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Advancing net zero carbon construction: A techno-economic and environmental analysis of onsite microgrids and prosumer energy adoption

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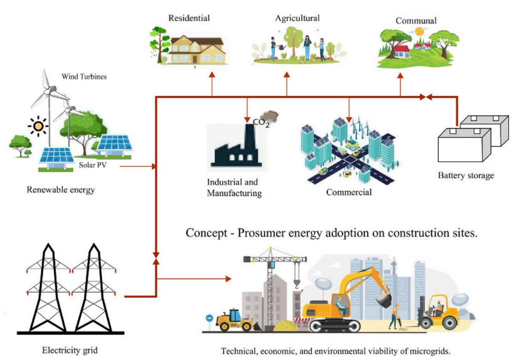
HIGHLIGHTS

- Systematic review and meta-analysis of technical, economic, and environmental microgrid data.
- Microgrids can achieve up to 80 % savings in carbon emissions compared to the conventional grid-based system.
- Hybrid grid-connected photovoltaic-wind turbine (G-PV-WT) systems reduce emissions by up to 91 %.
- The G-PV-WT systems are economically superior than other systems.
- A novel framework developed guides prosumer energy adoption for net zero carbon construction.

GRAPHICAL ABSTRACT



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ABSTRACT

Traditionally reliant on fossil fuels, the construction industry faces increasing pressure to adopt sustainable energy solutions to reduce carbon emissions and achieve Net Zero Carbon Construction (NZCC). This study examines the potential for integrating grid-connected microgrids into construction projects, leveraging renewable energy sources such as solar and wind, combined with energy storage systems, as a pathway to transform construction sites into energy prosumers – entities that produce and consume green energy. A systematic review and meta-analysis were conducted to comprehensively analyse the technical, economic, and environmental dimensions of commonly used microgrid configurations across sectors. The findings demonstrate that microgrids can reduce carbon emissions by up to 80 % compared to traditional grid-based systems, showcasing their superior environmental performance. The hybrid Grid-Connected Photovoltaic-Wind Turbine (G-PV-WT) configuration achieves up to 91 % emission savings, offering 50 % lower costs and payback periods compared to other alternatives. The study recommends site-specific configurations with G-PV-WT systems for construction sites with abundant wind and solar resources. However, it emphasises the need for a multi-criteria decision-making approach that balances technical, economic, environmental, and policy factors to select optimal microgrid solutions for construction sites. A prosumer energy adoption framework is proposed, positioning construction sites as active producers and consumers of green energy, supporting NZCC goals, driving innovation, and promoting sustainable construction practices.

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1. Introduction

Over the past few decades, the construction industry has increasingly prioritised sustainability, driven mainly by the urgent need to address climate change and its associated extreme weather effects. In 2023, the building and construction industry was responsible for 34 % of global carbon emissions (CO_2), 32 % of energy use, and 34 % of energy-related CO_2 emissions. 11 % of the CO_2 emissions were directly attributed to construction activities [1]. This energy consumption, primarily from diesel (55–75 %) and electricity (10–34 %), is mainly associated with the mechanical plant used for transportation, levelling, earthworks, lifting, compaction, and mixing of materials on site [2,3]. For example, constructing a 1 km two-lane asphalt-paved road can require up to 7.0 TJ of energy, while a commercial building may consume 3.43 kgce/m^2 [4]. Given the increasing trend of construction activities worldwide, the upward trajectory of energy consumption and subsequent CO_2 emissions is worrying as it exacerbates the challenge of meeting the industry's carbon reduction goals, thus widening the gap between current practices and the global Net Zero Carbon (NZC) targets. This reality puts pressure on the construction industry to decarbonise its operations, particularly during the building phase.

In this context, the study adopts the term Net Zero Carbon Construction (NZCC) to specifically refer to achieving zero or negative carbon emissions during the construction phase. Unlike broader whole-life concepts such as Net Zero Buildings (NZB) or Net Zero Energy Buildings (NZEB), NZCC focuses on short-term high-emission activities associated with construction activities. It seeks to balance construction-related emissions through carbon absorption and offsetting initiatives such as carbon capture and tree planting [5], and/or emission reduction or elimination strategies such as transitioning to onsite renewable energy (RE) [6]. Integrating temporary onsite microgrids and prosumer energy systems during construction offers a practical and sustainable pathway to achieving NZCC. When implemented on construction sites, these systems enable construction companies to transition from traditional energy consumers to prosumers - entities that both produce and consume green energy [4]. This dual role empowers sites to directly contribute to Sustainable Development Goals (SDG 7) - affordable and clean energy, and SDG 13 - climate action [7], as it promotes the widespread adoption of green energy, fostering localised energy resilience and cost efficiency, and lowering carbon footprints.

The growing energy demand trajectory presents an opportunity to adopt prosumer models in the construction phase of projects. In this context, a prosumer refers to an active energy consumer, either an individual or group, who not only consumes but also generates, stores and potentially sells energy. However, this research adopts a consolidated definition of the prosumer by [8–10] viewing them as final customers or a group of jointly acting customers who actively participate in energy generation, self-consumption, storage, or sale of RE, operating within their premises that are typically confined to defined boundaries. The transition to such active participation is enabled by technologies such as onsite microgrids and RE systems (e.g. solar PV and wind turbines) that allow construction sites to harness RE sources like solar and wind, thus significantly reducing their dependence on fossil fuels and contributing to broader goals of energy justice [11]. By leveraging these technologies, construction projects can align with global NZC targets by 2050, mitigate the impacts of climate change, and promote sustainable development. However, despite the evident benefits of adopting these RE solutions, the construction industry has been slower to embrace these innovations compared to other sectors [4]. Advancing the integration of these technologies during the construction phase is, therefore, critical to achieving NZCC.

Microgrids are decentralised energy systems that enable energy generation, storage, and consumption at a localised level. According to [12,13], microgrids function as small-scale, distributed energy networks comprising interconnected loads, energy resources, and active users that can operate autonomously or in conjunction with the primary grid, thereby providing a suitable ecosystem for distributed power generation. They are usually characterised by high penetration of Renewable Energy Sources (RES), with scalable structures and increased reliability [14]. A typical microgrid is comprised of three primary components: components for electricity generation, storage, and control systems [15]. [16,17] emphasise that effective planning and design are required to carefully select these components in order to optimise microgrid performance. Thus, the list of secondary components may vary based on several factors, including the available energy sources, requirements, applications, and type of connection. Microgrids are gaining traction across various sectors, including the manufacturing and automotive sectors, which have successfully transitioned to green energy throughout their production processes [18]. However, integrating microgrids in the construction phase presents unique technical, economic, social, and political challenges, given the variability of the project durations, location, and sizes.

Research has been conducted on onsite microgrids and prosumer energy adoption across various sectors, including residential, commercial, industrial, and agricultural. The research spans a diverse array of aspects, including grid design and architecture [12,19–22], techno-economic aspects of different energy systems or configurations [23–32], and ecological analysis [33–35] of microgrid implementation. More research has also been done on the social-technical considerations for selection of microgrid sites [36], the different battery systems that can be used for energy storage, their characteristics, merits and demerits [14] business cases and models pertaining to demand and supply management [15,37], as well as the social context in terms of public awareness, acceptance, and attitude towards microgrid adoption [38,39]. Most of the literature recognises the expected benefits of deploying onsite microgrids integrated with prosumer energy systems. These include, reduction in costs especially when supported by financial or government incentives [40], grid stabilisation and resilience [41], and carbon emission reduction [42,43], as well as energy autonomy and flexibility. Several challenges have also been reported, including RE curtailment and variability [43], high storage costs and technology limitations [44], volatility and integration complexity and regulatory and policy barriers [45,46]. Given their potential to advance the energy transition and NZC goals, the literature suggests that microgrid configurations offer adaptable setups that can be effectively tailored to fit the energy demands and sustainability goals of the construction industry.

However, a vast majority of these studies have focused on the application of microgrids in static environments, including residential, institutional, or commercial buildings, leaving a significant gap in understanding their application, particularly on construction sites. Construction projects are characterised by transient energy demands, temporary durations, and changing operational conditions, and most of them present unique challenges that have not been thoroughly addressed in existing research. Additionally, the studies have been conducted in isolation, with no effort to pool or compare the technical, economic, and environmental aspects of different microgrid configurations across various applications. This lack of consolidated data makes it challenging to effectively adapt existing configurations to new sectors or contexts, such as the construction sector. The research, therefore, set out to promote the implementation of microgrids and prosumer energy adoption in the construction industry based on the following specific objectives:

1. Examine the current practices and technological advancements in onsite microgrid systems across various sectors globally.
2. Evaluate and compare the economic and environmental performance of the widely adopted microgrid configurations.
3. Assess the impact of prosumer energy adoption on decarbonisation of the construction industry.
4. Develop a framework for implementing prosumer-based microgrids on construction sites.

2. Methods

The research was conducted following the systematic review methodology in [47], and meta-analysis guidelines set out in [48]. This entailed a comprehensive and unbiased exploration and analysis of results pertaining to onsite microgrids from across studies in a structured and systematic process. Meta-analysis was adopted as it provides an efficient way to summarise results from a wider range of studies and uncover associations that had not previously been identified. The structured approach aimed to identify, analyse, and synthesise existing research across residential, commercial, agricultural and industrial sectors to identify adaptable microgrid configurations and evaluate the potential for NZCC.

2.1. Search strategy

Searches were conducted across major academic databases, including Scopus, Web of Science and Google Scholar, to gather relevant studies. Keywords and Boolean operators were carefully selected to capture the main themes of the study, which included "*microgrids*", "*prosumer*", and "*renewable energy*". "To enhance the precision of the search, terms such as "*technical*", "*economic*", and "*environment*"were also incorporated to ensure the inclusion of studies focusing on the multifaced dimensions of the microgrid implementation. Several pilot searches were performed to refine the key Boolean parameters through trial and error. The final search string illustrated in Fig. 1 was used to retrieve the most relevant studies. (See Fig. 1.)

2.2. Screening and selection process

Records on recent microgrid developments were retrieved from various databases, including Scopus, Web of Science, and Google Scholar, covering a 10-year period from 2015 to 2024. These were processed through a three-stage process using Covidence - a web-based tool designed to streamline the systematic review process, from literature screening to data extraction. The process involved 1) title and abstract screening, 2) downloading and importing full-text articles (PDF format), and 3) full-text screening to select the most relevant articles for inclusion in the review. To minimise bias, the screening was conducted in two rounds, with a third round used to resolve any inclusion clashes. Given the study's focus on prosumerism, specific inclusion and exclusion criteria were applied to select relevant studies centered on onsite grid-connected microgrids across various sectors. Detailed selection criteria for the meta-analysis are provided in Appendix A. While this review acknowledges that contextual differences in country policies and infrastructure exist, these factors were noted and reported, but not systematically controlled, as the review aimed at thematic generalisation, not strict comparability of national contexts.

2.3. Data extraction

Based on the guidelines set out by [49], data were extracted to identify and record the relevant information from the selected articles. An extraction spreadsheet created in Microsoft Excel was used to categorise and extract the data from each article [50]. This included descriptive data (publication year, author, title, journal, and country of origin), technical parameters (type of microgrid configuration, application, i.e. residential, commercial, industrial, agricultural, component parameters including type, capacity, efficiency, lifespan, etc.), economic parameters (component costs, system capital costs (CC), operation and maintenance costs (O&M), Net Present Costs (NPC), Levelised Costs of Energy (LCOE), payback period (PBP)), and environmental indicators (carbon emissions (CO_2), Sulfur dioxide (SO_2), and Nitrogen Oxides (NO_x) emissions).

2.4. Data analysis

Thematic analysis was employed to categorise the extracted data into three key dimensions of interest: technical, economic, and environmental parameters. For consistency across studies, all numerical data were thoroughly cleaned and converted to similar standardised units, enabling the comparative analysis of the results. This involved transforming measurements with units such as Megawatt (MW) to Kilowatt (kW) (1 MW = 1000 kW), Watt (W) to Kilowatt (kW) (1 W = 0.001 kW), and Megawatt-hour per year (MWh/year) to Kilowatt-hour per year (kWh/year) (1 MWh/year = 1000 kWh/year). Additionally, currencies such as the Indian Rupee, Brazilian Real, and Euros were converted to US dollars based on exchange rates as of January 2025. Since the costs were captured at different time points, they were discounted using a rate of 4.5 %, the rate as of January 2025 [51]. For consistency, the NPC was recalculated using the CC and O&M costs given by different researchers, discounted over 25 years (the period referenced by most researchers). Only the data sets that reported both CC and O&M values were included in the calculation. The Capital Recovery Factor (CRF) was used to convert the annual O&M costs to present value, and the NPC was then obtained by adding the CC to the present value-annual costs, modifying

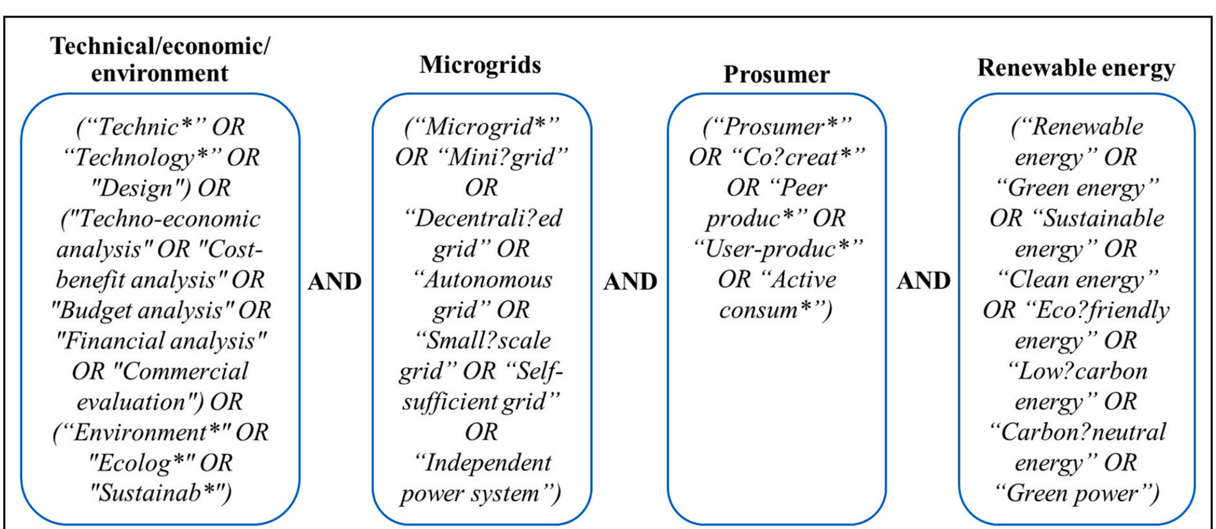

Fig. 1. Visual Representation of the Boolean Search Strategy

the method outlined by [26]. In eqs. (1) and (2), i represents the yearly real interest rate in %, n denotes the duration of analysis (25 years), and N represents the research publication year.

$$NPC_N = CC + \frac{Net\ Annual\ Cost}{CRF(i,n)} \tag{1}$$

$$CFR(i,n) = \frac{i(1+i)^n}{i(1+i)^n + 1} \tag{2}$$

The Resulting NPC - (from eq. 1) and LCOE values (as reported in literature) were then discounted using the compound factor (CF) based on the baseline year of 2025. While most studies use LCOE and COE interchangeably, their calculation approach follows the standard LCOE methodology – system NPC divided by the total energy output over its lifespan [52]. Thus, for consistency, this study adopts the term LCOE throughout.

$$CF\ (i,n) = (1+i)^n \tag{3}$$

$$NPC \Big/ COE = \frac{Cost\ at\ year\ N}{CF(i,n)} \tag{4}$$

2.4.1. Assessing economic performance

The study examines key variables, including Net Present Costs (NPC), Levelised Cost of Energy (LCOE), and Payback Period (PBP), to evaluate and compare the economic performance of the commonly used energy configurations. It analyses the ranges and medians of these indicators and employs the Kruskal-Wallis non-parametric test to assess differences across various microgrid configurations based on the following hypothesis:

- Null hypothesis **(H_0):** There is no significant variation in economic performance (NPC, LCOE, and PBP) across different microgrid configurations:

H_0: β_m (G-PV) = β_m (G-PV-BS) = β_m (G-PV-WT) = β_m (G-WT) = β_m (G-WT-BS) = β_m (G-PV-WT-BS), $\forall m \in$ {NPC, LCOE, PBP}

- Alternative hypothesis **(H_A):** At least one microgrid configuration shows a significant difference in economic performance (NPC, LCOE, or PBP)

H_A: $\exists m \in$ {NPC, LCOE, PBP}, such that $\beta m \neq 0$.
Where:

- $\beta_m(G_k)$: Represents the economic performance metric m for microgrid configuration G_k.
- $m \in$ {NPC, LCOE, PBP}: Indicates that the economic performance is assessed using NPC, LCOE, and PBP.

2.4.2. Assessing the environmental impact of prosumer energy adoption

The impact of prosumer energy adoption on decarbonisation was assessed by analysing the environmental impact of different microgrid configurations, focusing on CO_2, SO_2 and NO_x emissions and their emission reduction potential compared to the traditional grid-only configuration. Two hypotheses were tested in this analysis: a general and a configuration-specific hypothesis.

General hypothesis – This hypothesis tested whether the adoption of microgrids or prosumer energy significantly reduces carbon emissions compared to traditional grid-based systems. The analysis involved a graphical representation followed by a Mann-Whitney *U* test to assess the relationship and statistical significance of differences in carbon emissions between the traditional grid-based and microgrid systems. Furthermore, the study quantifies the emission reduction potential of microgrid systems by analysing the relationship between the share of RE (RE%) and associated carbon emissions. Specifically, it investigates whether a higher RE% results in a more significant reduction in emissions. In this context, a 0 % RE share represents traditional grid-based systems, whereas an RE share greater than 0 % indicates that it is associated with microgrid systems.

- Null hypothesis **(H_0):** The average carbon emissions from microgrid adoption are not significantly different from traditional grid-based systems.

H_0:$\mu_{microgrids} = \mu_{baseline}$

- Alternative hypothesis **(H_A):** The average carbon emissions from microgrid adoption are significantly lower than emissions from traditional grid-based systems.

H_A: $\mu_{microgrids} < \mu_{baseline}$.
Where:

- $\mu_{microgrids}$ = Mean carbon emissions with microgrid adoption (combined data across all configurations).
- $\mu_{baseline}$ = Mean carbon emissions from traditional grid-based systems.

Configuration specific: This hypothesis compared the carbon reduction potential among different microgrid configurations. Regression analysis was conducted to examine the relationship between RE share (RE%) and carbon emissions per kWh, assessing the emission reduction potential of each configuration and identifying the groups that differ.

- Null hypothesis **(H_0):** There is no significant difference in carbon reduction potential among different microgrid configurations.

H_0: μG-PV = μG-PV-BS = μG-PV-WT = μG-PV-WT-BS = μG-WT = μG-WT-BS

- Alternative hypothesis **(H_A):** At least one microgrid configuration has a significantly different carbon reduction potential compared to others.

H_A: $\exists(\mu_i \neq \mu_j)$ for some configurations *i* and *j*.
Where: $\mu_{i,\ j}$ = Mean carbon emission for each microgrid configuration.

All study results were visualised using graphs and tables created with Stata 18 and OriginPro version 2024b software.

3. Results

The screening process was based on the PRISMA flow diagram depicted in **Fig. 2**. A total of 490 records were initially gathered. After 107 duplicates and irrelevant entries were removed during the initial screening stage in Endnote, 383 records remained. Of these, 221 were excluded during the title and abstract screening stage in Covidence software. Subsequently, the full texts of 158 out of the remaining 162 articles were reviewed, and only 30 articles that met the inclusion criteria were included in the study. While this PRISMA flow diagram indicates a final selection of 30 articles, these studies collectively presented 148 unique records of microgrid configurations [50]. Whereas the descriptive section focused on the most suitable configuration for each specific application, the technical, economic, and environmental analyses considered all reported configurations across the literature to enable a broader comparative evaluation.

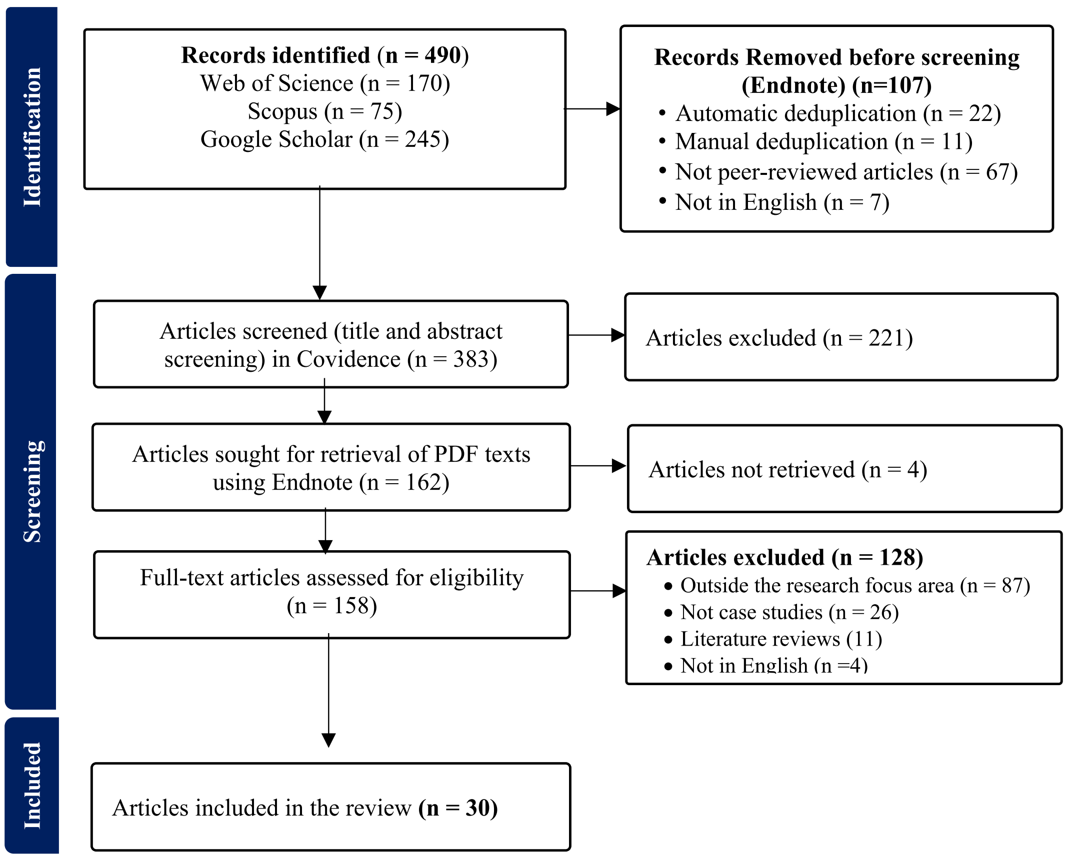

Fig. 2. PRISMA Flow diagram for the systematic review and meta-analysis applied in the study

3.1. Study characteristics

All the articles included in the study were peer-reviewed articles published by a diverse range of journals. The journals Energies and IEEE Access were the most frequently cited ($n = 4$, each), followed by Energies, Sustainable Cities and Society, Energy Procedia, Energy & Environment, Applied Energy, Energy, Energy Procedia, and Sustainable Cities and Society ($n = 2$). The variation reflects a well-rounded approach in selecting sources across multiple dimensions of technology, economics, and sustainability, but with a strong focus on energy. Regarding the publication years, most journals (77 %) were published between 2020 and 2023, as depicted in Fig. 3, indicating a recent surge in research interest in the topic. The peak of ($n = 6$) publications in 2023 and ($n = 4$) publications gathered by July 2024 reflects increasing academic focus on green energy technologies in recent years, likely driven by the growing global awareness and policy initiatives related to the transition to green energy.

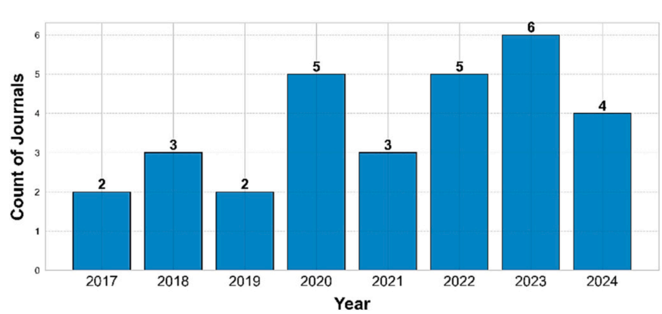

Fig. 3. Distribution of article publications by year.

Further analysis was done to determine the interconnectedness of the papers included in the study. The network diagram in Fig. 4 illustrates the relationships between papers, with publication years plotted against the citation count. The graph shows that over 90 % of the studies are interconnected in terms of content, findings, and research themes. Additionally, recent research is seen to be built upon foundational studies, with the majority of the latter studies referencing influential studies, such as [30], which are represented by larger nodes. This interconnectedness suggests the evolution and progression of knowledge, where more recent studies (represented by lighter colour shades) increasingly draw insights from earlier work (depicted in darker colour shades), thereby advancing research on onsite microgrids and green energy adoption.

3.2. Current microgrid practices

The research examined various microgrid systems, their global application, and common components across agricultural, commercial, communal, industrial, institutional, and residential applications. This analysis aimed to assess current practices and technological advancements in onsite microgrid systems.

3.2.1. Global application of microgrids

Based on the case studies covered by various researchers included in the current study, a map was created to illustrate the global distribution of microgrids by their primary applications across different sectors, including agricultural, commercial, communal, industrial, institutional, and residential, as shown in Fig. 5. Each dot on the map represents the location of a microgrid, colour-coded according to its application type. The size of the dots corresponds to the application's frequency, with smaller dots representing a single occurrence and larger dots doubling in size for each subsequent occurrence.

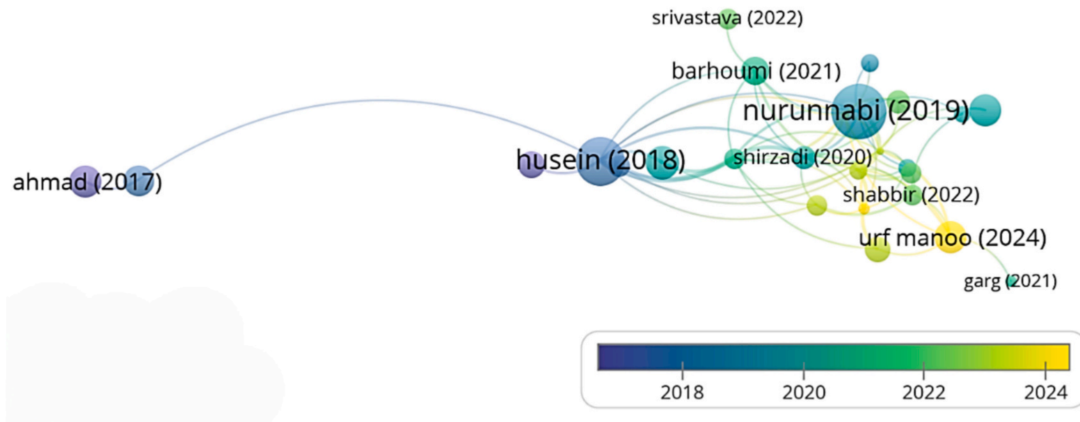

Fig. 4. Citation network of articles included in the study.

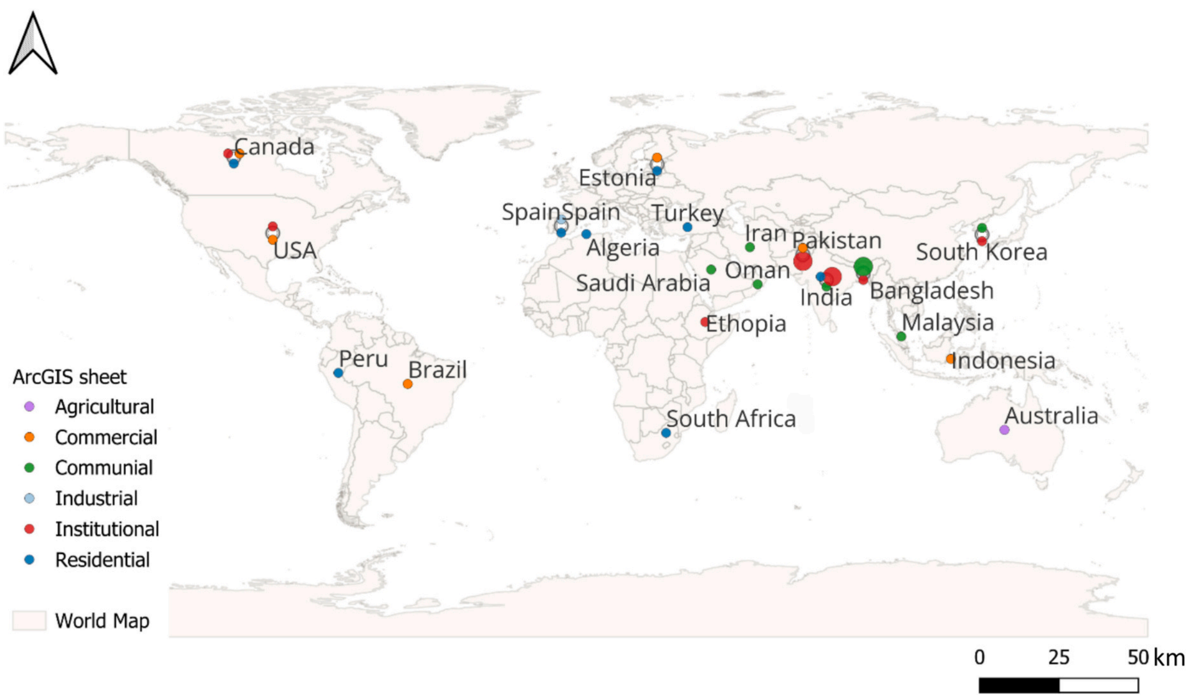

Fig. 5. Global distribution of microgrids by application.

The map clearly shows the diversity and adaptability of microgrids in meeting various energy needs across different regions, with most applications noted in Asia ($n = 18$), Africa ($n = 4$), and North America (n = 4). As denoted by the colour schemes, the majority of microgrids, dispersed across the globe, have been used for institutional purposes ($n = 9$), communal purposes ($n = 8$), and residential purposes ($n = 7$). However, Asia has a mix of applications, with the majority, 44 %, used for communal purposes and 33 % applied in institutions. Another small business application is noted in Brazil, and another is an agricultural application on a farm in Australia. No record was found of the application of microgrids in the construction industry worldwide.

3.2.2. *Technological advancements*

The study categorised the different microgrid configurations and their corresponding applications based on the author and year to understand the trends in microgrid research with emphasis on grid-connected energy systems, as shown in Fig. 6. The studies span from 2017 to 2024, indicating consistency in research interest in microgrids, but with a noticeable increase in studies between 2021 and 2024. Each colour-coded dot represents a study, where colours denote the application type as explained in the legend, and a dot position aligns with a specific system configuration. Configurations like G-PV-WT-BS (Grid-Photovoltaic-Wind Turbine-Battery storage) dominate the chart across all applications ($n = 12$, 40 %), reflecting the widespread adoption of hybrid energy systems that combine solar and wind energy. In addition, the chart highlights more complex configurations in recent years integrating multiple technologies, such as fuel cells in 2023 and electric vehicles in 2024, indicating advancements in microgrid design.

From the visual analysis, it is evident that residential applications (blue) are more frequent across the years, suggesting a consistent interest in household-level energy needs. A noticeable shift occurs in 2023, where institutional (red) and communal (green) applications become more prominent, highlighting a shift from meeting household energy demands towards public and shared energy solutions. The Fig. also reveals that certain configurations are more commonly associated with specific applications. For example, whereas residential and institutional applications predominantly favour photovoltaic (PV) configurations, communal applications tend to lean towards configurations

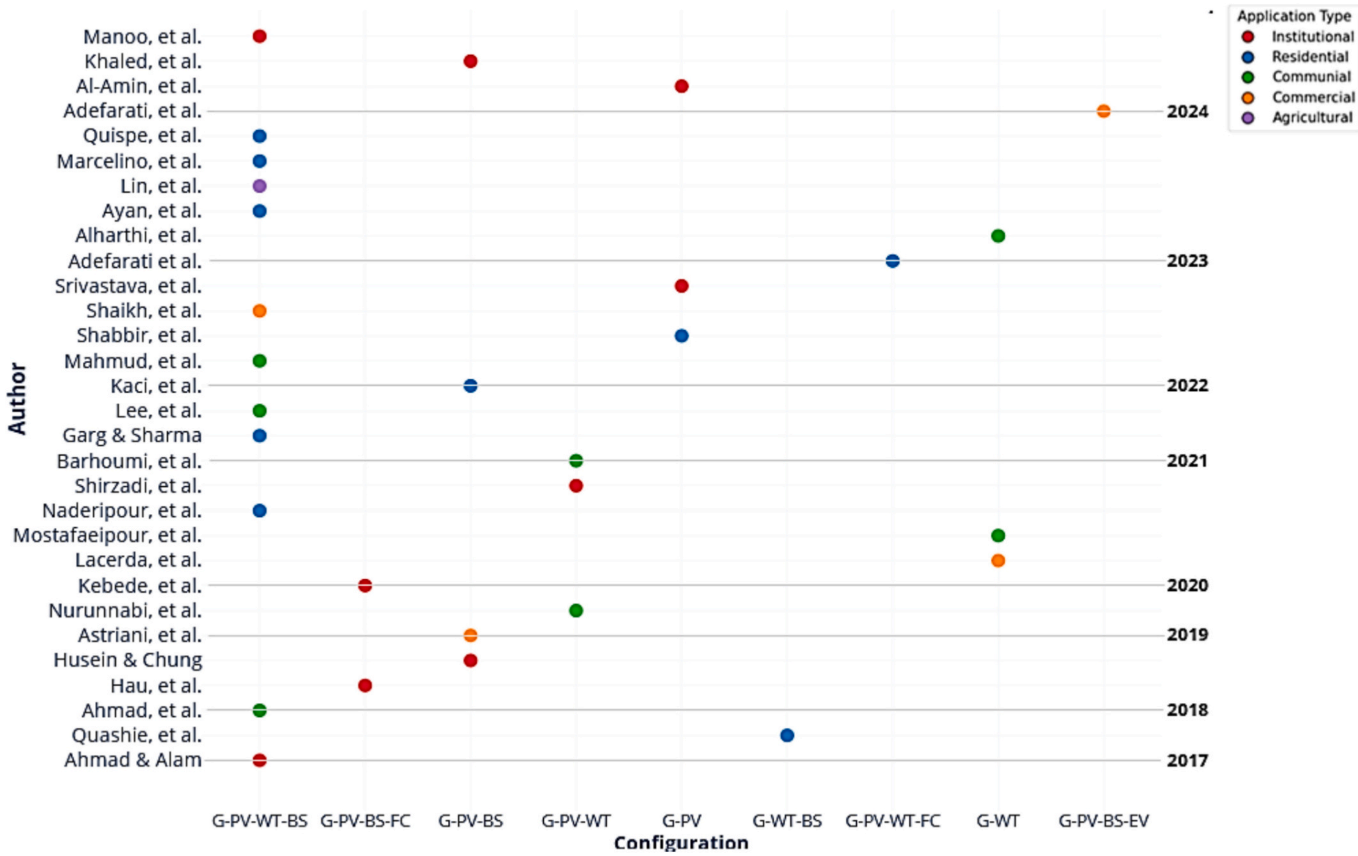

Fig. 6. Evolution of research on microgrid configurations across different sectors – 2015-2024 (Authors are listed alphabetically within each year).

incorporating wind turbines. The relationship between configuration type and application was further examined using the chi-square test of independence, which confirmed a statistically significant association (Pearson $\chi^2(28) = 78.5066$, $p = 0.000$) at the 5 % significance level.

3.2.3. Technical parameters of microgrid components

The technical specifications of the major components that could make up a microgrid, including solar photovoltaic (PV) panels, wind turbines, batteries and converters, were examined to identify common characteristics across sectors that can guide the adaptability of the

Table 1
Technical specifications of microgrid components.

Description	Residential	Commercial	Communal	Industrial	Agricultural
PV Panels					
Type	Flat plate	Flat plate	Flat plate	Flat plate	Flat plate
Capacity (kW)	0.15–3	0.29–1000	50–330	7.3	0.253
Size (mm)	1062x530x35 - 1700x1016x40	1062x530x35 - 1700x1016x40	N/A	N/A	N/A
Efficiency (%)	80–95	15.89–22.7	N/A	N/A	N/A
Lifespan (yrs)	25	25,30	25	N/A	15
Wind Turbines					
Type	Upwind	Upwind	Upwind, Tree shape	N/A	N/A
Capacity (kW)	2–100	3–330	3–1500	30	10
Cut-in speed (m/s)	3,3.5	2.75	2–4	3	3
Cut-off speed (m/s)	20, 25	20	N/A	20	25
Tower height	12–37	16–80	9.9–80	N/A	12
Efficiency (%)	78–95	N/A	78	85	N/A
Lifespan (yrs)	20	20, 25	20, 25	24	20
Battery Storage Systems					
Type	Lead Acid, Lithium-ion	Lead Acid, Lithium-ion	Lithium-ion	N/A	Lithium-ion
Nominal Voltage (V)	12, 21	N/A	1.2	N/A	13.5
Maximum capacity (Ah)	83.4	83.4–202	N/A	N/A	N/A
Round trip efficiency (%)	80	80, 90	80, 90	N/A	90
Maximum charge current (A)	16.7	16.7, 24.3	16.3	N/A	52
Maximum Discharge Current (A)	24.3	24.3	N/A	N/A	52

N/A denotes that the relevant data for the specified component was not reported in the reviewed sources.

components to a construction site setting as summarised in Table 1.

As shown in Table 1, the PV panels documented in the literature used across different sectors exhibit significant variations in capacity, size, efficiency, and derating factors. Flat panel PV systems are the most common type implemented across all applications, with standard sizes but varying manufacturers. However, PV panels in the commercial sector exhibit higher rated capacities, ranging from 0.29 kW to 1000 kW. Lower capacities, such as those below 0.5 kW, have been applied in single-building university applications [34,53,54].

Medium-range capacities, ranging from 125 kW to 550 kW, have been deployed across entire university campuses with multiple buildings [19,23,26,55]. The largest reported capacity of 1000 kW was considered to power one of the largest shopping malls in Arizona [56]. In contrast, residential sector PV panels typically have lower capacities, ranging from 0.15 kW and up to only 20 kW [25,52,54], while communal installations exhibit moderate to high capacities between 50 kW and 330 kW [22,30]. Only one solar panel, a flat plate type with a capacity of 7.3 kW, was extracted for the industrial sector [57]. Interestingly, residential systems demonstrate higher efficiency, with ranges of 80–95 %, compared to commercial systems, which have a range of only 15.89–22.7 %. The standard lifespan for all PV systems is generally noted to be 25 years, with one exception: a 30-year lifespan for the Peimar Inc. flat plate panel manufactured in Italy [23].

Data on the types, capacities, cut-in and cut-out speeds, tower heights, and efficiencies of the wind turbines were gathered to compare the specifications across all sectors. Apart from the Tree Shaped Wind Turbine (TSWT), which was under testing and evaluation [58], most residential and commercial microgrids deploy upwind direct-drive Permanent Magnet Generators (PMGs) turbines with small and medium-sized models, including the Bergey Excel 5 and Eocycle EO10. Larger models, such as the GE 1.5 MW and XANT M-21-ETR, are deployed for communal purposes. Regarding turbine capacity, residential turbines typically range between 2 and 100 kW, commercial turbines range from 3 to 330 kW, and communal turbines range from 50 to 330 kW. The industrial and agricultural turbines typically had capacities of 30 kW and 10 kW, respectively. In terms of operational characteristics, all the turbines had a cut-in speed of at least 2–4 m/s, with cut-off speeds ranging from 15 to 25 m/s. The tower heights also vary depending on the application. In communal and commercial settings, tower heights range from 9.9 m to 80 m, while agricultural and residential turbines are installed at lower heights between 12 and 37 m. Despite these variations, all the turbines, irrespective of application, had efficiency rates ranging from 78 % to 95 %, showing their effectiveness in converting wind energy into electrical power.

Regarding battery storage systems, various technologies have been developed and are used in microgrids to balance generation and demand fluctuations while providing ancillary services, especially when connected to the grid [14] The researchers categorised the systems by the form of energy - mechanical, electromechanical, electrical, chemical, and thermal, or by size - utility-scale (over tens of kW and tens of kWh) requiring a large area or very specific localisations and smaller scalable applications (typically single of kW and single of kWh [36]. Each of these storage technologies differs in parameters such as capacity, charge/discharge rates, and efficiency, factors that can influence their suitability for different applications. Lithium-ion and lead-acid batteries are the most widely used across all sectors. In residential systems, these batteries typically have nominal voltages of 12 V for lead-acid and 21 V for lithium-ion types, with maximum capacities of 83.4 Ah.

Commercial systems, however, exhibit a broader maximum capacity range, from 83.4 to 202 Ah. Communal and agricultural systems, by contrast, had smaller capacities, with nominal voltages of 1.2 V and 13.5 V, respectively. Both residential and commercial systems have comparable maximum charge/discharge rates of approximately 16.7 and 24.2 A, while agricultural systems have much higher rates of 52 A, indicating a higher capability to handle power flows. All systems' charge/discharge efficiencies range from 80 % to 90 %, indicating that a substantial amount of energy is retained in the systems during operation.

3.3. Economic performance of widely adopted microgrid configurations

The economic sustainability of microgrids is crucial in guiding the adaptability of these systems in the construction industry. Several studies have been conducted to determine the economic viability of different energy configurations based on several metrics, including capital costs (CC), replacement costs (RC), operation and maintenance costs (O&M), net present costs (NPC), levelised cost of energy (LCOE), payback period (PBP), discounted payback period (DPBP), net present value (NPV), internal rate of return (IRR), rate of return (ROI) and benefit-cost ratio (BCR) as shown in Table 2.

As depicted in Table 2, most studies have examined CC, O&M costs, NPC, and LCOE for various energy configurations. A few have also investigated the simple PBP of these systems. This insight formed the foundation for a comparative examination of the common parameters influencing the long-term financial viability of different microgrid configurations.

3.3.1. Component costs

The cost of microgrid systems is largely influenced by the expenses associated with key components, including the CC, O&M and RC for solar PV panels, wind turbines, batteries, and other auxiliary elements like converters. This study performed a comparative cost distribution analysis to determine the feasible cost range for each component per unit capacity. Based on the literature gathered, a range of values was obtained and plotted to denote the range of costs and their median, as shown in Fig. 7.

The range of capital cost (CC) for installing different solar PV systems, as shown in Fig. 7, ranged from 110 to $2390/kW, with a median CC of $655/kW, a slightly lower range of replacement cost (RC) from $205 to 1340/kW – a median of $472/kW, and operation and maintenance costs (O&M) of only $10 kW/year. All these costs, as plotted on the box plots, were closely distributed, apart from a few outliers. In contrast to PV systems, wind turbines exhibit a much wider dispersion in costs. Initial capital costs ranged from as low as $ 41.42/kW, attributed to a prototype tree-shaped wind turbine under evaluation in Iran [58], to as high as $6891/kW for a 10 kW turbine applied on the farm in Australia [21]. The median CC obtained was $1773.17/kW, the RC was $1000/kW, and the O&M costs were $25/kW/year. Surprisingly, a 1.5 MW General Electric turbine analysed in Saudi Arabia was cost-efficient with a CC and RC of $400/kW and O&M of only $4 kW/year, despite its large capacity [59].

For battery systems, the cost data showed slight variability, with a median CC of $350 kW, a median RC of $238.34/kW, and O&M costs of $7.50/kW/year. It is also interesting to note that a lead-acid battery analysed by [53] was among the least expensive, with CC, RC, and O&M costs of $60/kW, $50/kW, and $5/kW/year, respectively. In contrast, [33] [54] reported exorbitantly high costs for a similar battery type, with CC, RC, and O&M costs of $9000/kW, $7000/kW, and $270/kW/year, respectively, far exceeding the range of $3.2–15/kW/year reported by other studies, [19,22,26,52,53,55,56,60]. Meanwhile, [23] considered zero or no O&M costs for a Li-ion battery system, suggesting potential cost-efficiency. Except for a few outliers, the costs of converters were relatively consistent. Most studies have placed the cost of converter CC between $200/kW and $400/kW, RC between $150/kW and $400/kW, and O&M between $4/kW/year and $15/kW/year. [33,54], reported extreme values of $7500/kW for CC and RC and O&M costs of $75/kW/year. On the lower end, [17] documented a CC of only $40/kW, which was significantly below the range reported by most authors.

Table 2
Summary of economic parameters studied in microgrid research by the authors.

Author	CC	RC	O&M	NPC	COE	PBP	DPBP	NPV	IRR	ROI	BCR	PI
[56]	√	√	√	√	√	√						
[20]	√	√	√	√	√	√			√	√		
[33]			√	√	√							
[54]	√		√	√	√							
[34]	√		√		√							
[59]				√	√	√	√					
[24]	√							√	√			
[52]				√	√							
[35]				√	√							
[25]	√		√	√	√	√		√		√	√	
[26]	√					√					√	
[19]	√		√									
[27]				√	√							
[23]	√		√	√	√							
[28]								√				
[60]	√		√	√	√							
[21]	√		√			√						
[22]	√		√	√	√	√						
[55]	√		√	√	√							
[57]												
[29]						√	√	√				√
[58]	√	√	√	√	√							
[17]	√		√	√								
[30]				√	√							
[37]											√	
[61]				√								
[31]	√							√				√
[53]	√			√	√	√						
[62]	√		√	√	√							
[63]	√					√	√					

Prob F = 0.0018, R-squared = 0.2294, Adj R-squared = 0.2092.
** Significant at the 0.05 level, *** Significant at the 0.01 level.

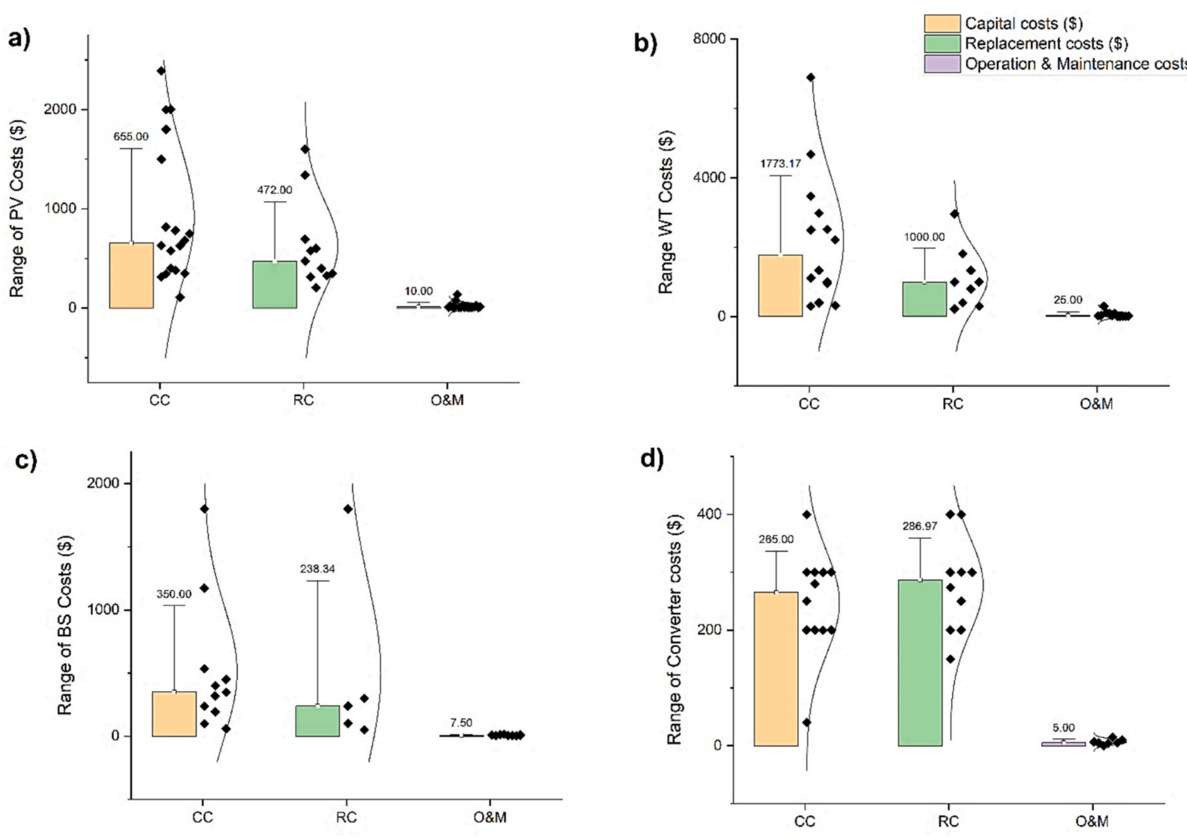

Fig. 7. Box plots comparing the costs of microgrid components: a- PV costs, b- WT costs, c – BS costs, and d – Converter costs.

3.3.2. System costs

The economic performance of the systems was examined based on the NPC and LCOE of the common configurations applied across the different sectors.

3.3.2.1. Net present costs (NPC). The NPC represents the total life-cycle costs of the energy systems discounted to present-day values. It accounts for all costs over the project lifespan, including capital, replacement, operation, maintenance, and sometimes disposal costs. For the current study, only capital costs (CC) and operations and maintenance costs (O&M) of the common configurations - G-PV, G-PV-BS, G-PV-WT, G-PV-WT-BSS, G-WT, and G-WT-BS, were extracted, standardised and presented as graphically shown in Fig. 8.

The graph shows that the G-PV-WT configuration exhibits the lowest median NPC at $1386/kW, with a cost range of $1297 – $2093/kW, indicating relatively low cost variability. This low cost is attributed to its lower capital cost (CC) median of $888/kW and an annual maintenance cost (O&M) of $35/kW, compared to G-PV, which has a higher CC of $967/kW and O&M of $42/kW. The G-PV configuration exhibits a wider cost range of $992 – $16,476/kW, with a moderately low median NPC of $1691/kW. The G-PV-BS and G-PV-WT-BS configurations demonstrate greater cost variability, with wider NPC ranges of $2044 – $35,424/kW and $1894 – $25,913/kW, and median values of $2044/kW and $4820/kW, respectively. Compared to the median of the singular G-PV system, the results reflect an average added cost of approximately 21 %, highlighting the additional cost of integrating battery storage into the G-PV system. The G-PV-WT-BS configuration shows a 248 % increase in median NPC compared to the G-PV-WT configuration; however, this finding could not be substantiated due to insufficient data related to the G-PV-WT-BS configuration. The G-WT configuration recorded the highest NPC range of $1180–$19,872/kW, with a median of $6900/kW, primarily due to its relatively higher upfront costs of $3738/kW and annual operational costs of $69/kW. Not enough data were available for the G-WT-BS configuration, with only [33] reporting the O&M and NPC costs. The scarcity of data on the G-WT-BS configuration may suggest limited deployment, potential infeasibility, or higher costs, which prevent practical implementation.

The Kruskal–Wallis equality-of-populations rank test was conducted to assess differences in NPC across the five configurations - G-PV, G-PV-BS, G-PV-WT, G-PV-WT-BS, and G-WT. The test results showed no significant differences with $\chi^2(4) = 7.127, p = 0.1293$, at a 5 % significance level. Therefore, the null hypothesis was accepted, indicating that there was no statistically significant difference in NPC across the five microgrid configurations.

3.3.2.2. Levelised cost of energy (LCOE). LCOE, a crucial economic indicator representing the average cost required to produce one unit of electricity, was used to assess the cost-effectiveness and competitiveness of the different energy configurations. The heat map in Fig. 9a visually represents the median LCOE (in US$ per kilowatt-hour (kWh)) for different microgrid configurations with bin ranges of 0.05 $/kWh as reported in the literature. The colour gradient indicates the LCOE values, with blue representing lower costs and red representing higher costs.

As shown in Fig. 9a, the G-PV configuration exhibited the lowest cost range of $0.0349 – $0.1172/kWh, with a moderate median of $ 0.0687/kWh. In comparison, the G-PV-WT configuration displayed a wider cost range, with a minimum value of $0.0262/kWh reported by [52] and a maximum of $0.1667/kWh observed at one of the locations studied by [30]. Despite this variability, it had the lowest median cost of 0.0109 $/kWh. The G-PV-BS configuration had a cost range of $0.0183 to $0.1460/kWh, with a median of $0.0563/kWh. Similarly, the G-WT-BS configuration had a moderate range, between $0.1408 and $0.1951/kWh, but recorded the highest median value of $0.1680/kWh. In contrast, the G-WT and G-PV-WT-BS configurations presented wider cost ranges of $0.0481–$0.2852 and $0.0128–$0.1620/kWh, with corresponding medians of $0.1262 and $0.0704/kWh, respectively.

On running the Kruskal–Wallis equality-of-populations rank test on all six configurations - G-PV, G-PV-BS, G-PV-WT, G-PV-WT-BS, G-WT, and G-WT-BS, the test results showed there were significant differences in LCOE with $\chi^2(5) = 25.822$, $p = 0.0001$ at 5 % significance level.

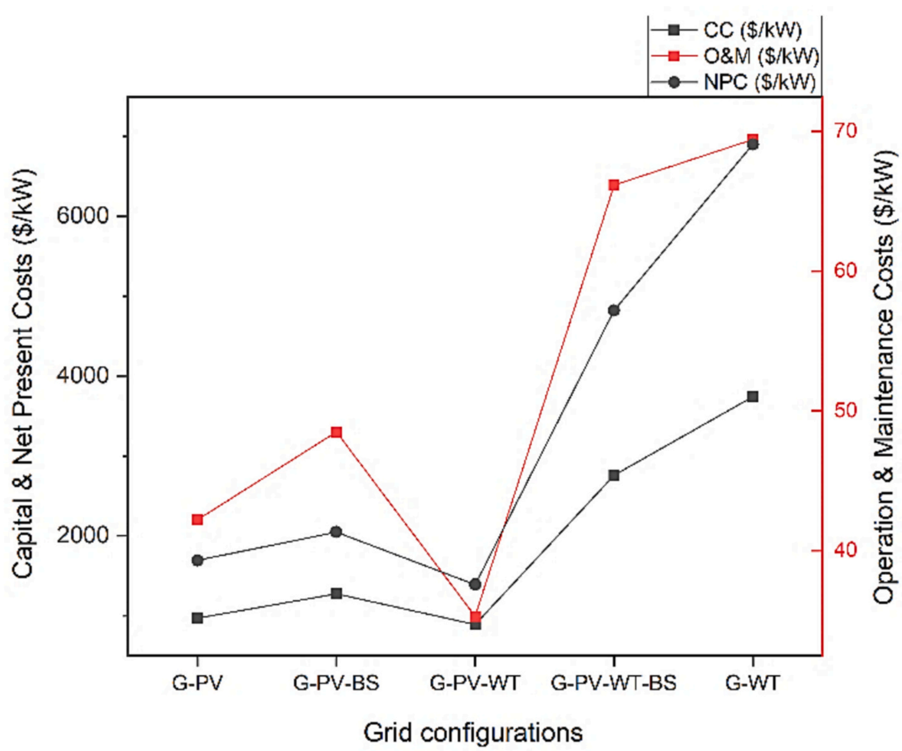

Fig. 8. Comparative analysis of Life cycle costs across different microgrid configurations.

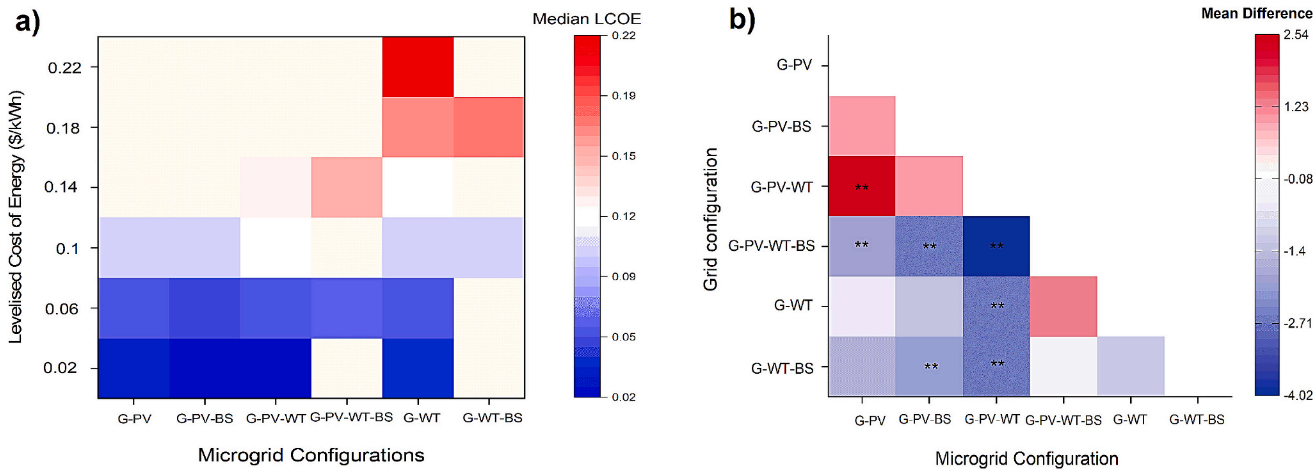

Fig. 9. a - Comparative analysis of LCOE across different microgrid configurations (Royal blue represents – none), b - Mean difference of LCOE across different microgrid configurations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Therefore, the null hypothesis was rejected, indicating that at least one microgrid configuration shows a significant difference in LCOE. This was followed by the Dunn test to identify specific configurations with significant differences. The resulting *Z*-scores and significance levels are presented in the heat map in Fig. 9b. The colour scale indicates the magnitude and direction of the mean differences: red shades represent positive differences (where the column configuration has a higher LCOE than the row configuration), while blue shades indicate negative differences (vice versa). Darker colours signify larger differences, while lighter colours denote more minor differences. Significant differences at a 5 % confidence level are marked with double asterisks (**).

Based on the Dunn test, significant mean differences in the LCOE exist among various microgrid configurations. The analysis reveals that the G-PV-WT configuration differs from all other configurations, except for the G-PV-BS. However, the most notable positive difference is observed between G-PV and G-PV-WT, as indicated by the intense red colour, suggesting that the LCOE of G-PV is significantly higher than that of the G-PV-WT. In contrast, a strong negative mean difference is evident between G-PV-WT and G-PV-WT-BS, as indicated by the darker blue shading, which suggests a significantly lower LCOE for G-PV-WT compared to G-PV-WT-BS. Significant differences are also observed between G-PV-BS and G-WT-BS, with the former having a lower LCOE compared to the latter configuration. It is also noted that whereas the addition of BS to G-PV configuration lowers the LCOE, its addition to G-PV-WT and G-WT configurations increases their LCOEs.

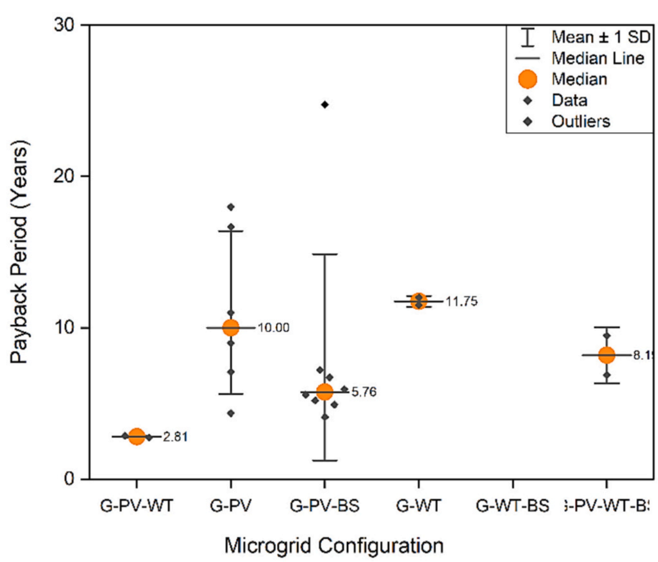

Fig. 10. Comparative analysis of simple Payback Period across different microgrid configurations.

3.3.2.3. Payback period. The Payback Periods (PBP), expressed in years, were examined to evaluate the amount of time required for different energy configurations to recover their initial investment through cost savings or revenue generation, as shown in Fig. 10. Most of the researchers focused on calculating the simple payback period. However, [59] and [63] extended their analysis by comparing the discounted payback (DPBP) period to the simple payback period. These studies revealed slight deviations between the two metrics, with DPBP accounting for the time value of money which covers inflation and changes in interest rates over time.

The interval plot in Fig. 10 illustrates the payback periods (PBP) in years for different micro configurations, displaying their median values with error bars representing one standard deviation. Although the medians of G-PV-WT, G-WT, and G-PV-WT-BS are based on only two data points, each finding provides valuable insights into the economic performance of these systems. The most widely studied configurations are G-PV ($n = 6$) and G-PV-BS ($n = 8$) configurations. Among the configurations, G-PV-WT exhibits the shortest PBP with a minimum of 2.75 years [56], a maximum of 2.86 years [53], and a median of 2.81 years. In contrast, G-WT records the longest PBP, with a median of 11.75 years, a minimum of 11.5 years [59] and a maximum of 12 years [28]. The G-PV-WT-BS configuration shows a median PBP of 8.19 years, with a minimum of 6.88 years [27] and a maximum of 9.49 years [24]. G-PV-BS shows a relatively narrow range from 4.1 to 7.22 years, except for a significant outlier of 24.75 years reported by [22] for a communal microgrid system in Bangladesh. Despite this, the configuration achieves a relatively low median of 5.76 years. In contrast, the G-PV configuration displays the most diverse payback period, ranging from 4.36 to 18 years, with differences of 2 to 3 years between the individual values. Once more, no study reported on the payback period of the G-WT-BS microgrid configuration.

A few researchers, including [59,63], compared the simple payback period and discounted payback period (DPBP) of the configurations. Whereas the former researcher reported a simple PBP of 9 years and a DPBP of 11 to 12 years for a G-WT configuration, the latter researchers compared the simple PBP and DPBP of the G-PV configuration, revealing values of 7.1 years and 8.75 years, respectively. These results generally indicate a 22 % incremental effect on the time value of money.

The variation in PBP across the five configurations - G-PV, G-PV-BS, G-PV-WT, G-PV-WT-BS, and G-WT was further tested using the

Kruskal–Wallis equality test. The results showed no significant differences $\chi^2(4) = 8.267, p = 0.0823$ at 5 % significance level. Therefore, the null hypothesis was accepted, suggesting that there is no statistically significant difference in PBP across the different microgrid configurations.

3.4. Impact of Prosumer energy adoption on decarbonisation of the construction industry

As the construction industry shifts towards sustainability, adopting prosumer energy models -where green energy is actively produced and consumed onsite through microgrids - presents a promising pathway. The section examines the potential impact of prosumer energy adoption on decarbonisation, highlighting key insights that could build confidence among stakeholders who may be sceptical about implementing microgrid technologies on construction sites

3.4.1. Emission reduction potential of microgrids compared to traditional grid-based systems

The environmental impact and emission reduction potential of the different microgrid configurations were graphically assessed in comparison to the baseline - traditional grid-based system, as shown in Fig. 11. The results show that all microgrid configurations substantially reduce emissions compared to the traditional grid-based option. Among the configurations tested, the G-PV-WT exhibited the greatest emission reduction potential with median emission intensities of 0.0943 kg/kWh for CO_2, 0.0007 kg/kWh for SO_2, and 0.0003 kg/kWh for NOx gases, and a CO_2 reduction potential of 0.5715 kg/kWh relative to the grid (85.8 %). Similarly, the G-WT and G-WT-BS also demonstrated strong performances with CO_2 emission intensities of 0.1443 and 0.0002 Kg/kWh. Interestingly, the addition of battery storage (BS) to the G-PV and G-PV-WT configurations resulted in an increase of approximately 28 % in CO_2 emissions (from 0.2796 to 0.3859 kg/kWh), highlighting the need for careful evaluation of the environmental impacts of combining these technologies in microgrid systems.

To further validate these findings, the Mann-Whitney *U* test was conducted to determine the statistical significance of the difference depicted in Fig. 11. The results indicate a statistical significance, with a z-value of 3.984 and a *p*-value of 0.0001, which is well below the 0.05 significance level. The rank sum comparison further supports this finding, as the traditional grid-based system had a much lower expected rank sum (196) than its observed rank sum (340), whereas the microgrid systems had an observed rank sum (836) that was lower than their expected rank sum (980). This suggests that microgrid configurations generally produce significantly lower carbon emissions than the grid-based system, allowing the rejection of the null hypothesis (H0) and concluding that microgrid adoption has a significant impact on emissions.

The study further quantified the emission reduction potential by analysing the relationship between the share of RE (RE%) and CO_2 emissions to examine whether higher RE% leads to even greater emissions reduction, as well as the magnitude of reduction, as shown in Table 3.

The regression results indicate an intercept of 0.2982 kg CO_2/kWh per year when RE% = 0, corresponding to the traditional grid-based systems. The RE% LCOEfficient of 0.2381 kg CO_2/kWh indicates that every 1 % increase in RE% produced for use onsite reduces CO_2 emissions by 238.1 g/kWh. The negative sign confirms the inverse relationship between RE% and CO_2 emissions. The large t-value ($-3.36 < -2$) and the *p*-value ($0.002 < 0.05$) indicate that the relationship is

Table 3
Summary of general regression analysis.

	LCOEfficients			
C02 (kg/kWh)	LCOEf. (B)	Std. Error	t	P > |t|
Constant	0.2982	0.0418	7.13	0.000***
RE%	−0.2381	0.0708	−3.36	0.002**

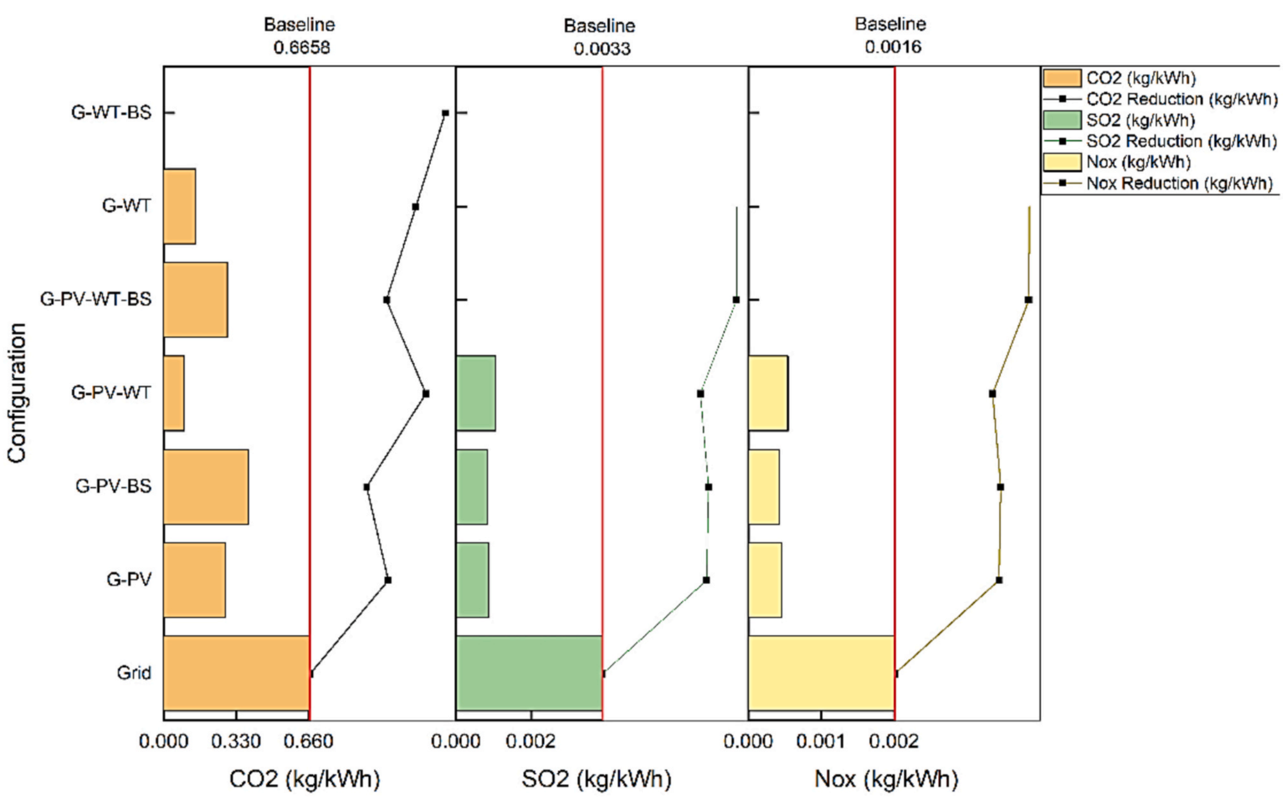

Fig. 11. Comparison of emission reduction in microgrids vs. traditional grid-only systems.

statistically significant, confirming that prosumer energy adoption through microgrid systems plays a substantial role in reducing emissions.

3.4.2. Assessment of carbon emission reduction across various microgrid configurations

Building on the results presented in Table 3, further regression analysis was conducted to assess the carbon reduction potential of prosumer energy adoption across various microgrid configurations. Separate linear regressions were conducted for each configuration to examine their effect of RE% on carbon emissions, giving results presented in Table 4.

The table presents the results of individual regressions for different microgrid configurations, examining their effect on carbon emissions. The G-PV and G-PV-WT configurations demonstrate significant relationships between RE% and carbon emissions, as evidenced by *p*-values less than 0.05 for their respective coefficients (B). The negative LCOEfficients of RE% suggest that increasing RE penetration generally reduces CO_2 emissions at varying levels. Specifically, the G-PV configuration has a LCOEfficient of −0.336 (*p*-value = 0.037), while G-PV-WT has a LCOEfficient of −0.200 (p-value = 0.000), indicating a stronger statistical significance for the latter. In contrast, the G-WT-BS configuration presents a statistically significant intercept but a non-significant RE% LCOEfficient, most likely due to insufficient data. Similarly, the G-PV-WT-BS and G-WT configurations were not assessed due to insufficient data. On the contrary, the G-PV-BS configuration lacks statistical significance, showing no apparent reduction in emissions. Based on the findings, the study affirms that carbon reduction potential varies across different microgrid configurations. This confirms the hypothesis that at least one microgrid configuration has a distinctly different carbon reduction potential compared to other configurations.

4. Discussion

4.1. Synthesis of findings: Technical, economic, and environmental implications

The study highlights the increasing reliance on microgrids for energy provision across various sectors, with a notable shift from residential to commercial, institutional, industrial, and even agricultural applications. These deployments are geographically dispersed, leveraging various RES and technological advancements that influence the configuration choice. Various energy configurations were observed across all sectors, with the most common being the G-PV and G-PV-WT, where the selection was significantly associated with application type and location. Residential and institutional setups predominantly used PV systems, while communal applications leaned more towards WT configurations. This could be attributed to the distinct size, installation, and spatial requirements. Due to the ease of rooftop installation, PV systems are more practical for institutional settings. In contrast, communal applications favour WT systems, which often require larger physical sizes and larger land areas and usually offer collective benefits gained from collaborative deployment. Technical parameters such as component size, capacity, and efficiency varied significantly with the application, with commercial and communal applications exhibiting broader capacity ranges, reflecting their diverse energy demands. However, limited data on industrial and agricultural applications hindered comprehensive performance assessments. The findings suggest that the choice of microgrids for use on construction sites depends on location-specific factors, such as the availability of RE, site size, and energy requirements.

A comparative economic analysis was conducted to assess the feasibility of the most common microgrid configurations using the Net Present Cost (NPC), Levelised Cost of Energy (LCOE), and payback period (PBP) as key metrics. Regarding the component costs, wind turbines (WT) exhibited the highest costs with CC, RC, and O&M costs, which were about 60 % higher than PV systems. Despite the higher component costs, the WT, when combined with PV systems in a hybrid G-PV-WT configuration, showed superior economic performance, with a low median of $ 1212/kW, LCOE of $ 0.0275/kWh, and PBP of 2.81 years. Statistical analysis revealed no significant differences in NPC or PBP among configurations, indicating no clear economic advantage based on the two metrics. This could be attributed to the variability of values obtained from the literature, which represents different applications and locations. Regarding LCOE, the G-PV-WT once again demonstrated the lowest value, over 50 % lower than other configurations, confirming its cost-effectiveness and competitiveness in energy production. Integrating battery systems (BS) was also found to increase system costs by approximately 21 % for the G-PV system, emphasising the need for strategic decision-making regarding the inclusion of BS.

Upon analysing the environmental performance of microgrid systems compared to traditional grid-based systems, the findings indicate that microgrids offer substantial carbon reduction potential; for every 1 % increase in onsite RE production, annual emissions decrease by approximately 238.1 g CO_2/kWh. Given the baseline emissions of 0.2982 kg/kWh (when RE% is 0 %), this reduction represents approximately an 80 % decrease in emissions per 1 % increase in RE production annually. Further examination of the carbon reduction potential of the different microgrids reveals that the G-WT-PV configuration achieves the highest emission reduction, reaching up to 91 % compared to the other configurations. This shows the environmental benefits of integrating wind and solar energy into microgrids. These results underscore the substantial carbon reduction potential of microgrid systems, especially the G-PV-WT system. As the RE% increases, CO_2 emissions decrease significantly, reinforcing the role of prosumer energy adoption through microgrids in advancing the construction industry towards NZCC goals.

These findings are consistent with previous studies while also highlighting contextual differences. [54] identified the G-PV-BS configuration as the most cost-effective option for a university setting compared to G-WT-BS. Similarly, [35] concluded that hybrid-grid-connected systems, particularly the G-PV-BS system, offered the lowest LCOE. However, nuances arise in comparison to [61], who present a different perspective from a study in rural Peru. Their analysis showed that the G-

Table 4
Summary of configuration-specific regression analysis.

Configuration	Prob F	R-Squared	Coef. (B) (Constant, RE%)	t	P > |t|	Significance
G-PV	0.0368	0.3999	0.4076	5.55	0.000	
			−0.3336	−2.45	0.037	**
G-PV-BS	0.4328	0.3217	0.6386	1.90	0.198	
			−0.5918	−0.97	0.433	
G-PV-WT	0.0003	0.6813	0.2202	7.94	0.000	
			−0.2000	−5.07	0.000	**
G-WT-BS	0.3351	0.1547	0.1661	3.34	0.016	
			−0.1177	−1.05	0.335	

** Significant at the 0.05 level.

PV-WT-BS configuration offered the lowest annual LCOE among hybrid configurations, with minimal variation in performance compared to G-PV-BS and G-PV-WT. Whereas these studies collectively emphasise the efficiency and sustainability performance of a hybrid system, the variations underscore the importance of context-specific assessments in microgrid selection.

4.2. Knowledge gaps and future directions for microgrid deployment in construction

Despite the growing attention and significant progress in microgrid research and deployment across residential, commercial, institutional, industrial and even agricultural sectors, the results reveal the critical gap that remains in understanding their application within construction site operations. Construction projects present transient demand profiles and other unique features, including their temporary nature, logistical challenges, and regulatory context that differentiate them from permanent infrastructure. The current literature lacks empirical studies and documented case studies of microgrid deployment during the construction phases of projects. Key knowledge gaps that have been identified include:

- Insufficient understanding of the requirements for microgrid components and design in dynamic site environments.
- Lack of decision-making frameworks tailored to temporary energy systems and short project durations, and
- Lack of a guiding framework for implementing the prosumer concept on construction sites.

Addressing these gaps is critical to help the construction sector transition from diesel generators to not only consuming, but also producing and supplying clean RE. The following sections examine the key factors influencing microgrid deployment and prosumer energy adoption in construction sites and propose practical guidelines to support this transition.

4.3. Factors influencing the choice of microgrid configuraions

4.3.1. Cross sector considerations

The findings reveal that microgrid configurations vary significantly across different sectors and locations. The choice of microgrids is primarily influenced by an interplay of several factors, including technical, economic, environmental, social, regulatory, and site-specific considerations.

a) Technical and operational considerations: Microgrid configurations are primarily shaped by the technical requirements of the target sector, encompassing system design, energy storage, power quality, grid integration, and the ability to operate in islanded mode. For example, while industrial microgrids prioritise resilience and high power quality to support energy-intensive processes often requiring hybrid AC/DC architectures and advanced storage systems [17,18], residential and commercial applications tend to emphasise RE integration, demand side management, and net-metering mechanisms to optimise self-consumption and grid interaction [53,57]. Furthermore, new emerging technologies, such as smart controls and other energy generation methods, are reshaping the possibilities of microgrids. For example, [58] demonstrated that an innovative tree-shaped wind turbine can enhance RE integration, particularly in urban areas with limited space. However, before deployment on construction sites, contractors must ensure compatibility with existing infrastructure to ensure the robustness and reliability of the selected microgrid systems.
b) Economic and financial factors: Economic factors such as capital costs, operational and running costs, payback periods and other related costs of integrating RE are central to determining the feasibility of different configurations. Studies highlight that sectors with high energy demand variability, such as commercial buildings, benefit from hybrid RE sources combining PV-WT and BS to reduce costs [20,23]. Additionally, the availability of government incentives, feed-in tariffs, and other cost-reduction strategies has also proven to influence configuration choices [32]. However, [64] argue that the economic feasibility of onsite microgrids hinges on optimising system configurations to minimise LCC. Thus, evaluating the total cost of ownership and potential savings can guide construction stakeholders in deciding whether an onsite microgrid is economically viable compared to the traditional grid system or diesel generators.
c) Environmental considerations: The growing emphasis on achieving NZC targets has influenced the adoption of microgrid configurations that maximise RE penetration and minimise carbon emissions [4,5]. This is particularly important in the construction sector, where integrating RE in green building practices requires configurations that balance construction energy use and long-term operational sustainability [6].
d) Socio-political and regulatory context: Policy and regulatory frameworks, as well as social attitudes, significantly influence the selection and deployment of microgrids. Prosumers' microgrids heavily rely on favourable energy policies, social acceptance, and participatory site selection processes [65]. [58] note that supportive policies such as RE incentives and streamlined permission processes facilitate microgrid adoption. Similarly, studies conducted in Kenya by [38,39] in Greece underscore the importance of public awareness and acceptance in successful microgrid adoption and sustainability. Thus, for construction sites, engaging local stakeholders, including physical planners, local authorities, and the nearby community, can help secure approval and ensure the smoother implementation of microgrid systems on construction sites.
e) Site-specific energy profiles: Site-specific energy profiles, including demand patterns, peak demand periods, and user behaviour, have been identified as key factors in determining the appropriate capacity and mix of energy resources. While residential and institutional sectors predominantly favour PV-based systems due to their moderate and predictable loads, commercial and communal settings often deploy hybrid PV-WT systems reflecting larger, more variable energy requirements, and access to open spaces required for wind installations. Alongside [19] who emphasise the importance of understanding the actual energy consumption of a site, [20] highlight that changes in energy demand should play a crucial role in designing microgrids. This means that instead of using a standard setup everywhere, it is better to customise each microgrid to fit the specific energy needs of each site. Therefore, it is essential for construction sites to tailor microgrid configurations to the unique size and energy requirements of each site, rather than adopting a one-size-fits-all approach. Conducting an initial energy audit of both typical and peak loads can help contractors and developers select microgrid configurations that match their operational needs.
f) Geographic and climatic conditions: Geographic and climatic conditions affect the availability and reliability of RE sources. [21,35] demonstrate how local weather patterns and resource availability affect the techno-economic sizing of microgrid systems. While locations with high solar irradiance favour PV systems, regions with reliable wind resources support WT system integration, and those with complementary solar and wind profiles support hybrid configurations. Thus, assessing local climatic conditions at the construction site helps identify the most feasible resources and plan for any future seasonal variations that may occur during the entire construction phase.

4.3.2. Architectural and site-specific considerations for construction sites

While broader technical, economic, social and policy factors influence the overall feasibility and selection of microgrid systems, architectural and physical site features are also fundamental in determining how microgrid systems are designed, configured, and integrated, especially as temporary and modular energy solutions for construction sites. According to [12], microgrid architecture, including its physical layout, component siting, and interconnection, must be tailored to match specific constraints and opportunities of each site. The nature and size of the construction, site layout, available footprint, and installation type (fixed or temporary) are among the key architectural elements that need to be considered, as they directly influence the spatial deployment, operational flexibility, and usability of microgrids. For example, crowded urban construction sites often face space constraints, limiting the deployment of ground-mounted PV arrays or wind turbines. In such cases, rooftop or pole-raised PV systems can be adopted to optimise space.

In contrast, rural or large-scale infrastructure projects, such as road construction, typically offer ample space that allows for the flexible deployment of larger PV, WT, or hybrid PV-WT systems. On the other hand, the dynamic and temporary nature of most construction sites means that microgrid solutions must be quick to set up, easy to dismantle, transport, and re-use. This flexibility is particularly important for projects with multiple phases or at different locations, where energy systems must adapt without causing high reinstallation costs. The influence of such architectural and site-specific design constraints on system selection is well illustrated in several case studies. For example, [66] highlights the need for compact and vertically integrated energy solutions in especially dense urban construction zones. Similarly, they emphasises need for flexible and relocatable energy setups for temporary installations, such as site offices. However, to make informed decisions, construction project teams need to adopt a balanced approach that considers technical, economic, environmental, social, political, and site-specific factors. Tools incorporating multi-criteria decision-making frameworks, such as weighted scoring or scenario analysis, can help teams select the most suitable configuration.

Real-world case studies illustrating the use of multi-criteria decision support in microgrid planning include a 2023 analysis of Yongxing Island in China done by [67]. The researchers employed HOMER Pro software, along with a reference point method, to identify an optimal microgrid configuration based on economic, resilience, energy, and environmental criteria. Similarly, [68] applied Multi-Objective Particle Swarm Optimisation (MOPSO) to design grid-connected hybrid systems in Sierra Leone, combining PV, WT, BS, biomass, and diesel backup. The model systematically evaluated the technical reliability, economic viability, social, and environmental impacts of enabling policymakers to identify optimal configurations that balance these competing objectives. The case-based tools applied in both studies provide practical guidelines for evaluating trade-offs across configurations to optimise decision-making in complex construction environments.

4.4. *Practical guidelines for selecting construction site microgrid configurations*

The integration of onsite microgrids into the construction phase presents a significant opportunity to reduce carbon emissions and help move the industry towards the NZCC. By leveraging RES, such as solar and wind, along with energy storage systems, microgrids offer construction projects a practical and sustainable alternative, as well as a promising pathway to achieving NZCC. These microgrid systems can be integrated as temporary or fixed onsite energy systems during the construction phase of projects to replace diesel-powered generators, significantly reducing emissions while creating opportunities for business innovation. For example, construction companies can invest in microgrids for both personal use and rental purposes, adding a new dimension of profitability to the industry. Modular systems, conversely, cater to the dynamic nature of construction activities. Their ability to be relocated and re-used across multiple sites maximises their lifecycle value and minimises waste. For example, for the 20–25-year lifespans of most PV panels and wind turbines, construction organisations can amortise costs over several projects spanning 5–10 years, rendering the systems both economically and environmentally viable. However, selecting a suitable microgrid configuration for construction site applications highly depends on project-specific objectives, stakeholder priorities, regulatory frameworks, and technical constraints, such as resource availability and other site-specific factors.

Table 5
Recommended microgrid configurations for construction sites.

Site characteristic	Recommended configuration	Rationale
High solar irradinace, limited space	G-PV, G-PV-BS	Rooftop or pole mounted PV suitable for dense urban sites. Storage adds reliability where grid is intermittent.
High solar irradinace, abundant space	G-PV, G-PV-BS	Ground mounted PV in wide open space. G-PV-BS offers lower LCOE and shorter PBP, while G-PV reduces emissions by ~15 %.
Abudant solar and wind resources	G-PV-WT	Maximises renewable generation with superior technical and environmental performance.
Short project duration	G-PV (portable modules)	Low upfront cost, quick to deploy, and easy to remove after project completion.
Large infrastructure project	G-PV-WT-BS	High capacity, resilience, and storage to support energy-intensive, long-term construction activities.
Emission reduction priority	G-PV-WT	Offers up to 91 % CO_2 reduction for projects targeting environmental sustainability.
Cost minimisation priority	G-PV-BS	Lowest LCOE, faster payback period make it ideal where cost saving is the primary goal.

Based on the current study findings and sectoral insights, the guidelines presented in Table 5 are proposed for selecting microgrid configurations at construction sites. When both wind and solar sources are available in good measure, a hybrid G-PV-WT configuration is recommended due to its superior technical, economic, and environmental performance. This system typically comprises three main components: the national power grid (G), photovoltaic (PV) solar panels, which can be on-ground or pole-mounted, and wind turbines (WT), as shown in Fig. 12. Otherwise, in tropical climatic regions, where solar irradiance is consistently high, both G-PV and G-PV-BS configurations are viable options, depending on the project's objectives, whether economic or environmental impact. If cost minimisation is the primary target, then G-PV-BS is preferable; despite a slightly higher NPC, it offers a lower LCOE and shorter PBP, making it more cost-effective in the long run. Conversely, if environmental sustainability is the primary focus, G-PV is advisable as it results in approximately 15 % lower carbon emissions compared to G-PV-BS. Unfortunately, the limited data on WT systems restricts the research's ability to draw definitive conclusions about the G-WT and G-WT-BS configurations.

4.5. *Pathways to integrating prosumer-based microgrids into construction for NZCC*

To support the transition of the construction sector towards NZCC, the study proposes a conceptual framework that represents a conceptual leap beyond microgrid deployment into prosumerism. It repositions construction sites from a passive consumer to an active prosumer within the energy ecosystem. Here the construction site becomes a primary agent, generating, storing, and selling onsite green energy to promote both operational sustainability and sector-wide decarbonisation. Building on the framework developed by [10], the proposed framework holistically integrates technical, economic, environmental, social and policy dimensions, recognising that the deployment of microgrids on

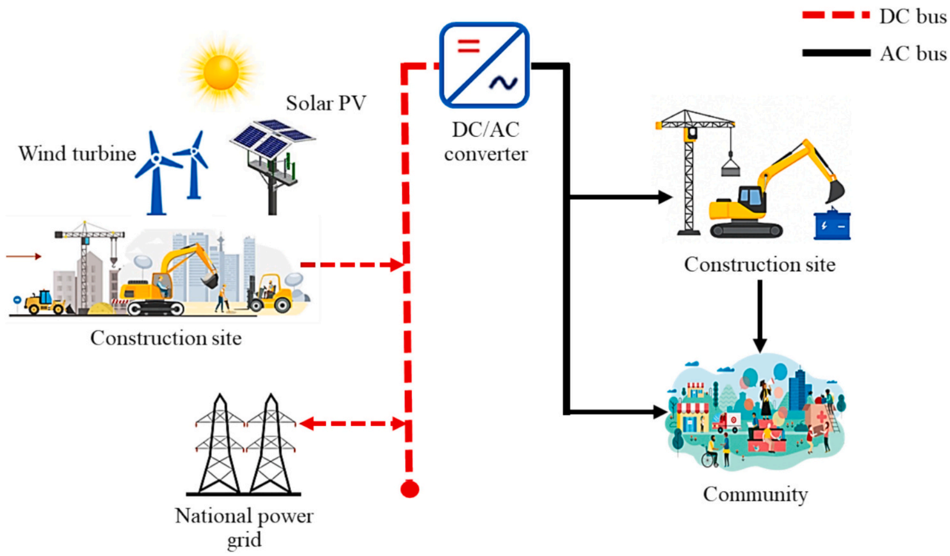

Fig. 12. Schematic diagram of the proposed hybrid power system.

construction sites is not only a technical decision, but also a strategic shift towards sustainability. This prosumer-centric approach enables construction sites to not only meet their energy needs and sustainability goals but also contribute to the decarbonisation of the broader construction industry and support collective Net Zero Carbon targets, as shown in the framework in Fig. 13.

As depicted in the framework in Fig. 13, the adoption of prosumer energy by construction sites enables them to generate RE for their own use and societal use, creating a decentralised low-carbon energy ecosystem. By implementing onsite microgrids, the sites may choose path 1 - to reduce reliance on conventional fuels and integrate RES, including solar PV, wind turbines, and battery storage systems, which, when coupled with offsetting measures like tree planting and carbon capture, can enable them to attain NZC. On the other hand, the site may choose path 2 - to eliminate the use of fossil fuels, relying solely on RES and other sustainable practices for the attainment of zero. Path 2 also depicts that although achieving zero often involves a progression through net zero as an intermediate step, a site can transition directly to zero. In addition to individual site achievement of net zero or zero, the supply of excess energy to the community, path 3, may also enable the community to attain net zero or zero (paths 4 and 5, respectively). This, in turn, will enable the communal or global achievement of net zero (path 6). However, this process involves a combination of mitigation and adaptation that can only be successfully implemented with the right

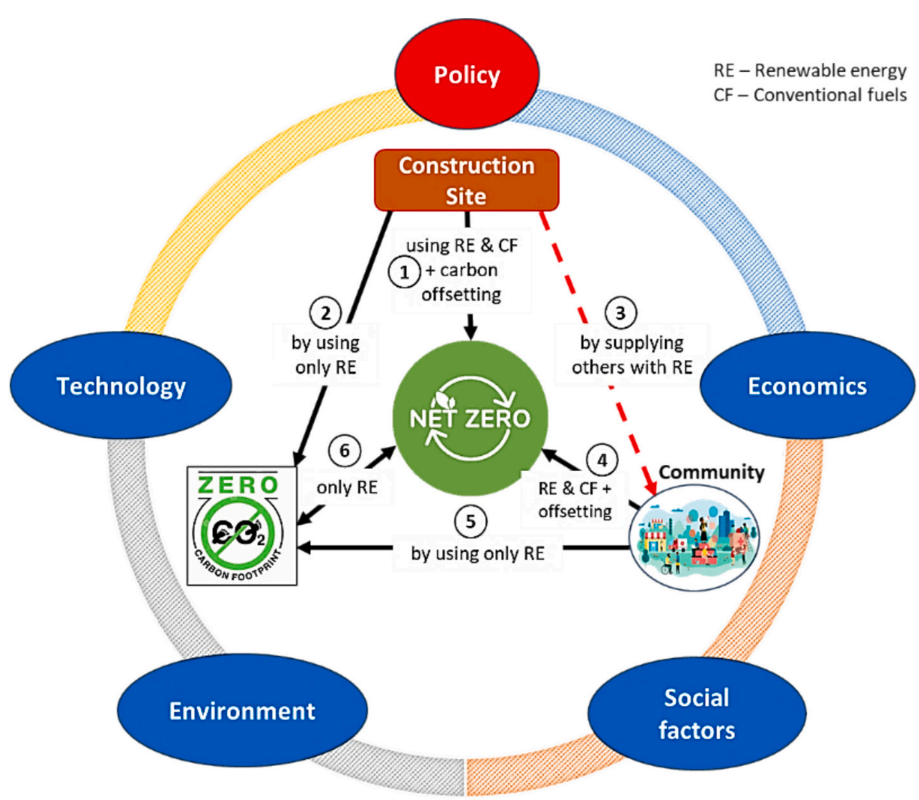

Fig. 13. Integrated prosumer energy adoption framework for achieving Net Zero Carbon.

policies and technical, economic, environmental, and social support from all players, including government, construction organisations/ contractors, and the public. Although [10] considered national conditions, the current research suggests that these can still fall into the policy, economic, technical, or social aspects, and instead considers the environmental factors that highly affect the sustainability and eco-conscious operation of microgrids [69].

5. Conclusion

The study aimed to evaluate and compare the technical, economic, and environmental performance of various microgrid configurations to assess the impact of prosumer energy adoption on the decarbonisation of the construction industry, in line with NZCC goals. The study fills a critical gap in the literature by examining the key factors influencing microgrid deployment and prosumer energy adoption in construction sites, and proposes practical guidelines to support this transition. By systematically analysing existing literature on microgrid application across different sectors and regions, the study was able to reveal that:

1. Microgrids are increasingly adopted across diverse sectors, transitioning from predominantly residential to commercial and industrial applications. However, a notable gap exists in their application within the construction industry, highlighting an opportunity for innovation and research. The G-PV and G-PV-WT configurations are the most prevalent, with technical parameters such as component size, capacity, and efficiency varying significantly based on application and site-specific characteristics.
2. Hybrid configurations, particularly G-PV-WT, demonstrate superior economic performance, with a 50 % lower LCOE and a short PBP of 2.85 years. However, the study emphasises the need for site-specific economic assessments. While integrating BS could enhance system reliability, it increases costs by up to 21 %, necessitating careful cost-benefit evaluation. Environmentally, microgrids contribute significantly to carbon reduction, by up to 80 % compared to traditional grid-based systems. G-PV-WT exhibits the highest carbon reduction potential of up to 91 %, thereby supporting NZC goals.
3. A guide and conceptual framework for prosumer energy adoption in the construction industry is presented, positioning construction sites at the centre of decentralised energy generation and distribution. The framework provides multiple pathways for sites to reduce their carbon footprint by generating their clean energy, selling excess energy to nearby communities, or offsetting emissions through complementary measures. These strategies are shaped by and must be optimised within the broader context of policy, technology, economics, environment and social factors.

Overall, the integration of microgrids in construction projects presents a viable pathway towards achieving NZCC by enhancing energy resilience, reducing emissions, and promoting long-term cost efficiency. However, the proposed framework emphasises the need for a multi-criteria decision-making approach that balances technical, economic, environmental, social, and policy factors to optimise system selection and prosumer energy adoption on construction sites. A key limitation of this review is that variations in national energy policies, regulatory environments, infrastructure capacity, and social factors were not systematically controlled. The focus remained on identifying thematic trends in onsite grid-connected microgrids and their application across the different sectors. These insights not only address the current knowledge gap but also provide a guide for integrating sustainable microgrid solutions into the construction phase of projects. However, to advance this deployment, future research should focus on developing scalable and modular microgrid models tailored to specific site conditions; developing comprehensive energy demand profiles across different project types and pahses to inform system sizing and configuration; investigate modular microgrid architectures that support flexible deployment, conducting cross-country policy and performance comparisons; develop multi-criteria decision making frameworks integrating technical, economic, environmental, and social parameters to guide contractors in optimal microgrid selection; and explore financial and policy mechanisms to support the widespread prosumer energy adoption in the construction industry.

Data access statement

The data associated with this paper are openly available from the University of Leeds Data Repository. https://doi.org/10.5518/1672.

CRediT authorship contribution statement

Racheal Wesonga: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Apollo Tutesigensi:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Krisen Moodley:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare no actual or potential conflict of interest that could have an influence on the work reported in this paper.

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Appendix A. Detailed Selection Criteria and Screening Process

The articles involved in the study were screened based on the following inclusion and exclusion criteria:

- Inclusion criteria - Peer-reviewed journal articles published within the last ten years (2015–2024) to capture recent and relevant advancements in on-site microgrids; research focusing on onsite grid-connected microgrids – to maintain a clear scope aligned with the study's goal of energy production, consumption, and sale of excess energy to nearby communities; studies presenting primary data across all sectors - construction, residential, commercial, agricultural, industrial; articles addressing the technical, economic, social, or environmental dimensions of microgrid applications.While contextual differences in country policies and infrastructure exist, these factors were noted and reported, but not systematically controlled in this review as it aims at thematic generalisation, not strict comparability of national contexts.
- Exclusion criteria – Articles not written in English, studies lacking primary data collection (e.g. review papers or purely theoretical research), research unrelated to renewable energy microgrids or prosumer energy, and papers exclusively focused on non-renewable energy sources or off-grid systems.

Data availability

We have shared the link to our dataset, which has been published by the University of Leeds Library.

References

[1] United nations environment Programme (UNEP). Making peace with nature: a scientific blueprint to tackle the climate, biodiversity and pollution emergencies. United Nations 2021:20. https://wedocs.unep.org/20.500.11822/47214.

[2] Sharrard AL, Matthews HS, Roth M. Environmental implications of construction site energy use and electricity generation. J Constr Eng Manag 2007;133:846–54. https://doi.org/10.1061/(asce)0733-9364(2007)133:11(846).

[3] Palm J, Bryngelson E. Energy efficiency at building sites: barriers and drivers. Energ Effic 2023;16. https://doi.org/10.1007/s12053-023-10088-7.

[4] Chen L, Hu Y, Wang R, Li X, Chen Z, Hua J, et al. Green building practices to integrate renewable energy in the construction sector: a review. Environ Chem Lett 2024;22:751–84. https://doi.org/10.1007/s10311-023-01675-2.

[5] Karlsson I, Rootzén J, Johnsson F, Erlandsson M. Achieving net-zero carbon emissions in construction supply chains – a multidimensional analysis of residential building systems. Dev Built Environ 2021:8. https://doi.org/10.1016/j.dibe.2021.100059.

[6] Yeolekar-Kadam B, Sudarsan &. Feasibility study on integration of green Technologies in Prospective Construction Projects: a case of Vishakhapatnam. Technology, and social sciences (IJMTS) A Refereed Int J Srinivas Univ 2022;7:2581–6012. doi: https://doi.org/10.5281/zenodo.6336679.

[7] United Nations (UN). Department of Economic and Social Affairs: Sustainable Development. The 17 goals, https://sdgs.un.org/goals; 2015 [accessed 16 Sep 2024].

[8] European Commission, (EU).. Study on residential prosumers in the European energy union. G B consortium. https://commission.europa.eu/system/files/2017-11/study-residential-prosumers-energy-union_en.pdf; 2017.

[9] Brown D, Hall S, Davis ME. Prosumers in the post subsidy era: an exploration of new prosumer business models in the UK. Energy Policy 2019:135. https://doi.org/10.1016/j.enpol.2019.110984.

[10] Kotilainen K. Energy prosumers' role in the sustainable energy. System 2020:1–14. https://doi.org/10.1007/978-3-319-71057-0_11-1.

[11] Lin B, Liu H. CO2 mitigation potential in China's building construction industry: a comparison of energy performance. Build Environ 2015;94:239–51. https://doi.org/10.1016/j.buildenv.2015.08.013.

[12] Bullich-Massagué E, Díaz-González F, Aragüés-Peñalba M, Girbau-Llistuella F, Olivella-Rosell P, Sumper A. Microgrid clustering architectures. Appl Energy 2018; 212:340–61. https://doi.org/10.1016/j.apenergy.2017.12.048.

[13] Carpintero-Rentería M, Santos-Martín D, Guerrero JM. Microgrids literature review through a layers structure. Energies (Basel) 2019:12. https://doi.org/10.3390/en12224381.

[14] Farrokhabadi M, Solanki BV, Canizares CA, Bhattacharya K, Koenig S, Sauter PS, et al. Energy storage in microgrids: compensating for generation and demand fluctuations while providing ancillary services. IEEE Power Energy Magazine 2017; 15:81–91. https://doi.org/10.1109/MPE.2017.2708863.

[15] Villa C, Henao F. Oversizing grid-connected microgrids as a business model—an optimisation assessment approach. Energy Rep 2022;8:2100–18. https://doi.org/10.1016/j.egyr.2022.01.117.

[16] Santos AQ, Ma Z, Olsen CG, Jørgensen BN. Framework for microgrid design using social, economic, and technical analysis. Energies (Basel) 2018:11. https://doi.org/10.3390/en11102832.

[17] Naderipour A, Saboori H, Mehrjerdi H, Jadid S, Abdul-Malek Z. Sustainable and reliable hybrid AC/DC microgrid planning considering technology choice of equipment. Sustainable Energy, Grids Net 2020:23. https://doi.org/10.1016/j.segan.2020.100386.

[18] Gutiérrez-Oliva D, Colmenar-Santos A, Rosales-Asensio E. A review of the state of the art of industrial microgrids based on renewable energy. Electronics (Switzerland) 2022:11. https://doi.org/10.3390/electronics11071002.

[19] Husein M, Chung IY. Optimal design and financial feasibility of a university campus microgrid considering renewable energy incentives. Appl Energy 2018; 225:273–89. https://doi.org/10.1016/j.apenergy.2018.05.036.

[20] Adefarati T, Obikoya GD, Sharma G, Onaolapo AK, Akindeji KT. Design and feasibility analysis of grid-connected hybrid renewable energy system: perspective of commercial buildings. Energy Systems 2024;15:403–62. https://doi.org/10.1007/s12667-023-00578-z.

[21] Lin Y, Wang J, Zhang J, Li L. Microgrid optimal Investment Design for Cotton Farms in Australia. Smart grids and sustainable. Energy 2024:9. https://doi.org/10.1007/s40866-023-00184-z.

[22] Mahmud DM, Ahmed SMM, Hasan S, Zeyad M. Grid-connected microgrid: design and feasibility analysis for a local community in Bangladesh. Clean Energy 2022;6: 447–59. https://doi.org/10.1093/ce/zkac022.

[23] Khaled O, Zahid M, Zahid T, Ilahi T. Techno-economic feasibility of hybrid energy systems installation in Pakistan. IEEE Access 2024;12:41643–58. https://doi.org/10.1109/ACCESS.2024.3376409.

[24] Astriani Y, Shafiullah GM, Anda M, Hilal H. Techno-economic evaluation of utilizing a small-scale microgrid. Energy Procedia, vol. 158, Elsevier Ltd; 2019, p. 3131–7. doi: https://doi.org/10.1016/j.egypro.2019.01.1013.

[25] Garg VK, Sharma S. Optimum sizing and economic assessment of hybrid microgrid for domestic load under various. Scenario 2021;11.

[26] Hau VB, Husein M, Chung IY, Won DJ, Torre W, Nguyen T. Analyzing the impact of renewable energy incentives and parameter uncertainties on financial feasibility of a campus microgrid. Energies (Basel) 2018:11. https://doi.org/10.3390/en11092446.

[27] Kebede AA, Berecibar M, Coosemans T, Messagie M, Jemal T, Behabtu HA, et al. A techno-economic optimization and performance assessment of a 10 kWP photovoltaic grid-connected system. Sustainability (Switzerland) 2020:12. https://doi.org/10.3390/su12187648.

[28] Lacerda LS, Junior PR, Peruchi RS, Chicco G, Rocha LCS, Aquila G, et al. Microgeneration of wind energy for Micro and small businesses: application of ANN in sensitivity analysis for stochastic economic feasibility. IEEE Access 2020;8: 73931–46. https://doi.org/10.1109/ACCESS.2020.2988593.

[29] Mohand Kaci G, Mahrane A, Ghedamsi K, Chikh M. Techno-economic feasibility analysis of grid-connected residential PV systems in Algeria. Energy Environ 2024; 35:1936–66. https://doi.org/10.1177/0958305X221146953.

[30] Nurunnabi M, Roy NK, Hossain E, Pota HR. Size optimization and sensitivity analysis of hybrid wind/PV micro-grids- a case study for Bangladesh. IEEE Access 2019;7:150120–40. https://doi.org/10.1109/ACCESS.2019.2945937.

[31] Shabbir N, Kütt L, Raja HA, Jawad M, Allik A, Husev O. Techno-economic analysis and energy forecasting study of domestic and commercial photovoltaic system installations in Estonia. Energy 2022:253. https://doi.org/10.1016/j.energy.2022.124156.

[32] Wang R, Hsu SC, Zheng S, Chen JH, Li XI. Renewable energy microgrids: economic evaluation and decision making for government policies to contribute to affordable and clean energy. Appl Energy 2020:274. https://doi.org/10.1016/j.apenergy.2020.115287.

[33] Ahmad F, Alam MS. Economic and ecological aspects for microgrids deployment in India. Sustain Cities Soc 2018;37:407–19. https://doi.org/10.1016/j.scs.2017.11.027.

[34] Al-Amin M, Hassan M, Khan I. Unveiling mega-prosumers for sustainable electricity generation in a developing country with techno-economic and emission analysis. J Clean Prod 2024:437. https://doi.org/10.1016/j.jclepro.2024.140747.

[35] Barhoumi EM, Farhani S, Okonkwo PC, Zghaibeh M, Bacha F. Techno-economic sizing of renewable energy power system case study Dhofar region-Oman. Int J Green Energy 2021;18:856–65. https://doi.org/10.1080/15435075.2021.1881899.

[36] Jarnut M, Wermiński S, Waśkowicz B. Comparative analysis of selected energy storage technologies for prosumer-owned microgrids. Renew Sust Energ Rev 2017; 74:925–37. https://doi.org/10.1016/j.rser.2017.02.084.

[37] Quashie M, Bouffard F, Joós G. Business cases for isolated and grid connected microgrids: methodology and applications. Appl Energy 2017;205:105–15. https://doi.org/10.1016/j.apenergy.2017.07.112.

[38] Oluoch S, Lal P, Susaeta A, Vedwan N. Assessment of public awareness, acceptance and attitudes towards renewable energy in Kenya. Sci Afr 2020:9. https://doi.org/10.1016/j.sciaf.2020.e00512.

[39] Stephanides P, Chalvatzis KJ, Li X, Mantzaris N, Prodromou M, Papapostolou C, et al. Public perception of sustainable energy innovation: A case study from Tilos, Greece. Energy Procedia 2019;159:249–54. https://doi.org/10.1016/j.egypro.2018.12.058. Elsevier Ltd.

[40] Kuznetsova E, Anjos MF. Prosumers and energy pricing policies: when, where, and under which conditions will prosumers emerge? A case study for Ontario (Canada). Energy Policy 2021:149. https://doi.org/10.1016/j.enpol.2020.111982.

[41] Khan Shahzad, Paul Devashish, Momtahan Parham. Moayad Aloqaily. Artificial Intelligence Framework for Smart City Microgrids: State of the art, Challenges, and Opportunities, IEEE; 2018.

[42] Mojumder MRH, Hasanuzzaman M, Cuce E. Prospects and challenges of renewable energy-based microgrid system in Bangladesh: a comprehensive review. Clean Techn Environ Policy 2022;24:1987–2009. https://doi.org/10.1007/s10098-022-02301-5.

[43] Soudagar MEM, Ramesh S, Yunus Khan TM, Almakayeel N, Ramesh R, Nik Ghazali NN, et al. An overview of the existing and future state of the art advancement of hybrid energy systems based on PV-solar and wind. Int J Low-Carbon Technol 2024;19:207–16. https://doi.org/10.1093/ijlct/ctad123.

[44] Mohanty A, Mohanty S, Satapathy AS, Soudagar MEM, Shahapurkar K, Cuce E. Empowering smart city through smart grid communication and measurement technology. Int J Low-Carbon Technol 2025;20:404–20. https://doi.org/10.1093/ijlct/ctae224.

[45] Kataray T, Nitesh B, Yarram B, Sinha S, Cuce E, Shaik S, et al. Integration of smart grid with renewable energy sources: opportunities and challenges – a comprehensive review. Sustain Energy Technol Assess 2023:58. https://doi.org/10.1016/j.seta.2023.103363.

[46] Mojumder MRH, Hasanuzzaman M, Cuce E. Prospects and challenges of renewable energy-based microgrid system in Bangladesh: a comprehensive review. Clean Techn Environ Policy 2022;24:1987–2009. https://doi.org/10.1007/s10098-022-02301-5.

[47] PRISMA. Flow diagram. https://www.prisma-statement.org/prisma-2020-flow-diagram; 2020.

[48] Littell JH, Corcoran J, Pillai V. Systematic reviews and Meta-analysis. Oxford University Press; 2008. https://doi.org/10.1093/acprof:oso/9780195326543.001.0001.

[49] Kitchenham Barbara. Procedures for performing systematic reviews. 2004.

[50] Wesonga R, Tutesigensi A, Moodley K. Dataset of technical, economic, and environmental parameters of microgrids: A literature-based analysis. Leeds: University of Leeds; 2025. https://doi.org/10.5518/1672.

[51] Federal Open Market Committee (FOMC). Minutes of the board's discount rate meetings on January 21 and 29. Washington, DC: The Federal Reserve; 2015. 2015. https://www.federalreserve.gov/newsevents/pressreleases/files/monetary20250225a1.pdf.

[52] Ayan O, Turkay BE. Techno-economic comparative analysis of grid-connected and islanded hybrid renewable energy systems in 7 climate regions. Turkey IEEE Access 2023;11:48797–825. https://doi.org/10.1109/ACCESS.2023.3276776.

[53] Shaikh A, Shaikh PH, Kumar L, Mirjat NH, Memon ZA, Assad MEH, et al. Design and modeling of a grid-connected PV–WT hybrid microgrid system using net metering facility. Iran J Sci Technol Trans Electr Eng 2022;46:1189–205. https://doi.org/10.1007/s40998-022-00530-4.

[54] Ahmad F, Alam MS. Feasibility study, design and implementation of smart polygeneration microgrid at AMU. Sustain Cities Soc 2017;35:309–22. https://doi.org/10.1016/j.scs.2017.08.007.

[55] Urf Manoo M, Shaikh F, Kumar L, Arıcı M. Comparative techno-economic analysis of various stand-alone and grid connected (solar/wind/fuel cell) renewable energy systems. Int J Hydrog Energy 2024;52:397–414. https://doi.org/10.1016/j.ijhydene.2023.05.258.

[56] Adefarati T, Bansal RC, Shongwe T, Naidoo R, Bettayeb M, Onaolapo AK. Optimal energy management, technical, economic, social, political and environmental benefit analysis of a grid-connected PV/WT/FC hybrid energy system. Energy Convers Manag 2023:292. https://doi.org/10.1016/j.enconman.2023.117390.

[57] Marcelino CG, Leite GMC, Wanner EF, Jiménez-Fernández S, Salcedo-Sanz S. Evaluating the use of a net-metering mechanism in microgrids to reduce power generation costs with a swarm-intelligent algorithm. Energy 2023:266. https://doi.org/10.1016/j.energy.2022.126317.

[58] Mostafaeipour A, Rezaei M, Jahangiri M, Qolipour M. Feasibility analysis of a new tree-shaped wind turbine for urban application: a case study. Energy Environ 2020; 31:1230–56. https://doi.org/10.1177/0958305X19888878.

[59] Alharthi Z, Performance Y. Analysis using multi-year parameters for a grid-connected wind power system. Energies (Basel) 2023;16. https://doi.org/10.3390/en16052242.

[60] Lee HJ, Vu BH, Zafar R, Hwang SW, Chung IY. Design framework of a stand-alone microgrid considering power system performance and economic efficiency. Energies (Basel) 2021:14. https://doi.org/10.3390/en14020457.

[61] Quispe JC, Obispo AE, Alcantara FJ. Economic feasibility assessment of microgrids with renewable energy sources in Peruvian rural areas. Clean Techn Environ Policy 2024;26:1415–38. https://doi.org/10.1007/s10098-023-02463-w.

[62] Shirzadi N, Nasiri F, Eicker U. Optimal configuration and sizing of an integrated renewable energy system for isolated and grid-connected microgrids: the case of an urban university campus. Energies (Basel) 2020:13. https://doi.org/10.3390/en13143527.

[63] Srivastava R, Amir M, Ahmad F, Agrawal SK, Dwivedi A, Yadav AK. Performance evaluation of grid connected solar powered microgrid: a case study. Front Energy Res 2022:10. https://doi.org/10.3389/fenrg.2022.1044651.

[64] Arunachalam RK, Chandrasekaran K, Rusu E, Ravichandran N, Fayek HH. Economic feasibility of a hybrid microgrid system for a distributed substation. Sustainability (Switzerland) 2023:15. https://doi.org/10.3390/su15043133.

[65] Chalaye P, Sturmberg B, Ransan-Cooper H, Lucas-Healey K, Russell AW, Hendriks J, et al. Does site selection need to be democratized? A case study of grid-tied microgrids in Australia. Energy Policy 2023:183. https://doi.org/10.1016/j.enpol.2023.113854.

[66] Vilá C, Martínez M, Palacios F, Anduaga J, García S, García E. Development of portable microgrids to increase flexibility in grid operations. CIRED - Open Access Proceed Jl, vol 2020, Institution of Engineering and Technology 2020:315–8. https://doi.org/10.1049/oap-cired.2021.0045.

[67] Miao H, Yu Y, Kharrazi A, Ma T. Multi-criteria decision analysis for the planning of island microgrid system: a case study of Yongxing island, China. Energy 2023:284. https://doi.org/10.1016/j.energy.2023.129264.

[68] Konneh DA, Howlader HOR, Shigenobu R, Senjyu T, Chakraborty S, Krishna N. A multi-criteria decision maker for grid-connected hybrid renewable energy systems selection using multi-objective particle swarm optimization. Sustainability (Switzerland) 2019:11. https://doi.org/10.3390/su11041188.

[69] Hoummadi MA, Aroussi HA, Bossoufi B, Karim M, Mobayen S, Zhilenkov A, et al. A review of constraints and adjustable parameters in microgrids for cost and carbon dioxide emission reduction. Heliyon 2024:10. https://doi.org/10.1016/j.heliyon.2024.e27489.