, Sustain. Cities Soc. 99 (2023) 104946.

[126] Y. Zhou, X. Liu, Q. Zhao, A stochastic vehicle schedule model for demand response and grid flexibility in a renewable-building-e-transportation-microgrid, Renew. Energy 221 (2024) 119738.

[127] W. Zou, Y. Sun, D.C. Gao, X. Zhang, J. Liu, A review on integration of surging plug-in electric vehicles charging in energy-flexible buildings: Impacts analysis, collaborative management technologies, and future perspective, Appl. Energy 331 (2023) 120393.