Optimal design of a microgrid for carbon-free in-use housing developments: A UK-based case study

Hewitt, J., Sprake. D., Vagapov, Y. and Monir, S.

Recommended citation:

Hewitt, J., Sprake. D., Vagapov, Y. and Monir, S. (2024), 'Optimal design of a microgrid for carbon-free in-use housing developments: A UK-based case study', *Environment, Development and Sustainability*. doi: 10.1007/s10668-024-04695-2

Optimal Design of a Microgrid for Carbon-Free In-Use Housing Developments: A UK-based Case Study

James Hewitt, David Sprake, Yuriy Vagapov, Shafiul Monir

Faculty of Arts, Computing and Engineering, Wrexham University,
Plas Coch, Mold Road, Wrexham LL11 2AW, UK

Abstract: The UK Government's plan to be net-zero by 2050 means that decarbonising the national grid whilst continuing to provide steady and reliable electricity is paramount. The microgrids, formed by a combination of renewable energies, energy storage systems and a connection to the grid can pave the way to changing the UK energy landscape. Microgrids have been providing power to small communities on UK shores for over 20 years. The rationale of this work is to present the optimal microgrid design for new housing developments in various UK locations. The power sources for each case study comprised of wind turbines, photovoltaic panels, hydro turbines, battery energy storage systems and a connection to the grid. Environmental impact, load performance and economic feasibility were key performance indicators when selecting the optimal microgrid design for each location. The objective is to find optimal combinations of wind turbines, hydro turbines, and a connection to the grid for case studies and to demonstrate that microgrids can provide consumers with free, carbon-reduced electricity throughout their 25-year project lifetime, and be funded entirely by consumers alone. Based on this research findings the optimal configuration of the microgrid is determined and analysed; the recommendations for the stakeholders are developed.

Keywords: Renewable energy; Microgrid; Net-zero; Carbon-free; Island mode; Grid-connected; Optimisation; HOMER Pro

Data Availability Statement: All data used in this study for analysis and processing are publicly available on-line. The appropriate on-line hyperlinks to the dataset sources used in this study are available in the list of references. The data produced during this study are tabulated in the manuscript text.

Conflict of Interest Statement: The authors have no conflicts of interest to declare.

1. Introduction

With the ever-increasing costs of electricity and the rising levels of carbon dioxide (CO_2) within the atmosphere, the requirement to decarbonise the UK electrical distribution network has never been stronger. Although recent statistics have identified that UK energy consumption has declined over the past five years (Martin, 2022), there is increasing pressure on the UK Government to reduce its carbon emissions.

At the recent UN COP26, the UK Government committed to decarbonising the electrical distribution system by 2035, which is 15 years earlier than previously set out in the Energy White Paper report (HM Government, 2020). A total of 317.5 TWh of power was generated in the UK in 2018, with 34.6% of this contributed by renewable energy sources. To reach their stated targets, renewable energies need to be contributing at least 60% of the power generated by 2035 (Cossutta et al., 2021).

The rapid advancement of renewable technology has helped to drive down the cost of renewable energies, making it a favourable energy source within the UK. Since 2010, renewable energy generation has increased fivefold and has recently overtaken fossil fuel generation (Martin, 2022). This success has led the government to reassess the current electrical grid and look to decentralise generation by providing a means of local, low-cost, carbon-free energy to consumers (Ofgem, 2016). Recent studies have suggested that long-distance electrical transmission can be costly compared to hydrogen, natural gas, and liquid fuel pipelines (DeSantis et al., 2021). It is estimated that 8% of the UK's generated electrical energy is lost during transmission (UK Parliament, 2015).

A Hybrid Renewable Energy System (HRES), such as a microgrid, is a small-scale localised power grid that comprises at least one renewable energy source and one conventional energy source (Bajpai & Dash, 2012; Pimm et al., 2018; Naz et al., 2021; Hecht et al., 2021). The ability to operate as a standalone system enables microgrids to operate effectively in some of the remotest parts of the world where the national grid can not reach (Brijesh et al., 2019). Microgrids can also operate in grid-connected mode, providing an operational interface with the national grid that provides economic benefits to both consumers and grid operators.

Numerous microgrid projects requiring extensive modelling and optimisation are proposed but at the time of writing no data can be accessed. For example, the UK Royal Mint has signed a tender to produce a microgrid development at Llantrisant, Wales with a long-term power purchase agreement (Hitchens, 2023). Another UK-based development is located at Sellindge in Kent and called Grove Park. This project includes housing and business developments and claims that energy for the project will be produced using renewable sources only with the support of a storage microgrid. The interaction between the system components will be ensured using a smart grid management controller (Curtis, 2023). Quinn Estates is a UK housing developer who works together with SNRG Smart Grids, a microgrid-as-a-service company operating under the "umbrella" of Centrica, which is a major player in the UK energy sector. Following the agreement, SNRG is responsible for the design, finance, building and operation of the privately owned microgrid covering 162 houses in accordance to a recent plan to deliver a housing project (Jackson, 2022). Other microgrid proposal examples around the world include San Diego, where Shell New Energies is developing 8 new microgrids according to a 25-year agreement signed with the San Diego city council and a MyTown microgrid model is being rolled out in small towns in Australia (Howland, 2022).

Community-based microgrid systems have proven to be a success on UK shores, with several systems already operating either as stand-alone systems or with a connection to the main utility grid (Ofgem, 2016). Most of the community microgrids that exist in the UK are based in remote areas where it is difficult for the national grid to reach and where grid outages are likely. The Centre for Alternative Technology (CAT) based in Wales, UK, houses an AC microgrid that has been operational with the grid for over 10 years (Kuriakose, 2011). They have conducted numerous studies on their microgrid system, including the operation of the system in island mode for a month during adverse weather conditions. Their results concluded that a combination of Photovoltaic (PV) modules and a Hydro Turbine (HT) was suitable to power the system during the day, while at night, the system relied on the Battery Energy Storage System (BESS) to provide its power needs (Kuriakose, 2011; Brandeis et al, 2016). The PV roof that is installed at CAT can produce 20kW of power, making it the largest generator out of renewable energies, however, shortfalls have been identified during the winter months due to the UK's winter weather conditions.

Contributing to nearly a third of the UK's carbon emissions (Boardman, 2007), a drastic change to the development of UK housing is paramount. If the UK Government is to reach its zero-emission targets by 2035, sustainable housing developments are vital (Sprake & Vagapov, 2021). Introducing renewable energy-based microgrid systems to the new housing developments will help to reduce carbon emissions and provide consumers with low-cost electricity (Tomin et al., 2022). Recent research (Sprake & Vagapov, 2021) has suggested that the UK public would be willing to pay an additional 1% for a house having lower running costs/carbon emissions, suggesting that if the microgrid is cost-effective then there is a possibility it could be funded by consumers alone.

This paper provides an analysis of the case study aimed to build on the UK microgrid success stories and determine if microgrids can assist in the decarbonisation of the UK power distribution network, by reducing carbon emissions of new housing developments. The number of households in the development selected for the case study analysis is 1000 houses. A 1-hour time span has been used in this analysis as any short-term spikes of demand or supply can be ironed out due to the presence of grid back up or energy storage, and it was considered suitable for this initial feasibility analysis. Breaking down time into smaller increments of say 1 second, also would considerably increase requirements for the computation resources and simulation time. Numerous microgrid locations within the UK are investigated to determine the optimal arrangement of the microgrid whilst adhering to an additional capital of 1% of the total cost of the housing development. An economic, performance and environmental assessment of each microgrid will determine the optimal arrangement for each area.

In the case study, the optimisation, performance, and economic analysis are conducted using HOMER Pro. HOMER (Hybrid Optimisation of Multiple Energy Resources) is a software designed by National Renewable Energy Laboratory (NREL). HOMER is widely used for the analysis of various energy systems and is considered a global standard in microgrid software. HOMER enables the economics and feasibility of microgrids to be analysed using optimisation and sensitivity algorithms. HOMER is commercial software, but it should be noted that other alternatives are available which are open source. All data used for the analysis are open-access and freely available in the public domain. Throughout the simulation process, various system inputs remain common, such as the cost of renewable energy and the load demand profile. However, metrological data and the average cost of UK house prices will vary depending on the location of the microgrid.

The basic concept of the microgrid is similar in all cases, but data on the performance of completed smart grids and its comparison to modelling is limited at present. The findings of this research will contribute to the current state of knowledge and practice in the field of microgrid design and optimisation as it can be contrasted and compared with existing and proposed models and developments.

It is anticipated that this research on microgrid optimisation will be of interest to many stakeholders and decision makers working in the area of design and implementation of advanced energy systems for new housing developments to ensure carbon-free in-use electricity consumption.

2. Case Study

Fig. 1 shows a visualisation of the methodological approach applied to the case study analysis. It demonstrates the algorithmic flowchart designed to determine the optimal arrangement of the microgrid system operating both with the connection to the main grid and in the stand-alone mode (island microgrid).

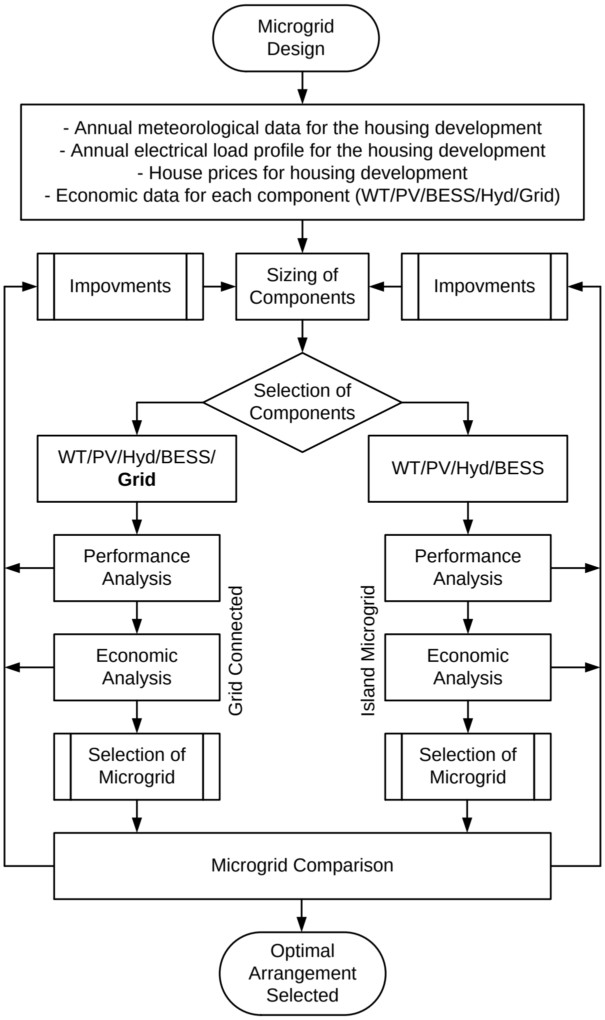


Fig. 1. Algorithmic flowchart to determine the optimal arrangement of the microgrid system.

Fig. 2 details the average household demand during the summer and winter periods within the UK. The load data has been derived from the CREST Demand Model (McKenna et al., 2020) over a 24-hour period during a summer week and weekend in July, and during a winter week and weekend in December. The graph highlights the morning and evening load peaks that occur during a 24-hour period in a household. Noting that the winter peaks are both higher and broader than those measured during the summer months due to an increase in heating and lighting loads. The total load demand of the new housing development is upscaled (by 1,000) from the worst-case scenario shown in Fig. 2 – a winter weekday, this will ensure that the microgrid system is suitably sized to accommodate the maximum loading of the development. For the case study discussed in this paper, the maximum peak demand for the new housing development is 800kW. This figure is based on the assumption that the maximum load of one household is about 0.8 kW.

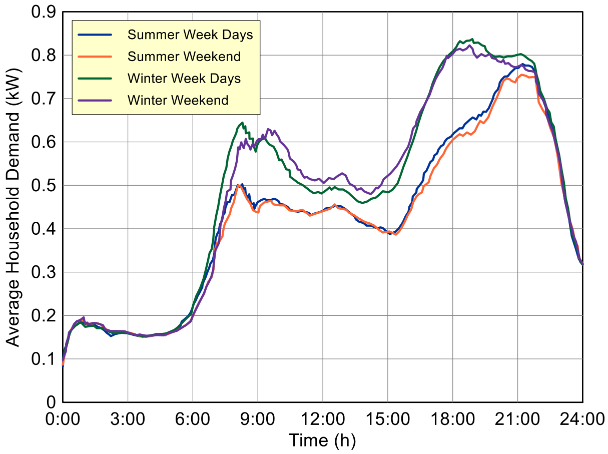


Fig. 2. Average UK household electricity demand for 15,000 households. The graphs visualise the data derived from CREST Demand Model (McKenna et al., 2020).

Table 1. UK Locations of Housing Development

Location	**Hydro Power Source**
Northwest England	River Ribble
Northeast England	River Ouse
Southeast England	River Thames
Southwest England	River Dart
Scotland	River Clyde
Wales	River Dee
Northern Island	River Bann

Due to the varied weather conditions across the UK, numerous microgrid locations have been specified, this will ensure that the optimal microgrid solution is relevant to a localised area. It is assumed that the new location of the housing development will be local to a main river running through the area (Table 1), this enables hydropower to be considered during the optimisation process of the microgrid.

As mentioned above, all historical data on the weather conditions, natural resources, price index etc. used in this analysis are obtained from open access sources and are freely available in the public domain. The data were processed to derive average values required for further computations.

The average monthly temperature (Table 2), wind (Table 3), and solar radiation (Table 4) data for each of the locations were obtained from the NASA Prediction of Worldwide Energy Resource (POWER) database (NASA, 2022). The wind speeds were recorded at an elevation of 50m above the surface of the air over a 30-year period.

During the optimisation process, the average annual wind speed in m/s was utilised for each of the locations. The monthly solar radiation averages were recorded over a 22-year period. The annual solar radiation (kWh/m²/day) was utilised for each of the locations. The monthly average temperature averages were recorded over a 30-year period.

The National Flow River Archive database was utilised to obtain the monthly average stream flow data (Table 5) for each of the main rivers (UK Centre for Ecology and Hydrology, 2022).

Table 2. Monthly Average Temperature (°C); derived from NASA (2022) dataset.

Month	**Northwest England**	**Northeast England**	**Southeast England**	**Southwest England**	**Scotland**	**Wales**	**Northern Island**
Jan	2.7	3.0	5.58	5.9	2.7	3.3	5.45
Feb	2.9	3.3	5.38	5.6	2.9	3.5	5.4
Mar	4.59	5.0	6.65	6.9	4.2	5.2	6.25
Apr	6.82	7.2	8.31	8.6	6.3	7.4	7.73
May	10.15	10.3	11.3	11.6	9.3	10.7	10
Jun	12.9	13.2	13.89	14.3	12.0	13.4	12.26
Jul	14.86	15.3	15.86	16.4	13.8	15.3	14.03
Aug	14.56	15.1	15.97	16.6	13.5	15.1	14.16
Sep	12.24	12.6	14.16	14.9	11.3	12.9	12.82
Oct	9.2	9.5	11.6	12.2	8.5	9.8	10.52
Nov	5.64	5.9	8.4	8.8	5.4	6.3	7.96
Dec	3.44	3.7	6.4	6.7	3.3	4.1	6.21
ANN	8.3	8.7	10.3	10.7	7.8	8.9	9.4

Table 3. Monthly Average Wind Speed (m/s); derived from NASA (2022) dataset.

Month	**Northwest England**	**Northeast England**	**Southeast England**	**Southwest England**	**Scotland**	**Wales**	**Northern Island**
Jan	8.68	9.0	9.27	9.3	9.2	8.5	10.77
Feb	8.46	8.8	8.67	8.7	8.8	8.2	10.35
Mar	7.91	8.1	8.04	8.0	8.3	7.7	9.6
Apr	6.94	7.1	7.34	7.3	7.2	6.7	8.2
May	6.66	6.7	7	7.0	6.7	6.4	7.61
Jun	6.21	6.2	6.56	6.5	6.2	6.0	7.04
Jul	6.25	6.2	6.53	6.5	6.2	6.0	7
Aug	6.39	6.5	6.57	6.5	6.4	6.2	7.27
Sep	7	7.2	7.11	7.1	7.2	6.7	8.28
Oct	7.74	7.9	8.26	8.3	7.9	7.5	9.29
Nov	7.9	8.2	8.45	8.5	8.3	7.7	9.87
Dec	8.21	8.4	9.02	9.0	8.4	8.0	10.14
ANN	7.4	7.5	7.7	7.7	7.6	7.1	8.8

Table 4. Monthly Average Solar Irradiation (kWh/m²/day); derived from NASA (2022) dataset.

Month	Northwest England	Northeast England	Southeast England	Southwest England	Scotland	Wales	Northern Island
Jan	0.67	0.6	0.8	0.8	0.6	0.7	0.57
Feb	1.33	1.3	1.5	1.5	1.3	1.3	1.26
Mar	2.32	2.3	2.5	2.5	2.3	2.3	2.36
Apr	3.65	3.5	3.9	3.9	3.7	3.7	3.98
May	4.9	4.7	5.1	5.1	5.0	4.9	5.32
Jun	4.99	4.7	5.4	5.4	5.1	5.0	5.35
Jul	4.86	4.6	5.3	5.3	4.7	4.9	4.9
Aug	4.01	3.9	5.3	4.4	4.0	4.0	4.14
Sep	2.78	2.7	3.1	3.1	2.8	2.8	2.92
Oct	1.56	1.6	1.8	1.8	1.5	1.6	1.56
Nov	0.81	0.8	1.0	1.0	0.7	0.8	0.72
Dec	0.5	0.5	0.7	0.7	0.4	0.5	0.4
ANN	2.7	2.6	3.0	3.0	2.7	2.7	2.8

Table 5. Monthly Average Stream Flow Data (L/s); derived from UK Centre for Ecology and Hydrology (2022) dataset.

Month	River Ribble	River Ouse	River Thames	River Dart	River Clyde	River Dee	River Bann
Jan	29,100	25,859	22,688	8,843	112,382	2,325	42,688
Feb	81,900	34,929	56,405	16,516	59,246	3,639	127,371
Mar	69,300	84,504	102,005	20,911	36,232	8,215	178,509
Apr	30,100	9,361	16,647	6,470	40,141	1,565	53,227
May	15,300	9,728	16,010	2,982	14,168	728	17,529
Jun	20,200	25,608	42,803	4,327	16,968	3,112	55,584
Jul	10,400	17,382	183,593	2,031	7,673	858	15,040
Aug	8,600	45,569	548,319	5,927	1,457	3,654	54,450
Sep	10,000	67,029	412,316	9,875	24,626	5,655	43,353
Oct	54,000	79,191	141,774	26,740	35,355	5,693	134,554
Nov	155,000	45,432	111,113	28,430	70,602	3,924	141,480
Dec	215,000	75,640	108,826	28,860	65,018	5,994	153,528

Table 6. Average UK house prices in 2022; derived from Lewis (2022) dataset.

Location	Average House Price (Feb 2022)	1% of Average House Price	Microgrid Budget
Northwest England	£197,965	£1,980	£1,979,650
Northeast England	£144,668	£1,447	£1,446,680
Southeast England	£499,249	£4,992	£4,992,490
Southwest England	£420,755	£4,208	£4,207,550
Scotland	£206,000	£2,060	£2,060,000
Wales	£181,000	£1,810	£1,810,000
Northern Island	£165,000	£1,650	£1,650,000

The latest house price data has shown that the UK average house price has increased by nearly 10% in the last 12 months, this rise is mainly due to the impact of the coronavirus pandemic, delays to builds have caused the demand to vastly outgrow the supply (Lewis, 2022). In the UK, the average house price is the highest in the Southeast of England, with the lowest in the Northern Island. Table 6 highlights the initial microgrid capital budget for each of the areas in the UK, and these figures have been derived by applying the research conducted by Sprake and Vagapov (2021) to the UK house price index for March 2022 (Lewis, 2022).

3. Design of Microgrid

For this case study, the microgrid system under review comprises of a hydro-power turbine, solar PV array, wind turbine, lithium-ion battery, AC/DC converter, and a load (Fig. 2). During the optimisation process, simulations run in both island mode and in grid-connected mode to determine if the microgrid system can run as a standalone system.

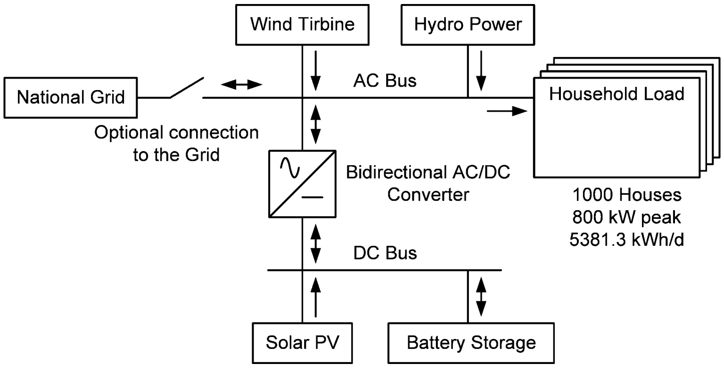


Fig. 2. Microgrid topology applied for the analysis. Optional connection to the grid reconfigures the island mode microgrid into the grid-connected microgrid.

An overview of the microgrid components is presented in Table 7. All parameter figures for each component are based on recent UK market data. The project lifetime has been set at 25 years with an inflation rate of 5% (OECD, 2022).

Table 7. Microgrid technical and economical parameters.

Component	Parameter	Total	Unit
Photovoltaic Flat Plate Panels	Capital Cost	857	£/kW
	Replacement Cost	857	£/kW
	O&M	10	£/kW
	Lifetime	25	Years
	Derating Factor	80	%
Wind Turbine	Capital Cost	777	£/kW
	Replacement Cost	777	£/kW
	O&M	28	£/kW
	Lifetime	20	Years
	Hub Height	65	m
Li-ion Battery Energy System	Capital Cost	550	£/kW
	Replacement Cost	550	£/kW
	O&M	10	£/kW
	Lifetime	15	Years
	Initial State of Charge	100	%
	Minimum State of Charge	20	%
Hydro Turbine	Capital Cost	5290	£/kW
	Replacement Cost	5290	£/kW
	O&M	110	£/kW
	Lifetime	25	Years
	Efficiency	80	%
Power Converter	Capital Cost	190	£/kW
	Replacement Cost	190	£/kW
	O&M	190	£/kW
	Lifetime	15	Years
	Efficiency	95	%
Grid	Purchase Price	0.29	£/kWh
	Sellback Price	0.09	£/kWh

3.1. PV Modules

The power output of the photovoltaic system (P_{PV}) under the neglected influence of ambient temperature can be calculated using a conventional formula shown below (Diaf et al., 2007):

$$P_{PV} = \eta_G k A_M G_{IR} \tag{1}$$

where η_G is the PV efficiency, k is the number of modules in the system, A_M is the area of a single module used in the system (m²), G_{IR} is the global irradiance incident on the tilted plane (W/m²).

Taking into account the derating operational conditions, equation (1) is rearranged to be suitable for simulation in the HOMER software environment (Yousef et al., 2022):

$$P_{PV} = g_{DR} Y_{PV} \frac{G_{IR}}{G_{ST}} \tag{2}$$

where g_{DR} is the derated factor (%); G_{ST} is the sun irradiation for the standard PV test conditions (1000 W/m^2); Y_{PV} is the rated power capacity of the PV installation ($Y_{PV} = \eta_G k A_M G_{ST}$).

Due to the roof space limitations within the housing development, it is estimated that a maximum of 15 of 1m² panels can be installed on a single roof in the housing development. Assuming that 1.5m^2 of a generic flat plate PV selected for the simulation has a rated output power of 200W, the total rated capacity of the PV house installation is 2kW. The solar panels selected for the simulation have a derated factor of 80% (Table 7). The total cost of the PV system (C_{PV}) is proportional to the number of modules k or to the rated power capacity Y_{PV} (Senjyu et al., 2007):

$$C_{PV} = C_{PVM} k = C_{PVY} Y_{PV} \tag{3}$$

where C_{PVM} is the cost of one PV module, C_{PVY} is the cost of PV per 1kW.

3.2. Wind Turbine

The power output of the wind turbine system P_{WT} is calculated using the table data formed into a look-up table to represent the power curve (turbine power output against wind speed). The slope of the power curve is corresponding to the following equation (Jayachandran & Ravi, 2017).

$$P_{WT} = P_R \frac{V_C^n - V^n}{V_C^n - V_R^n} \text{ if } V_C < V < V_R \tag{4}$$

where P_R is the rated power of the wind turbine, V_R is the rated wind speed, V_C is the cut-in wind speed, V is the wind speed at the desired height (h_{WT}) of the wind turbine, n = 3, “cubic” curve (Chang et al., 2014). The wind turbine speed in (3) V can be determined as follows:

$$V = V_{REF} \left(\frac{h_{WT}}{h_{REF}} \right)^{\alpha} \tag{5}$$

where h_{WT} is the turbine hub height, V_{REF} is the wind speed (m/s) at the reference height (h_{REF}), α is the ground surface friction coefficient. The database of the wind speed used for the simulation provides the wind speed readings recorded at the reference height of 50m (h_{REF} = 50m). The actual hub height for the selected wind turbine is h_{WT} = 65m (Table 7).

Taking into account the turbine efficiency, the wind turbine electrical output is

$$P_{WG} = P_{WT} \eta_{WT} \tag{6}$$

where P_{WG} is the electrical power generated by the wind turbine, and η_{WT} is the efficiency of the wind turbine.

During the optimisation process, the wind turbine capacity is capped at 1.5MW to limit initial construction costs. The 1.5MW wind turbine selected for the simulation has a combined tower and blade height of 328 feet (99.9m). Although there are no current published regulations stated by the UK government, the Republic of Ireland states that a wind turbine up to 100m in height shall be positioned 1000 metres away from residential properties (Cave, 2013).

3.3. Hydro Power Turbine

The power output of the HT system (P_{HT}) can be calculated using the following formulas (Keawsuntia, 2011).

$$P_{HT} = mgH_{NET} \eta_{HT} \tag{7}$$

$$\eta_{HT} = \frac{P_E}{P_W} \tag{8}$$

where m is the mass flow rate in (kg/s), g is the gravitational constant (9.81m/s^2), H_{NET} is the gross head minus any pipe loss (15%), η_{HT} is the overall efficiency of the components within the HT, P_W is the hydraulic power (W), P_E is the electric power (W).

Due to the high capital cost, the HT power has been capped at 100kW during the optimisation process.

3.4. Battery Energy Storage System

The required storage capacity of the BESS (C_{BAT}) (W/h) can be calculated using the following formula (Jayachandran & Ravi, 2017):

$$C_{BAT} = \frac{E_L \times AD}{DoD \times \eta_{INV} \times \eta_{BAT}} \tag{9}$$

where E_L is the estimated load in a day for the new development, Autonomy Days (AD) is how long the system can run without recharging, Depth of Discharge (DoD) is how much the batteries will be discharged during operations, η_{INV} is the efficiency of the semiconductor inverter, η_{BAT} is the efficiency of the battery.

4. Economic Analysis for Optimisation

The main economic metrics that will determine the optimal microgrid are the initial capital, the Net Present Cost (NPC), the Cost of Energy (CoE), and the Renewable Fraction (RF). The initial capital will be cross-referenced to Table 6 to confirm the arrangement is feasible.

4.1. Net Present Cost

The NPC is the total cost of the project over its 25-year lifetime, factoring in installation, maintenance, and replacement costs. The total NPC (C_{NPC}) is calculated as (Lambert at al., 2017).

$$C_{NPC} = \frac{C_{ANN,TOT}}{CRF\left(i, N\right)} \tag{10}$$

where $C_{ANN,TOT}$ is the total annualised cost, i is the annual interest rate, N is the number of years of the project lifetime. The capital recovery factor (CRF) is calculated using the following equation (Lambert at al., 2017).

$$CRF\left(i, N\right) = \frac{i\left(1+i\right)^N}{\left(1+i\right)^N - 1} \tag{11}$$

The total net present cost (C_{NPC}) accounts for initial capital costs, such as procurement and construction, maintenance costs, including replacement parts, and the cost of purchasing power from the grid.

4.2. Levelised Cost of Energy

The levalised CoE is defined in HOMER as “the average cost of useful electrical energy produced in the system”. To calculate the levelised CoE (£/kWh), the following equation is used (Lambert at al., 2017).

$$CoE = \frac{C_{ANN,TOT}}{E_{PR} + E_{GS}} \tag{12}$$

where E_{PR} is the total amount of annual primary load, E_{GS} is the amount of energy sold to the grid each year.

4.3. Renewable Fraction

The system is analysed to determine its use of renewable energies over the grid connections (Jayachandran & Ravi, 2017), this is defined as Renewable Fraction (RF). HOMER calculates RF using the following equation.

$$RF = \left(1 - \frac{E_{NR} + H_{NR}}{E_{SV} + H_{SV}}\right) \times 100\% \tag{13}$$

where RF is the renewable fraction in (%), E_{NR} is the non-renewable electrical production (kWh/yr), H_{NR} is the non-renewable thermal production, E_{SV} is the total electric load supplied (kWh/yr) and H_{SV} is the total thermal load supplied (kWh/yr).

5. Optimisation Results

The main objective is to ensure that the microgrid system can always meet the demand of the housing development without any interruption. Each optimised microgrid was evaluated based on the economic criteria outlined in the previous section. The 1% capital cost of the housing development was also factored in during the optimisation process. For each location, the optimisation process has been conducted twice, once in the island and once in grid-connected mode.

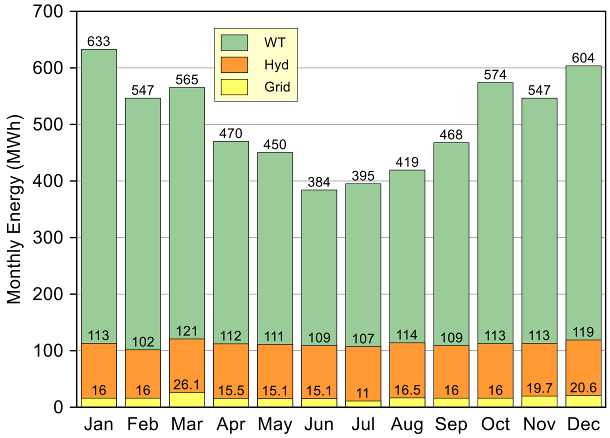
The software selected for the analysis and optimisation (HOMER) calculated the optimum microgrid architecture for each of the areas (Table 8) using the input data. The island mode simulation results for the Northwest of England, Southeast of England, Southwest of England, Scotland, and Northern Island demonstrated that a self-sufficient microgrid, that complies with the 1% capital cost budget, can be implemented. The microgrid located in the Southeast of England has the lowest CoE but the highest NPC out of the group. In this section, the Southeast England results in grid-connected mode and island mode have been analysed further.

Table 8. Optimised microgrid results.

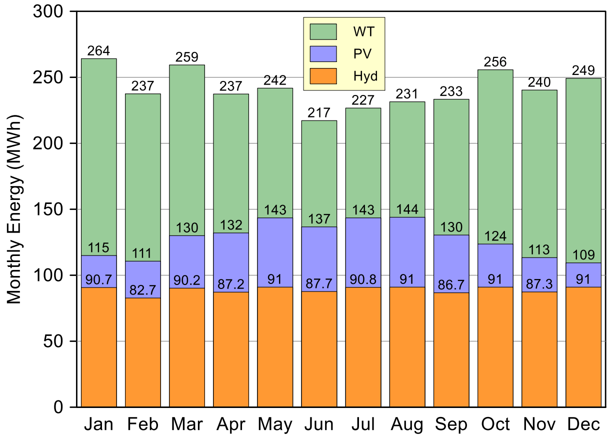
Location	**Grid Connection**	**PV (kW)**	**WT (kW)**	**ESS (kW)**	**Hydro (kW)**	**Converter (kW)**	**RF (%)**	**NPC (£)**	**CoE (£/kWh)**	**Operating Cost (£/yr)**	**Capital (£)**
Northwest England	Yes	N/A	1500	N/A	N/A	N/A	96.5	-4.04M	-0.0292	-259,608	1.69M
	No	N/A	682	1411	100	423	100	3.54M	0.0843	73,210	1.92M
Northeast England	Yes	N/A	1500	N/A	N/A	N/A	89.4	797,332	-0.00669	-88,602	1.17M
	No	306	450	1519	100	430	100	3.62M	0.0862	70,595	2.06M
Southeast England	Yes	N/A	1500	N/A	100	N/A	96	-3.38M	-0.0254	-228,945	1.69M
	No	452	434	1487	100	383	100	3.70M	0.0881	70,433	2.14M
Southwest England	Yes	N/A	1500	N/A	100	N/A	97.2	-5.36M	-0.0354	-318,565	1.69M
	No	127	648	1016	100	332	100	3.16M	0.0751	63,035	1.76M
Scotland	Yes	N/A	1500	N/A	100	N/A	96.6	-4.16M	-0.0297	-264213	1.69M
	No	N/A	818	1244	100	335	100	3.54M	0.0843	73,506	1.91M
Wales	Yes	N/A	1500	N/A	100	N/A	95.9	-3.17M	-0.0242	-219,536	1.69M
	No	283	721	1187	100	504	100	3.68M	0.0877	72,267	2.08M
Northern Island	Yes	N/A	1500	N/A	N/A	N/A	93.5	-3.95M	-0.0275	-231,105	1.17M
	No	115	469	1036	100	403	100	2.94M	0.0699	58,781	1.64M

5.1. Monthly Electrical Production of Microgrid

Fig. 4 highlights the monthly electrical production of both microgrids over a 12-month period. The grid-connected microgrid (Fig. 4a) reaches up to 600MWh during the winter months and as low as 400MWh during the summer months due to the reduced load demand. The island mode microgrid (Fig. 4b) has consistent generation throughout the year, ranging between 225-275MWh per month.



(a)

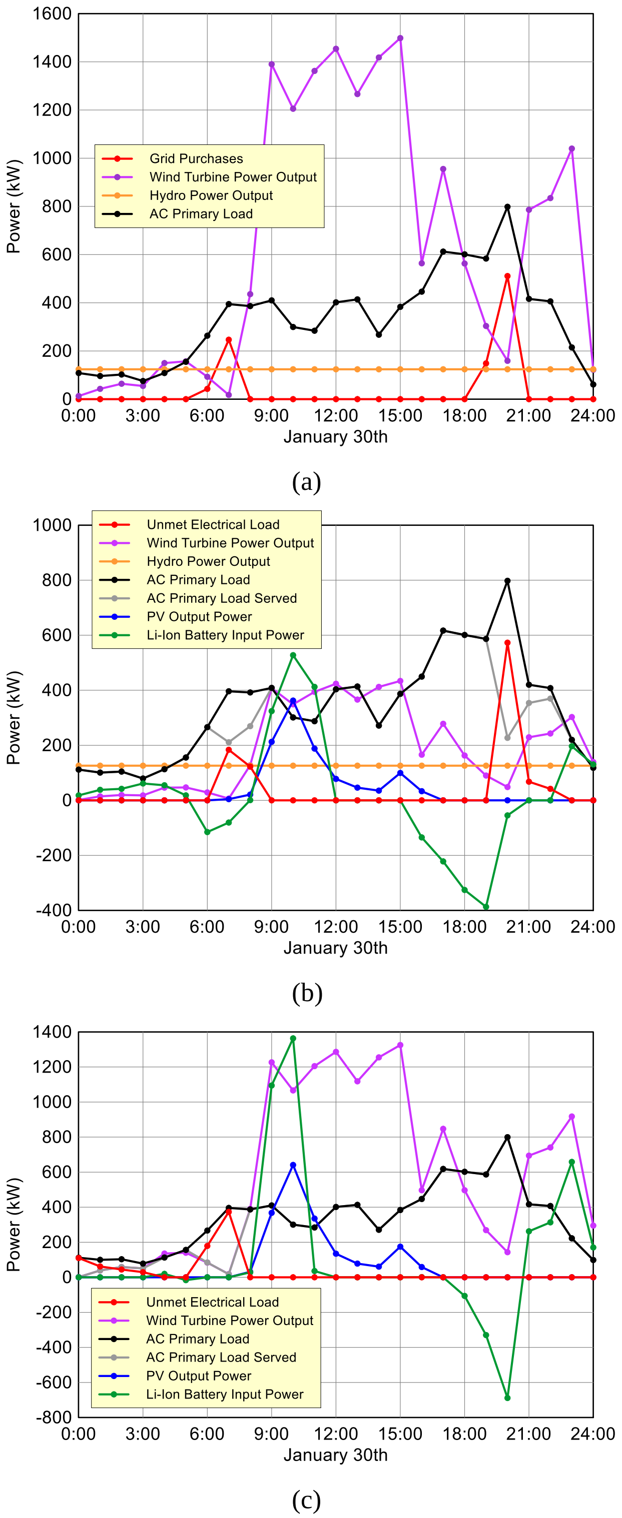


(b)

Fig. 4. (a) Monthly electric production of grid-connected microgrid; (b) Monthly electric production of microgrid operating without a grid connection.

5.2. Load demand of Housing Development

Each microgrid was analysed further over a 24-hour period in January to assess its performance and determine if it could handle the change in load demand from the housing development (Fig. 5). Fig. 5a shows the load demand of housing development and output of grid-connected microgrid whereas Fig. 5b and Fig. 5c demonstrate the performance of the microgrids in an island mode. A superior island mode microgrid shown in Fig. 5c is analysed to determine if it could supply the load peaks of the housing development and cover the shortfall witnessed by the chosen island mode microgrid (Fig. 5b).



(a)

(b)

(c)

Fig. 5. (a) Load demand of housing development and output of grid-connected microgrid; (b) Load demand of housing development and output of microgrid without grid connection (£2.14m Capital Cost); (c) Load demand of housing development and output of island mode microgrid (£3.49m Capital Cost).

5.3. Wind Turbine, Photovoltaic and Batter Energy Storage System

The wind turbine generation for both microgrids is analysed over a 365-day period. The wind turbine in the grid-connected microgrid generates 4,665,977 kWh/year, which is equivalent to 77.8% of the microgrid output. The wind turbine that forms part of the island mode microgrid generates 1,350,023 kWh/year, which equates to 46.8% of the output of the microgrid.

The output power of the PV panels is calculated over the same 12-month period for the island mode microgrid. It concludes that the PV panels provide a mean output of 1,199kWh/d throughout a 12-month period with a maximum output of 457kW. The PV panels contribute 15.2% of the total electrical energy generated by the microgrid. Analysis of the BESS shows that the system battery is in its fully charged state for nearly half of the 12-month period and has an autonomy of 5.31 hours.

5.4. Economic Results

The economic analysis of the two microgrids is presented in Table 9, the results show that the grid-connected microgrid has the highest present worth, highest annual worth, highest return on investment, and the shortest payback period when compared to the island mode microgrid.

Table 9. Economic comparison of the two microgrids.

Metric	**Grid-connected Microgrid**	**Island Mode Microgrid**
Present Worth (£)	15,996,160	66,711
Annual Worth (£/year)	722,066	3,011
Return on Investment (%)	43.2	3.0
Simple Payback (year)	2.09	15.95

6. Discussion

This section discusses the results of the various microgrid case studies presented in Section 5. The overall optimisation results for the different microgrid locations are discussed first to determine if microgrids are feasible within the UK. The Southeast UK case study is discussed further to determine the limitations and uncertainties that may be associated with a grid-connected or island mode microgrid.

6.1. Analysis of Optimisation Results for all Case Studies

The 1% capital cost budget of the overall housing development proved to be a success, demonstrating that across the UK, all areas could implement a grid-connected microgrid that would be funded by consumers alone (Brandeis et al., 2016). Only the island mode microgrids located in the Northeast and Scotland would require additional funding from third party investment, 30% and 5.5% of the initial capital respectively. The grid-connected microgrids had the lowest initial capital, CoE, NPC, and operating cost compared to the island mode microgrids. The optimisation process in HOMER takes advantage of the ability to sell excess electricity back to the grid and sees this as a profitable solution over the lifetime of the microgrid, ultimately providing free electricity to the consumers. All grid-connected microgrids comply with the Smart Export Guarantee (SEG) license requirements which enable the system to sell the excess back to the grid at an agreed kW rate. For this case study, an average rate of 9p/kW was established from average UK market data. No sale capacity was utilised during the simulations; however, these could be implemented by the national grid during the SEG contract agreements.

A wind turbine proved to be the dominant renewable energy in all microgrid case studies. The grid-connected microgrids maximise the wind turbine to the upper limit of 1.5MW in all scenarios. The ability to rely on the grid for any shortfall in energy production outweighs the use of Li-ion batteries in all scenarios. The high capital cost, maintenance cost, and short lifetime (15 years) of the batteries deemed them to be an unfavourable option when compared to a low-cost grid connection. Combined, the wind turbine, hydro turbine and grid connection was the optimised arrangement for 70% of the grid-connected case studies (Table 8). This arrangement is due to the reliability of the components within the system, the UK's location in the jet stream and adverse weather conditions mean that wind turbines are deemed more practical than PV panels, and the continuous flow of the river used for the system enables the hydro turbine to maintain a steady output. This validates the results obtained from the existing microgrid located at the CAT in Wales, their system concluded that hydro was a reliant source of generation; however, the PV panels provided shortfalls during the winter months due to adverse weather conditions in the UK (Kuriakose, 2011).

All microgrid case studies had a renewable factor greater than 89%, demonstrating that microgrids can assist in the decarbonisation of the UK's national grid. It is estimated that 37,164 new homes were built in the UK between April 2021 and March 2022 (Home England, 2022). With the average UK household consuming 9.6kWh (McKenna, 2020), this equates to an additional loading of 356.77MWh per day in a system which already has its shortfalls, reducing this load on the system by 89% would greatly assist in the decarbonisation of the national grid. The ability of microgrids to sell electricity to the grid provides additional economic and environmental benefits to both consumers and the grid; excess carbon-free electricity can be supplied to external consumers, thus reducing their reliance on fossil fuel-generated electricity.

6.2. Analysis of Optimisation Results for the Southeast Case Study

The grid-connected microgrid generated nearly three times as much power as the island mode microgrid during the winter months (Fig. 3). The larger WT in the grid-connected microgrid was able to take advantage of the increased wind speed that occurs during the winter months and sell this excess electricity back to the national grid for profit (Fig. 5a). During the optimisation process, HOMER advised increasing the upper capacity of the wind turbine to enable the microgrid to take full advantage of the available wind resource. The economic advantages of increasing the WT capacity can quickly become overshadowed by environmental impacts. Disruption to the local environment, noise pollution, and a general annoyance to the public are factors that all need to be considered during the installation of WTs.

The grid-connected microgrid demonstrated that it was able to meet the peak demands of the housing development (Fig. 5a). Throughout a 24-hour period, there were two instances where the load demand exceeded the output of the renewable energies, in these instances, the grid connection was able to provide the required power to prevent any shortfalls from occurring. The island mode microgrid could not cope with the peak demands of the housing development; Fig. 5b highlights two shortfalls that occur within a 24-hour period. The larger shortfall occurs in the evening when the load demand of the housing development is at its highest, and the output from the WT is near its lowest. The BESS provided the shortfall of power for 4 hours, but once it neared its discharged state, the demand exceeded the supply. A microgrid with greater output and capital cost was examined over the same 24-hour period to determine if the shortfalls still occurred (Fig. 5c). The superior microgrid was able to cope with the evening peak demand of the housing development due to the larger BESS capacity (2.98kW). However, shortfalls still occurred during the morning peak load, when the WT was at its lowest and the BESS was not sufficiently charged. These shortfalls highlight the importance of a grid connection, the unpredictability of renewable energies does not fully allow upscaled microgrids to operate effectively as a separate entity. Increasing the BESS further could combat the shortfall; however, throughout a 12-month period the BESS remained in its fully charged state for 48.94% of the time; these data deem it difficult to justify the increased capital, maintenance, and replacement cost that comes with a larger BESS when a connection to the grid can provide an economic solution to the shortfalls of the BESS.

As Table 8 and Table 9 indicate, the grid-connected microgrid provides better economic benefits when compared to the island mode microgrid. HOMER capitalised on selling electricity back to the grid, which ultimately resulted in the microgrid system becoming a profitable entity whilst providing consumers with free electricity. During the 25-year life-time of the project, it is estimated that the WT would need to be replaced at year 20. The profit generated from grid sales is enough to fund the replacement WT and annual maintenance. The PV panels would last the duration of the island mode microgrid lifetime, however, the BESS and WT would need to be replaced at year 15 and 20, respectively. These replacements would come from consumer funding or third-party investment. Due to the high maintenance and short lifetime, the BESS is the greatest expense for the island mode microgrid.

6.3. Recommendations

Based on the case study analysis the following recommendations are proposed. Recommendations to policy makers are to invest heavily in renewable energy smart grids that are complimented by the national grid system as an essential part of upgrading the current energy system. The benefits from this paper's findings and other studies are that renewable energy smart grids can contribute to a decentralised national grid, taking the strain off overloaded national system, whilst reducing carbon emissions and its contribution towards climate change. An achievable cost-effective self-sufficiency (renewable fraction) of around 80-90% can be achieved. The positive knock-on effects of renewable smart grids are less air pollution from burning fossil fuels and cheaper, less volatile, energy prices in the long term. Developers will be able to construct more desirable projects for an increasingly carbon-aware market, with lower long-term running costs. Consumers will benefit from less volatile long-term cheaper energy costs. The main barrier is increased upfront investment costs; however, these can be as low as 1% of the overall investment. Standalone energy island "off-grid" scenarios were found to be very expensive and offer little benefits in comparison to grid-connected systems. The study assumes that hydro will form part of the energy mix but, this may not be available nearby to any potential development site, whereas wind and solar (Planning permission aside) do not suffer from this limitation. Planning permission is a considerable barrier in the UK especially for wind turbines and therefore it is recommended that policy makers loosen the tight planning restrictions on wind turbine developments where appropriate.

7. Conclusions

During the simulations, the optimal design for each case study was established with comparisons made between grid-connected and island mode microgrids. The island mode microgrids were unable to cope with the peak demands of the housing development, however, the grid-connected microgrid did not experience any shortfalls due to the grid connection, and the microgrid ensured that the demand of the housing development did not exceed the supply. WTs proved to be the dominant renewable energy choice during the optimisation process, with the optimised solution mainly consisting of a WT, an HT, and a connection to the grid. The connection to the grid was not only reliable but it also proved to be an economic benefit to consumers. All grid-connected microgrids are experienced a lower initial capital cost, CoE, NPC, and even a lower operating cost compared to an island mode microgrid. The high capital, maintenance, and replacement costs outweighed the benefits of the BESS and a connection to the grid was preferred instead.

This research has demonstrated that microgrids can play an important role in the decarbonisation of the UK grid network by decentralising the generation of electricity and using localised renewable energy as an alternative. The potential for new housing developments to reduce their grid load by 89% will significantly assist in achieving the targets set by the UK government in the recent COP 26 (HM Government, 2020; Cossutta et al., 2021).

Therefore, the recommendations to policy makers are to invest heavily in renewable energy smart grids that are complimented by the national grid system as an essential part of upgrading the current energy system. The benefits from this paper's findings are confirmation that renewable energy smart grids can contribute to a decentralised national grid, taking the strain off overloaded national system, whilst reducing carbon emissions and its contribution towards climate change. It was shown that a cost-effective self-sufficiency (renewable fraction) of around 80-90% can be achieved. The positive knock-on effects of renewable smart grids are less air pollution from burning fossil fuels and cheaper, less volatile, energy prices in the long term. Developers will be able to construct more desirable projects for an increasingly carbon-aware market, with lower long-term running costs. Consumers will benefit from less volatile long-term cheaper energy costs. The main barrier is increased upfront investment costs; however, these can be as low as 1% of the overall investment. Standalone energy island “off-grid” scenarios were found to be very expensive and offer little benefits in comparison to grid-connected systems. The study assumes that hydro will form part of the energy mix but, this may not be available nearby to any potential development site, whereas wind and solar (planning permission aside) do not suffer from this limitation. Planning permission is a considerable barrier in the UK especially for wind turbines and therefore it is recommended that policy makers loosen the tight planning restrictions on wind turbine developments where appropriate.

As the movement away from fossil fuels gains greater momentum and technology continues to develop, the demand for UK household load demand is likely to change. Electric Vehicle (EV) charging and electric heating will be the main factors in changing this demand (Sprake et al., 2017; Singh & Letha, 2019). Further modelling simulations could be implemented to determine how the optimised microgrids handle future loadings. Advanced grid analysis should also be modelled to provide an accurate economic model of a grid connection microgrid. The simulations assume that the grid rates are fixed during a 24-hour period. However, the rates can fluctuate during this period, which could change the economic result of the grid-connected microgrid.

References

Bajpai, P., & Dash, V. (2012). Hybrid renewable energy systems for power generation in stand-alone applications: A review. *Renewable and Sustainable Energy Reviews*, *16*(5), 2926–2939. https://doi.org/10.1016/j.rser.2012.02.009

Boardman, B. (2007). *Home truths: A low-carbon strategy to reduce UK housing emissions by 80% by 2050*. Environmental Change Institute, University of Oxford.

Brandeis, L., Sprake, D., Vagapov, Y., & Tun, H. (2016, February 2–3). *Analysis of electrical energy storage technologies for future electric grid*. [Conference paper]. IEEE Young Researchers in Electrical and Electronic Engineering Conference, Saint Petersburg, Russia. https://doi.org/10.1109/EIConRusNW.2016.7448235

Brijesh, P., Jiju, K., Dhanesh, P.R., & Joseph, A. (2019, October 17–20). *Microgrid for sustainable development of remote villages*. [Conference paper]. Region 10 Conference TENCON 2019, Kochi, India. https://doi.org/10.1109/TENCON.2019.8929455

Cave, S. (2013). *Wind turbines: Planning and separation distances* (Research Paper NIAR 767-13). Research and Information Service, Northern Island Assembly. http://www.niassembly.gov.uk/globalassets/documents/raise/publications/2013/environment/12813.pdf

Chang, T.-P., Liu, F.-J., Ko, H.-H., Cheng, S.-P., Sun, L.-C., & Kuo, S.-C. (2014). Comparative analysis on power curve models of wind turbine generator in estimating capacity factor. *Energy*, *73*, 88–95. https://doi.org/10.1016/j.energy.2014.05.091

Cossutta, M., Foo, D.C.Y., & Tan, R.R. (2021). Carbon emission pinch analysis (CEPA) for planning the decarbonization of the UK power sector. *Sustainable Production and Consumption*, *25*, 259–270. https://doi.org/10.1016/j.spc.2020.08.013

Curtis, D. (2023). *Why microgrids will transform how we use, buy, and sell energy in Sussex and Kent*. BHESCo. https://bhesco.co.uk/blog/microgrids-sussex-kent

DeSantis, D., James, B., Houchins, C., Saur, G., & Lyubovsky, M. (2021). Cost of long-distance energy transmission by different carriers. *iScience*, *24*(12), 103495. https://doi.org/10.1016/j.isci.2021.103495

Diaf, S., Diaf, D., Belhamel, M., Haddadi, M., & Louche, A. (2007). A methodology for optimal sizing of autonomous hybrid PV/wind system. *Energy Policy*, *35*(11), 5708–5718. https://doi.org/10.1016/j.enpol.2007.06.020

Hecht, C., Sprake, D., Vagapov, Y., & Anuchin, A. (2021). Domestic demand-side management: Analysis of microgrid with renewable energy sources using historical load data. *Electrical Engineering*, *103*(3), 1791–1806. https://doi.org/10.1007/s00202-020-01197-y

Hitchens, K. (2023). *UK Mint launches new multiresource microgrid energy center*. Microgrid Knowledge. https://www.microgridknowledge.com/renewable-microgrids/article/33008510/uk-mint-launches-new-multiresource-microgrid-energy-center

HM Government. (2020). *The energy white paper: Powering our net zero future*. (CP 337). Her Majesty's Stationery Office. https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future

Home England. (2022). *Housing statistics 1 April 2021 to 31 March 2022*. [Dataset]. https://www.gov.uk/government/statistics/housing-statistics-1-april-2021-to-31-march-2022

Howland, E. (2022). *San Diego approves deal with Shell New Energies for 8 microgrids*. Microgrid Knowledge. https://www.microgridknowledge.com/editors-choice/article/11427885/san-diego-approves-deal-with-shell-new-energies-for-8-microgrids

Jackson, J. (2022). *UK microgrid project charts move to smart homes implementation*. EnergyCentral. https://energycentral.com/c/gr/exciting-microgrid-projects-moving-forward-2022

Jayachandran, M., & Ravi, G. (2017). Design and optimization of hybrid micro-grid system. *Energy Procedia*, *117*, 95–103. https://doi.org/10.1016/j.egypro.2017.05.111

Keawsuntia, Y. (2011, September 28–30). *Electricity generation from micro hydro turbine: A case study of crossflow turbine*. [Conference paper]. International Conference and Utility Exhibition on Power and Energy Systems: Issues and Prospects for Asia, Pattaya, Thailand. https://doi.org/10.1109/ICUEPES.2011.6497731

Kuriakose, J. (2011, December 5–7). *Microgrid system at Centre for Alternative Technology*. [Conference paper]. IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies, Manchester, UK. https://doi.org/10.1109/ISGTEurope.2011.6162725

Lewis, C. (2022). *UK house price index*. (March 2022) [Dataset]. Office for National Statistics. https://www.ons.gov.uk/economy/inflationandpriceindices/bulletins/housepriceindex/march2022

Martin, V. (2022). Chapter 5: Electricity. In Department for Business, Energy and Industrial Strategy, *Digest of UK energy statistics (DUKS) 2022* (pp. 28-37). UK Government. https://www.gov.uk/government/statistics/digest-of-uk-energy-statistics-dukes-2022

McKenna, E., Thomson, M., & Barton, J. (2020). *CREST demand model*. (Version 8) [Dataset]. Loughborough University. https://repository.lboro.ac.uk/ndownloader/articles/2001129/versions/8

NASA. (2022). *The prediction of worldwide energy resources*. [Dataset]. https://power.larc.nasa.gov/data-access-viewer

Naz, M.Y., Bou-Rabee, M., Shukrullah, S., Ghaffar, A., Gungor, A., & Sulaiman, S.A. (2021). A review of hybrid energy technologies tenets, controls and combinational strategies. *Cleaner Engineering and Technology*, *5*, 100340. https://doi.org/10.1016/j.clet.2021.100340

OECD. (2023). *Inflation (CPI)* (Indicator). https://doi.org/10.1787/eee82e6e-en

Ofgem. (2016). *Local energy in a transforming energy system* (Ofgem's Future Insights Series). Ofgem.

Pimm, A.J., Cockerill, T.T., & Taylor, P.G. (2018). The potential for peak shaving on low voltage distribution networks using electricity storage. *Journal of Energy Storage*, *16*, 231–242. https://doi.org/10.1016/j.est.2018.02.002

Senjyu, T., Hayashi, D., Yona, A., Urasaki, N., & Funabashi, T. (2007). Optimal configuration of power generating systems in isolated island with renewable energy. *Renewable Energy*, *32*(11), 1917–1933. https://doi.org/10.1016/j.renene.2006.09.003

Singh, A., & Letha, S.S. (2019). Emerging energy sources for electric vehicle charging station. *Environment, Development and Sustainability*, *21*, 2043–2082. https://doi.org/10.1007/s10668-018-0151-x

Sprake, D., & Vagapov, Y. (2021, January 26–29). *Stakeholder relationships towards influencing new zero carbon house building in the UK*. [Conference paper]. IEEE Conference of Young Researchers in Electrical and Electronic Engineering, Saint Petersburg, Russia. https://doi.org/10.1109/ElConRus51938.2021.9396488

Sprake, D., Vagapov, Y., Lupin, S., & Anuchin, A. (2017, September 12–15). *Housing estate energy storage feasibility for a 2050 scenario*. [Conference paper]. International Conference on Internet Technologies and Applications, Wrexham, UK. https://doi.org/10.1109/ITECHA.2017.8101925

Tomin, N., Shakirov, V., Kozlov, A., Sidorov, D., Kurbatsky, V., Rehtanz, C., & Lora, E.E.S. (2022). Design and optimal energy management of community microgrids with flexible renewable energy sources. *Renewable Energy*, *183*, 903–921. https://doi.org/10.1016/j.renene.2021.11.024

UK Centre for Ecology and Hydrology. (2022). *National river flow archive*. [Dataset]. https://nrfa.ceh.ac.uk

UK Parliament. (2015). *Energy network costs: Transparent and fair?* https://publications.parliament.uk/pa/cm201415/cmselect/cmenergy/386/38607.html

Yousef, B.A.A., Amjad, R., Alajmi, N.A., & Rezk, H. (2022). Feasibility of integrated photovoltaic and mechanical storage systems for irrigation purposes in remote areas: Optimization, energy management, and multicriteria decision-making. *Case Studies in Thermal Engineering*, *38*, 102363. https://doi.org/10.1016/j.csite.2022.102363