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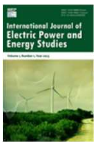

Integrating Renewable Energy, Storage, and Demand Management in Community Energy Systems: A Case Study of Trent Basin

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ABSTRACT

Community energy systems are considered a key means of achieving carbon neutrality at the local level. This paper evaluates the current and future energy systems of the Nottingham Trent Basin community, as a case study, and proposes strategies to reduce carbon emissions and enhance energy efficiency. Analyses of building energy demand, carbon emissions, and model accuracy were conducted based on simulation data from the IES model and measured electricity data from selected households. Results indicate that the community's average domestic electricity consumption exceeds the UK national average, while natural gas consumption is significantly lower, suggesting progress in heating decarbonization. Further simulations demonstrate that a 200 kWp photovoltaic system could cover approximately 82% of annual electricity demand. Integrating this with a 2 MWh energy storage system could reduce annual carbon emissions by nearly 80%. Future analysis indicates that introducing air-source heat pumps could reduce heating- related emissions by approximately 71%, while expanding PV and storage capacity would further decrease grid dependency. Concurrently, the research evaluated electric vehicle integration and load management strategies, exploring time- series based electricity demand forecasting models. Findings indicate that smart community energy systems, by integrating renewable energy, electrified heating, and electric vehicle management, can significantly advance carbon reduction at the community level. This paper highlights the importance of combining technical measures with demand side management in achieving carbon neutrality.

KEYWORDS

Community Energy System; Decarbonisation; Solar PV and Storage; Heat Pumps; Electric Vehicles; Energy Demand Forecasting.

1. INTRODUCTION

Smart energy system is essential for reducing carbon emissions and improving energy efficiency in residential communities. Trent Basin in Nottingham is an example of a community level energy system that includes solar PV, battery storage and smart data management. Since the objective of the community is to reduce dependence on gas and prepare for increased use of electric vehicles, further improvements are needed.

Trent Basin Energy Services Company commissioned this study to assess the current energy system and propose solutions to reduce carbon emissions. The aim of the project was to analyse current energy demand, assess the accuracy of the model, evaluate the impact of the current renewable energy system and develop a strategy for future system improvements, including low carbon heat and electric vehicle demand management.

Analyses were based on simulated data from the IES model and measured electricity data from selected properties. The methodology used for the study includes demand analysis, CO_2 emissions calculations, system performance comparison and basic time series forecasting.

2. CURRENT ENERGY SYSTEM

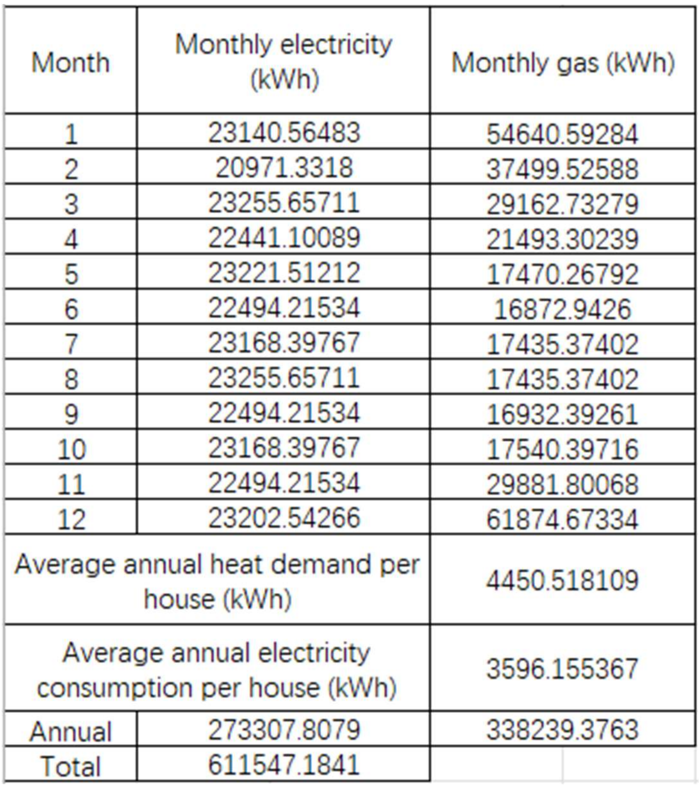
2.1. Building Energy Demand Analysis

This section mainly focused on analysed the simulated electricity and heat demand data for the 76 homes in the Trent Basin, which includes monthly and annual gas and electricity consumption of the community, and calculated the carbon emissions.

2.1.1. Monthly and Annual Energy Consumption

By analysing simulated building demand data files, it can be summarized as Table 1:

Table 1. Monthly and annual electricity and gas consumption



Month	Monthly electricity (kWh)	Monthly gas (kWh)
1	23140.56483	54640.59284
2	20971.3318	37499.52588
3	23255.65711	29162.73279
4	22441.10089	21493.30239
5	23221.51212	17470.26792
6	22494.21534	16872.9426
7	23168.39767	17435.37402
8	23255.65711	17435.37402
9	22494.21534	16932.39261
10	23168.39767	17540.39716
11	22494.21534	29881.80068
12	23202.54266	61874.67334
Average annual heat demand per house (kWh)		4450.518109
Average annual electricity consumption per house (kWh)		3596.155367
Annual	273307.8079	338239.3763
Total	611547.1841	

Based on the simulated data for 76 homes, it can be concluded that the:

Total annual electricity consumption: 273308 kWh

Total annual heating demand: 338239 kWh

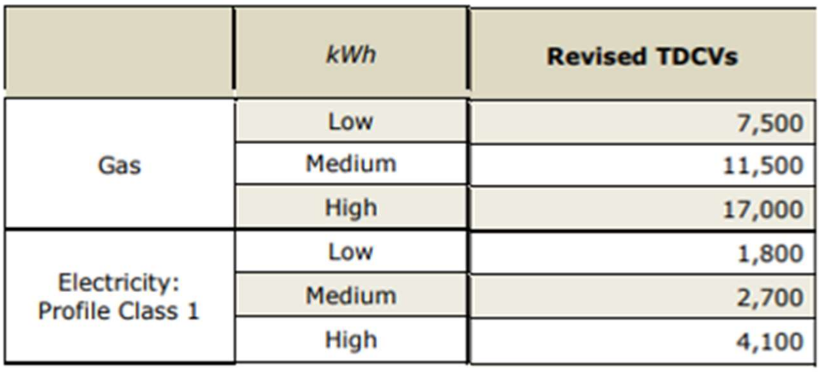
Since the efficiency of the gas boilers is 92%, the actual natural gas consumption should be

$$\text{Gas consumption}=\frac{\text{Heat demand}}{\text{Efficiency}}=\frac{338239\text{kWh}}{0.92}\approx 367652\text{kWh} \quad (1)$$

2.1.2. Comparison with Typical UK Domestic Energy Use

According to the assumptions, in the Trent Basin, 17, 19 and 40 belong to the typical low, medium and high domestic.

To compare with Figure 1, the average gas consumption and electricity use per house should be calculated:



	kWh	Revised TDCVs
Gas	Low	7,500
	Medium	11,500
	High	17,000
Electricity: Profile Class 1	Low	1,800
	Medium	2,700
	High	4,100

Figure 1. Typical Domestic Consumption Values for gas and electricity [1]

$$\text{Average electricity use}=\frac{273308\text{kWh}}{76}=3596.16\text{kWh} \tag{2}$$

$$\text{Average Gas consumption}=\frac{367652\text{kWh}}{76}=4837.53\text{kWh} \tag{3}$$

According to the calculations, the average electricity consumption per house in the Trent Basin is 3596 kWh per year, which is around 33% higher than the typical medium UK average of 2700 kWh/year. The average gas consumption per house, which is based on the boiler efficiency, is 4838 kWh per year, which is approximately 42% of the typical medium UK average of 11500 kWh/year. Overall, although the electricity demand of the Trent Basin is higher than the typical demostic consumption, the gas consumption is significantly lower than the typical demostic consumption, suggests that the heating system has achieved a certain degree of decarbonisation.

2.1.3. Monthly and Annual Carbon Emissions

According to the assumption, the CO_2 factor is 0.19 kg/kWh for indirect electricity emissions and 0.2 kg/kWh for gas. Thus, the total annual carbon emissions of the community were:

$$\text{Eectricity } CO_2 = 0.19\text{kg}/\text{kWh} \times 273307\text{kWh}=51928.3\text{kg} \tag{4}$$

$$\text{Gas } CO_2 = 0.2\text{kg}/\text{kWh} \times 338239\text{kWh}=67647.8\text{kg} \tag{5}$$

$$\text{Total } CO_2 \text{ emission}=67647.8\text{kg}+51928.3\text{kg}=119576.1\text{kg} \tag{6}$$

The Trent Basin electicity CO_2 emission is 51928.3 kg, while the gas CO_2 emission is about 67647.8 kg, totaling approximately 119576.1 kg of carbon dioxide.

The CO_2 emission is highest during the winter, which is mainly caused by increased demand of heating. Gas heating accounts for nearly 57% of total emissions. Thus, changing the heating system to electric heating could significantly reduce the community's carbon emissions. This transition will not only improve overall energy efficiency, but also enhance system flexibility through smart control. This transition will not only improve overall energy efficiency but also enhance system flexibility through intelligent control. As the renewable energy contribution increases, the environmental benefits of electric heating become more significant. Therefore, promoting heating electricity is a important strategic path to achieving the zero-carbon emissions goal for the Trent Basin community.

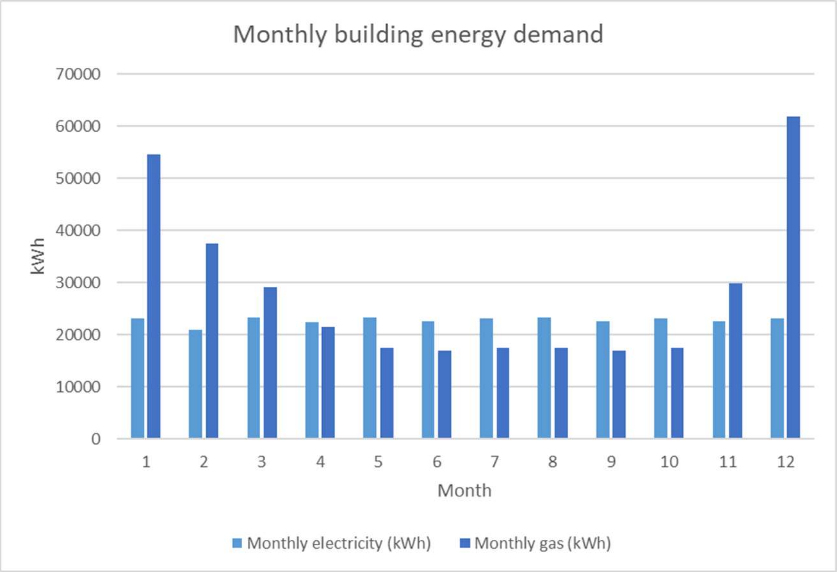


Figure 2. Bar chart of monthly building energy demand

2.2. Model Accuracy

To access the accuracy of the modelled data, monthly simulated data for Phase 1, Plot 23 was compared with the measured data as Table. 2.

Table 2. Comparison of the measured data with simulated data

Month	Measured electricity (kWh)	Simulate electricity (kWh)
1	446.347	314.96534
2	360.098	285.44024
3	273.92	316.53278
4	293.707	305.44476
5	364.5	316.06742
6	303.574	306.1686
7	297.839	315.34358
8	336	316.53278
9	330.197	306.1686
10	281.447	315.34358
11	332.863	306.1686
12	324.352	315.80894
Total	3944.844	3719.98522

For further assess and report the accuracy of the monthly simulation results, the Normalized Mean Bias Error and Coefficient of variation of the root mean square error can be calculated as follow:

$$\mathrm{NMBE}=100\times\frac{1}{m}\times\frac{\sum_{i=1}^{n}(M_i-S_i)}{n}=\frac{100\times224.86}{328.74\times12}=5.70\% \tag{7}$$

$$\mathrm{CvRMSE}=100\times\frac{1}{m}\times\sqrt{\frac{\sum_{i=1}^{n}(M_i-S_i)^2}{n}}=\frac{100\times\sqrt{\frac{30338}{12}}}{328.74}=15.30\% \tag{8}$$

According to the calculation method of CIBSE TM63:2020, the NMBE was 5.7% and CvRMSE was 15.3%, which were slightly higher than the TM63 recommended standards of ±5% and 15% [2]. It suggests that the model slightly underestimates the actual electricity consumption and has a certain deviation from the measured data. To improve the accuracy of the model, the internal heat gain, occupancy schedule, and equipment usage patterns can be further improved. Additionally, introducing actual energy consumption data could also improve the accuracy of the model.

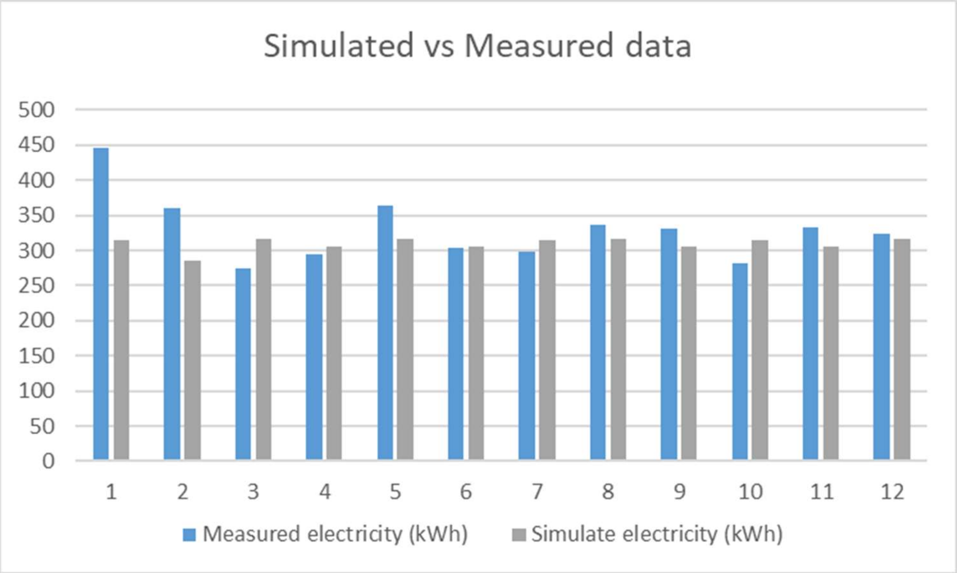


Figure 3. Bar chart of simulated and measured data

2.3. Current Electricity System Analysis

2.3.1. Solar PV Array

An additional 200 kWp solar PV array has been added to the energy model to assess the impact of the system on the electricity demand and carbon emissions of the Trent Basin. The simulated annual PV generation is 223954 kWh, while the total annual electricity demand of the community is 273308 kWh. It shows that the PV system can cover approximately 82% of the annual electricity consumption. Moreover, the monthly comparison of electricity generation and demand indicates that the PV generation exceeded demand from April to August, which resulted in grid export. The highest grid export was 8446 kWh in May. During the winter, the PV generation is significantly lower than in summer, which need extensive power imports from the grid. The annual carbon dioxide emissions of the Trent Basin without PV system are 51928 kg. However, after installing the PV system, the emissions decreased significantly to 9377 kg, which resulting in a reduction of nearly 80%. Carbon dioxide emissions will still occur during months with power exports, because of the time mismatch between solar power generation and electricity demand. Solar panels mainly generate electricity during the day, while evening and night demand still depends on grid supply, resulting in remaining emissions.

Table 3. Analysis of solar PV array

Month	Electricity demand(kWh)	PV Generation (kWh)	Grid Import (kWh)	Grid Export (kWh)	CO2 without PV (kg)	CO2 with PV (kg)
1	23140.56483	9715.80163	13424.7632	0	4396.70732	2550.70501
2	20971.3318	8986.58367	11984.7481	0	3984.55304	2277.10214
3	23255.65711	15140.58014	8115.07697	0	4418.57485	1541.86462
4	22441.10089	24747.71277	0	2306.61188	4263.80917	0
5	23221.51212	31667.97331	0	8446.46119	4412.0873	0
6	22494.21534	27605.90904	0	5111.6937	4273.90091	0
7	23168.39767	25456.919	0	2288.52133	4401.99556	0
8	23255.65711	25540.64565	0	2284.98854	4418.57485	0
9	22494.21534	21733.60082	760.61452	0	4273.90091	144.516759
10	23168.39767	17202.22928	5966.16839	0	4401.99556	1133.57199
11	22494.21534	9034.87276	13459.3426	0	4273.90091	2557.27509
12	23202.54266	7121.39539	16081.1473	0	4408.48311	3055.41798
Total	273307.8079	223954.2235	49353.5844	0	51928.4835	9377.18104

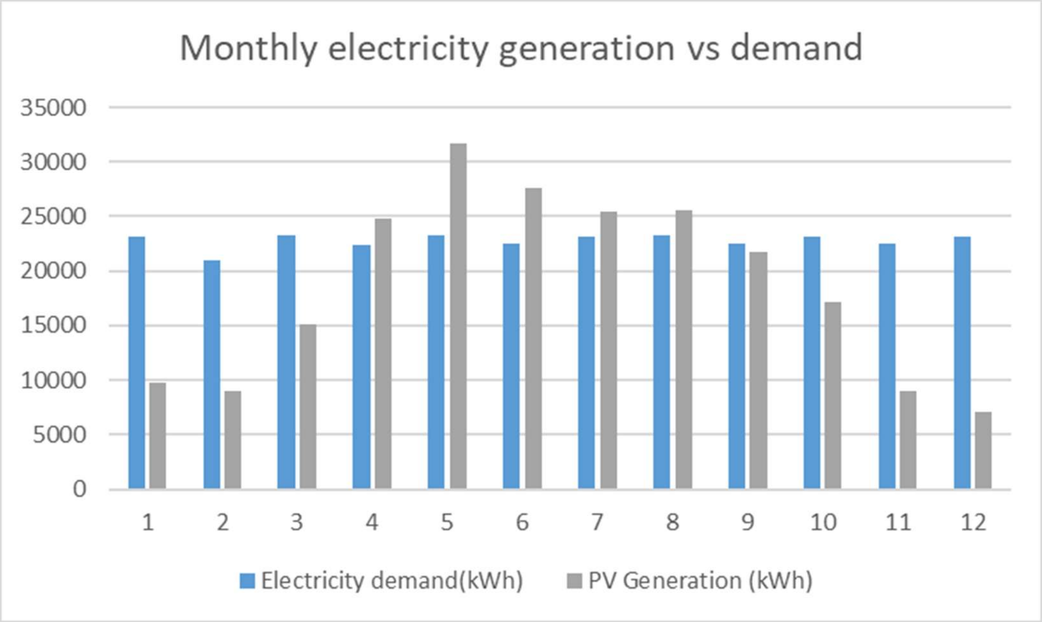


Figure 4. Bar chart of electricity generation vs demand

2.3.2. Battery Storage

A battery system with a capacity of 2MWh and an initial energy storage of 400 kWh was added into the simulation to assess its effect between PV power supply and building electricity consumption. According to the simulation, results show that the battery system can complete charging during daytime hours when there is sufficient PV power generation, and release energy at night when there is no solar radiation to meet the demand.

The simulation results also show that the total carbon emissions were 13895.27 kg CO_2 for the PV system over the year. After adding the battery system, the total emissions decreased to 9377.18 kg CO_2, resulting in a reduction of approximately 32.5%. During the spring and summer seasons, PV output is always high during the daytime, and batteries typically charge quickly by midday and begin discharging gradually in the evening to cover evening electricity demand. However, during winter, daylight hours shorten and light intensity decreases, resulting in a significant drop in PV power generation. As a result, batteries cannot charge effectively during the day, while evening demand remains, causing batteries to discharge rapidly in the evening and frequently reach SOC levels close to 0%. The system must then purchase electricity from the grid, leading to increased carbon emissions.

Thus, compared to situations without batteries, the total grid electricity consumption decreased significantly throughout the year. Therefore, to further improve the system's carbon reduction performance, increase energy storage capacity, like expand to 3 MWh or optimise PV capacity and orientation design can be helpful

3. FUTURE ENERGY SYSTEM

3.1. Decarbonisation of Heating

To help the Trent Basin community achieve its heating system decarbonisation objective, it is recommended to install air source heat pumps (ASHP) in each residential house. ASHP is a widely used low carbon heating technology, and has simple to operate, low maintenance costs, and no direct carbon emissions advantages. The monobloc air source heat pump is suitable for household deployment in this project because of its compact structure and flexible installation. The heat pump equipment can be install in the open space outside house, connected by pipes to the indoor hot water or heating system, and can be used with floor heating systems. In this project, the performance coefficient of an air source heat pump is 3.0, and the heating capacity is set to be 200 kW.

3.1.1. Heat Demand

According to the simulation results, as assumed that the efficiency of the gas boiler is 92%, the heat pump meets 99.76% of the annual heating demand. The total heat demand is 311179.6 kWh, while the heat supplied by heat pump is 310441.7 kWh, only 737.8 kWh of heat demand is unmet. It can be concluded that the selected heat pump can effectively meet the heating demands of the community.

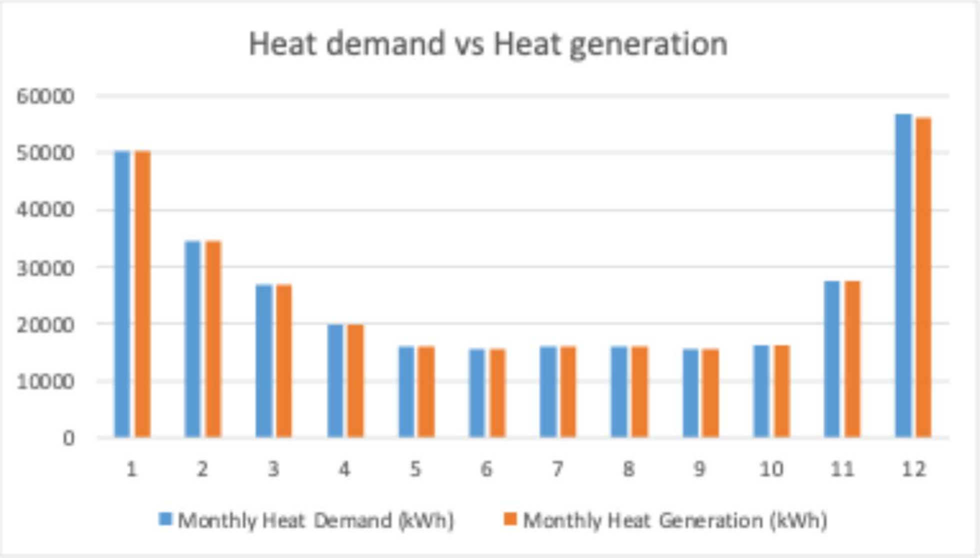


Figure 5. Bar chart of heat demand vs generation

3.1.2. CO_2 Emissions

To meet the annual required heating demand of 311179.6 kWh, the ASHP system is estimated to consume approximately 103480.6 kWh electricity energy. Based on the grid electricity emission factor of 0.19 kg/kWh, the electricity consumption of the heat pump resulted in approximately 19661kg of indirect CO_2 emissions. In addition, since there is still 737.8 kWh heat demand is still unmet, assumed the gas boilers efficiency is still 92%, the gas emissions for the unmet demand are 160kg. Therefore, the total annual heating emissions after using the heat pump is 19821 kg CO_2, resulting in a reduction of approximately 71% in carbon emissions compared to the 67640 kg CO_2 emissions produced by using a gas boiler. It suggests that the usage of electricity heating is helpful for reducing CO_2 emissions.

$$CO_2\text{ emissions}=\frac{\text{Heat demand}}{\text{efficiency}}\times\text{factor}=\frac{311180}{0.92}\times 0.2=67648\text{ kg} \tag{9}$$

$$\text{Heat Demand Satisfied}=\frac{19821\text{kg}}{67648\text{kg}}=29.3\% \tag{10}$$

3.1.3. Electricity Demand

After changing the heating system from gas boilers to heat pumps, the annual electricity consumption of the community increased by approximately 103480 kWh. The previous system depended on gas entirely, which wouldn't cause electricity demand. Although heat pumps will result in additional electricity consumption, the high efficiency and relatively low carbon emissions to the grid have resulted in a significant reduction in overall carbon emissions [3]. In conclusion, the ASHP is a technically feasible, environmentally friendly solution and can significantly boost the decarbonisiation of heating system of Trent Basin.

3.2. Updated Electricity Network Design

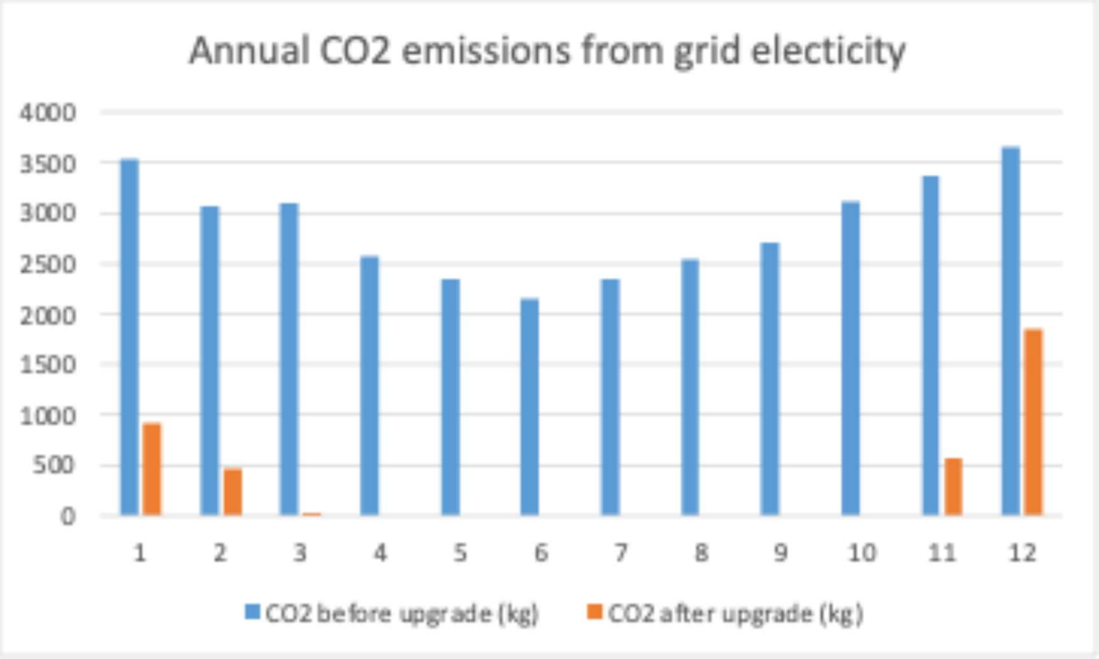


Figure 6. Bar chart of annual CO2 emissions

To further reduce indirect carbon emissions generated by electricity consumption in the Trent Basin community, it is recommended to increase the PV array sized from 200 kWp to 400 kWp and upgrade the battery storage capacity from 2 MWh to 3 MWh. This will allow more renewable energy to be generated and stored, reducing the purchase electricity demand. The main reason for this upgrade is that the current PV array system generate large amounts of surplus electricity at midday, most of which is fed back into the grid. However, in the evening, communities still need to purchase electricity from the grid, which indicates that the current energy storage capacity is unable to store large amount of energy, cannot balance the supply and demand in the day. By expanding PV size and energy storage capacity, the community's electricity purchase can be reduced, resulting in further reductions in carbon emissions. The Trent Basin community is new developed area and has some energy instructions, providing convenient conditions for expanding PV and energy storage systems. However, space limitations and initial investments costs may be challenging. The simulation results show that after the updated, the annual purchased electricity from the grid decreased from 73133 kWh to 20119 kWh, while the electricity related carbon emissions decreased from 37114.39 kg to 3822.64 kg. The grid export has increased significantly from 24096kWh to 194356 kWh, indicating that PV power generation has exceeded the local electricity demand.

To achieve a PV expansion from 200 kWp to 400 kWp in practice, the community can increase the number and area of PV panels by optimising the layout of existing roofs or installing PV structures in public areas [4]. Battery capacity can be expanded by adding modular energy storage units.

In summary, the simultaneous expansion of PV and battery capacity in this power upgrade design effectively reduces dependence on the grid and improves the efficiency of local renewable energy use, which is a critical step in advancing the Trent Basin community's goal of carbon neutrality.

3.3. EV Impact Analysis

The Trent Basin community is anticipating a fast-increasing adoption of electric vehicles. To provide fast chargers for 60 users, a communal parking bam with fast chargers are planned to be used [5]. According to the provided demand profile, the 60 users daily total demand is 345 kWh.

3.3.1. Impact of Addition EV

The line chart below illustrates the hourly load profile before and after electric vehicle integration. In the Figure. 6, the blue line represents the total charging demand for 60 users over a day. The orange line represents the base community electricity demand, calculated as the hourly average from the annual electricity demand data. The red line is the sum demand of EV load and the original community load. It can be observed from the figure that the original peak demand occurred at hour 21, reaching 66.04 kWh/h. After adding EVs, the peaking loads increased significantly in evening, which reaching to 100.24 kWh/h, representing an approximately 52% increase. It is suggested that if no load management strategies are applied, the local electricity network may be stressed.

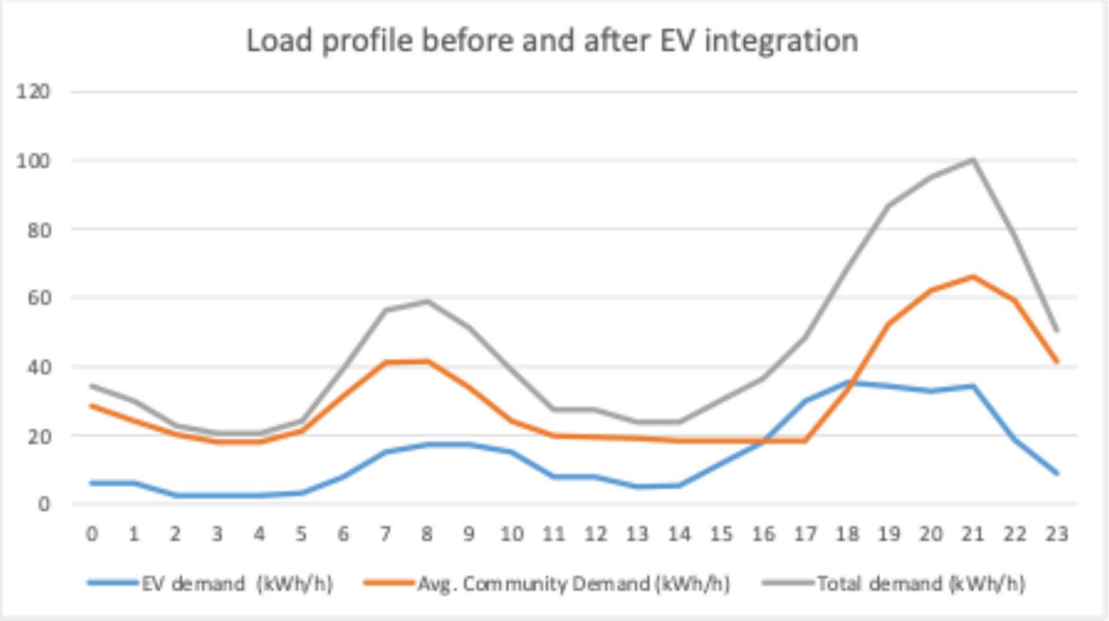


Figure 7. Bar chart of load profile comparison

3.3.2. Update EV Demand Profile

To assess the significant evening peak demand caused by EV charging, a new solution to help manage the additional demand need to be adopted. The EV load profile was adjusted to evenly distribute charging demand for 24 hours, the total charging load of 345 kWh a day is evenly distributed over 24hours, which is about 14.375 kWh per day. According to the new load profile, after evening the EV demand over 24 hours, the total demand curve becomes smooth, reducing the peak load at hour 21 from 100.24 kWh/h to 80.42 kWh/h. While the community's electricity demand still peaks at 21:00, the total demand curve has become flatter, with less peaking loads. It can not only improve the grid stability and reduce the risk of overloading.

Moreover, to further reduce the peak electricity loads and costs by EV charging, the Smart Charging Load Management Systems could be adopted. This system can automatically avoid existing peak periods and charge during off- peak hours when community demand is low, and electricity is cheap.

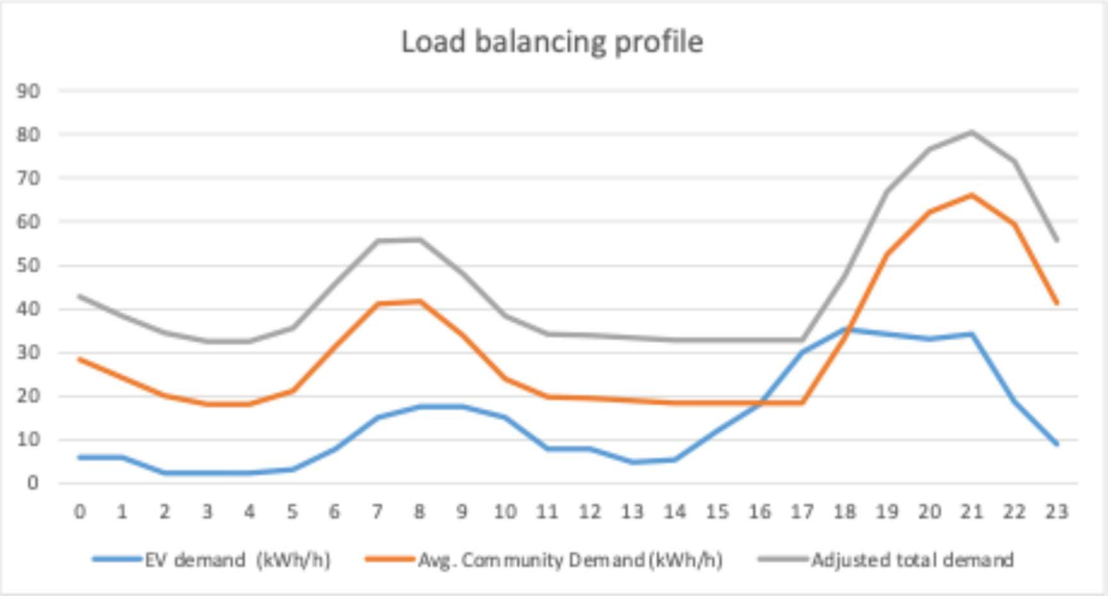


Figure 8. Bar chart of load balancing profile

3.4. Data Analytics

To help ESCO further understand the value of household energy data, a simple time series forecasting was used to measured and estimated daily electricity demand data.

3.4.1. Predict and Analyze Data

Initially, average daily electricity demand for each day of the week was calculated based on the data from January to November. Then, the average data were used to predict the energy demand for each day in December 2022.

The comparison between the measured and predict daily electricity demand for electricity demand for December is shown in Figure 9 as below. The mean absolute error (MAE) was calculated as 2724.47 kWh while the mean absolute percentage error (MAPE) was calculated as 38.7%.

$$MAE=\frac{1}{n}\sum_{i=0}^{n}|Ai-Pi|=\frac{84458.56kWh}{31}=2724.47\text{ kWh} \tag{11}$$

$$\text{MAPE}=\frac{1}{n}\sum_{i=0}^{n}\left|\frac{\text{Ai-Pi}}{\text{Ai}}\right|=\frac{12.00}{31}\times 100=38.7\% \tag{12}$$

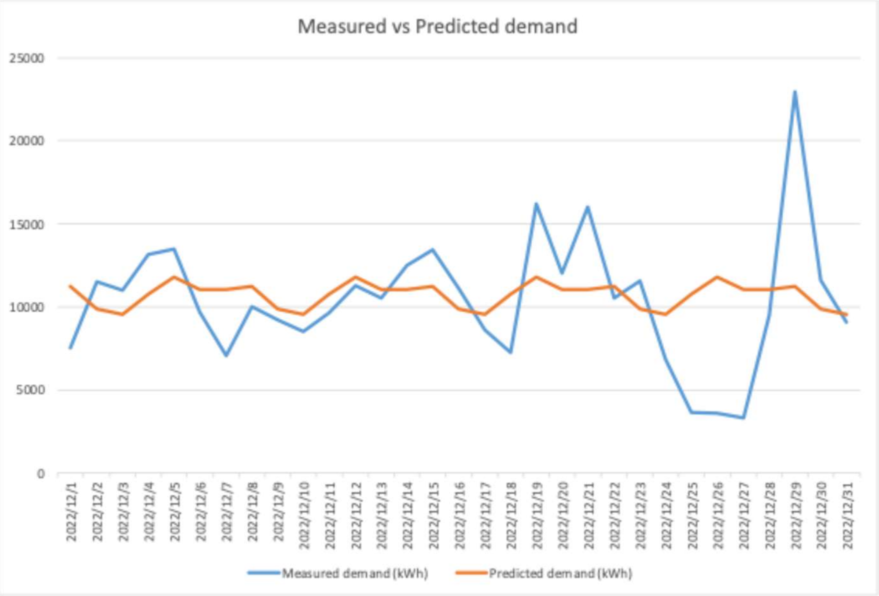


Figure 9. Bar chart of load balancing profile

3.4.2. Error Analysis and Future Implications

According to the excel data, the three days with the largest absolute prediction errors can be identified as Table 4.

Table 4. Three largest absolute prediction errors

Data	Measured demand (kWh)	Predicted Demand (kWh)	Absolute Error (kWh)
12.29	22947	11214.77	11732.23
12.26	3584	11776.08	8192.08
12.27	3302	11040.83	7738.83

The three days prediction errors over accounted to a significant portion of the overall error. December 26th and 27th were after the Christmas holiday, during which households' electricity consumption patterns may be different from usual. The actual electricity consumption decreased large amount from the average level of typical workday and causing significant prediction deviations. On December 29th, actual electricity consumption reached an abnormal peak, may be due to people return home after holiday or and working reasons.

If not excluded the three days from the error analysis, the overall MAE and MAPE will decrease significantly, indicating the prediction method is relatively reliable during normal working days and improve the forecasting model's accuracy.

$$\text{MAE}=\frac{1}{n}\sum_{i=0}^{n}|\text{Ai-Pi}|=\frac{5695.41\text{kWh}}{31}=2028.41\text{ kWh} \tag{13}$$

$$\mathrm{MAPE}=\frac{1}{n}\sum_{i=0}^{n}\left|\frac{\mathrm{Ai\text{-}Pi}}{\mathrm{Ai}}\right|=\frac{6.86}{31}\times 100=24.50\% \tag{14}$$

These abnormal situations indicate that simple prediction through weekly average have certain limitations. However, the reality factors such as holidays, special events and so on often influence the electricity consumption, which may lead to prediction errors. Thus, to further improve the accuracy of the prediction, it is suggested that introduce holiday or event markers in the model or adopt more advanced time series forecasting method such as ARIMA model and so on.

3.4.3. Data Privacy

Respecting users' privacy not only ensures legal compliance but also builds trust in community, which is important in data energy optimization initiatives. When collecting and utilizing household energy data, the ESCO must be aware of the following considerations:

- Comply with data protection regulations.
- Obtain explicit consent from residents before data collection and using.
- Use data anonymization techniques to prevent the exposure of identities of individuals.
- Store and process all collected data securely to protect against leaks or misuse.

These principles are in line with the UK's energy data governance framework, which emphasises transparency, informed consent, and secure storage of smart meter data [6].

4. CONCLUSION

This paper provided a detailed analysis of the current and upgrade energy systems of Trent Basin community. Initially, the annual and monthly electricity and gas consumption of the community was assessed through building energy consumption modelling and analysis, then compared with the typical UK residential building energy consumption errors. The results indicate that heating remains the main source of carbon emissions. Additionally, by comparing the simulation results with actual measurement data, the accuracy of the model was verified, with errors generally within reasonable limits.

Based on these findings, the paper suggests optimisation strategies for the existing electricity system, including expanding the PV array from 200 kWp to 400 kWp and increasing the battery capacity from 2 MWh to 3 MWh to effectively reduce indirect carbon emissions. By switching the heating method from gas boilers to air-source heat pumps (ASHP), the carbon emissions are expected to decrease by approximately 71%.

In summary, it is recommended that the ESCO invest in expanding the PV and energy storage systems, promote the application of heat pumps, and optimize power scheduling management to assist the Trent Basin community in achieving its carbon neutrality goal.

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