Techno-Economic-Environmental Analysis for Net-Zero Sustainable Residential Buildings

Ankita Garg
Department of Computer Science
Durham University, UK
ankita.garg@durham.ac.uk

Gagangeet Singh Aujla
Department of Computer Science
Durham University, UK
gagangeet.s.aujla@durham.ac.uk

Hongjian Sun
Department of Engineering
Durham University, UK
hongjian.sun@durham.ac.uk

***Abstract*—Carbon emissions are becoming a global concern responsible for climate change. The renewable energy sources (RESs) such as wind, solar, biomass are gaining importance to reduce emissions in the energy sector. However, these sources depend highly on various technical, economical, and environmental conditions and hence, a planned strategy is required to place different RESs based on their suitability. This paper presents a detailed analysis on energy purchased/sold, costs associated with installing new RESs and the operational costs of existing electricity sources to reduce the total carbon emissions in the UK's residential sector. Further, the case-study presented in this paper could be used by the builders to design the new residential buildings with low dependency on the grid, hence, aligning with the goal of net-zero emissions. Moreover, it would spread awareness among the energy users that renewable energy can generate revenue for individual households by simultaneously contributing towards saving the environment.**

***Index Terms*—carbon emissions, revenue generation, techno-economic-environmental parameters**

I. Introduction

Renewable energy contributed approximately 39.33% of the total electricity generation in the UK in 2020 [1]. As per the Paris Climate Agreement, to maintain the global warming temperature below 1.5 degree Celsius and to meet net-zero carbon emissions by 2050, the investment on renewable energy would increase by 25% over the next decade [2]. These renewable energy sources (RESs), however, come with inherent uncertainties (such as intermittency in generation) that need to be evaluated and therefore, optimal planning for renewable energy plants is required to replace the conventional fossil fuel-based plants and maintain the energy security. Solar and wind constitute the largest part in the total renewable energy generation. Interestingly, these clean sources of energy individually are sufficient to power the entire mankind. However, due to their intermittent nature and expensive initial investment, currently it is not possible to rely completely on only a single type of RES. For instance, solar energy is unevenly distributed across the planet therefore, some areas have more irradiance than others. Moreover, less solar energy is available on cloudy days or at night. Further, the efficiency of a solar cell itself is a challenge [3]. Moreover, in addition to the fluctuation in wind energy generation, no matter how large or efficient a turbine is, there is a limit to how much wind it can convert into electricity [4]. Therefore, different energy sources are integrated to form a hybrid energy system to maintain the energy security.

To leverage the available natural resources, smarter and efficient ways of deploying renewable energy plants needs to be employed and decentralised generation is one of them. Solar and wind plants can be built near the urban areas to provide affordable energy to the local households. This would reduce the dependency on the utility grid contributing to reduction in the fossil fuel-based energy generation and stepping towards a greener environment. In this regard, many researchers [5]–[10] are working on finding out the optimal combination of various renewable energy plants resulting in reduction in carbon footprints and cost per kWh based on the constraints such as location, weather, market trend, and other economic parameters (initial investment, payback period etc). For instance, in [8], a new model was proposed to reduce Iran's carbon footprints by considering different scenarios on renewable energy subsidies, and tariff variations. In [9], the effect of carbon emissions on agriculture was analysed and the role of RESs to reduce this problem. An eco-industrial park scheme was discussed in [10] to encourage industries to rely on renewable energy generation wherein the excess energy could be given to the nearby urban areas.

The energy sector contributed around 73.2% (24.2% by Industries, 16.2% by transportation, 17.5% by the residential buildings) of the total global carbon emissions in 2020 [1]. Often the residential sector is overlooked as it deals directly with consumer-end, however, it is important to reduce its emissions as it accounts for approximately one-fifth of the global emissions in the world [1]. Motivated from this, the main contributions of the paper are:

- Comparative analysis of different combinations of renewable energy generation and utility grid based on the technical, economic and environmental parameters to meet the load demand for the UK's residential sector.
- Optimal combination of RESs using Mixed Integer Linear Programming (MILP), and the validation of results using a simulation software.

Technical parameters discussed in this article includes the amount of energy generated from different sources, electricity purchased and sold to the grid, whereas, economic parameters cover costs associated, lifetime and payback period of the specified configuration. There are three types of costs discussed in this paper termed as net present cost (NPC), levelised cost per kWh of the energy produced (LCOE), and utility bill savings. NPC is defined as the difference between total cost that the designed project incurs (including capital cost, operational and maintenance cost) and the total revenue of the project over its lifetime. The environmental parameters include the total carbon emissions associated with different system configurations. Based on these parameters, the optimal solutions are classified in terms of cost and emissions that can be used as a decision making factor for the consumer to decide the type and capacity of the energy resource(s) on which they desire to power their homes.

II. Model Description

The techno-economic-environmental analysis in this paper is performed on a residential sector consisting of load(s), solar panels, wind turbine, battery storage, converter and the utility grid. Each of these are discussed briefly as below:

A. Load:

The electric load considered in this model is a residential building complex located in London, UK. The hourly demand data is generated for an entire year for these houses based on [11]. Figure. 1 depicts the monthly power demand for the residential sector where January month contributes towards the highest consumption and September towards the lowest.

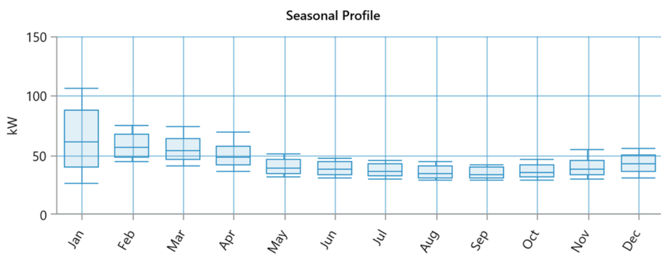

Fig. 1: Monthly profile of the residential sector

Moreover, it has been found that the largest annual peak demand occurred on 13^{th} January as shown in the Fig. 2. The reasons behind that are: 1) weekend during which people prefer to spend time with their families at home 2) the lowest temperature went to $-1^{o}C$ with high wind speeds. Therefore, instead of going out, residents must be at home most of the time doing household chores, watching movies, etc. which increased the electricity consumption.

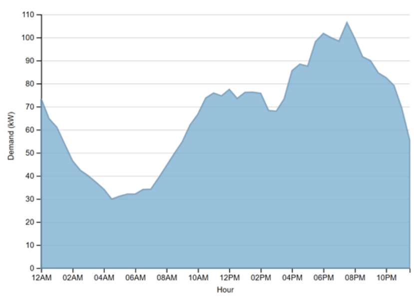

Fig. 2: Energy profile of the peak demand day

B. Solar Panels:

Solar panels are made up of small units called solar cells. The panels are connected in series and parallel to harness the solar energy and convert it into power. Light from the sun (also called solar irradiation) stimulates electrons on a solar panel that create direct current (DC) power. However, the derating factor and the temperature of the PV panels have a negative effect on the DC produced in proportion to the solar irradiation. Taking this into account, the power produced by the PV can be mathematically calculated as [7]:

$$P_{pv}(t) = \beta P_{peak} D_{pv} \left[\frac{G_T(t)}{G_{STC}}\right] [1 - \alpha_p(T_C - T_{C,STC})] \quad (1)$$

where P_{peak} is the peak PV module output power, D_{pv} is the derating factor (%), α_p is the power temperature coefficient, $G_T(t)$ and G_{STC} are solar irradiance incident on PV module at time t (kW/m^2) and under standard testing conditions respectively, T_C and $T_{C,STC}$ are PV panel temperature and PV cell temperature under standard testing conditions respectively, $\beta = N_s \times N_p$, i.e., number of panels connected in series and parallel respectively.

C. Wind Turbine:

The wind energy can be modelled as a series of blades mounted around a rotor catch the wind and translate its kinetic energy into rotational energy. Traditional windmills use this concept to grind wheat or pump water; whereas modern wind turbines turn a generator that creates electricity. This conversion from wind's rotational energy to electricity can be calculated as [6]:

$$P_w(t) = \alpha \mu P_w^r \quad (2)$$

where:

$$\mu = \begin{cases} 0 & ; \quad V(t) \leq V_i \ or \ V(t) \geq V_o \\ \frac{V(t)-V_i}{V_r - V_i} & ; \quad V_i \leq V(t) \leq V_r \\ 1 & ; \quad V_r \leq V(t) \leq V_o \end{cases} \quad (3)$$

where $V(t)$ is wind speed at time t, V_i and V_o are cut-in and cut-off wind speed respectively, V_r is rated wind speed, and P_w^r is rated power of wind turbine. α is the number of wind turbines installed. There are three primary factors that determine just how much energy turbines can produce: size and orientation of the blades, aerodynamic design of the blades, and the amount of wind turning the rotor.

D. Battery Energy Storage System (BESS):

The energy generated from the RESs gets stored in the battery during the off-peak period and could be used during the peak demand hours. BESS maximises the utilisation of energy generated by renewable sources and hence, contributes towards stable operation during the situation of mismatch between the energy generation and demand. The instantaneous power that could be supplied by the battery $P_B(t)$ can be defined as [7]:

$$P_B(t) = P_{pv}(t) + P_w(t) + P_g(t) - P_l(t) \quad (4)$$

where, $P_g(t)$ is the power fed by the utility grid and $P_l(t)$ is the instantaneous load demand.

E. Converter:

Power converters are employed to convert DC power to AC and vice-versa. For instance, DC electricity generated by PV panels is converted to usable electricity before sending to the consumer. In addition to this, AC power is converted into DC by the converter to charge the battery. The power conversion can be determined as follows [5]:

$$P_o^i = \eta_i P_{dc} \tag{5}$$

$$P_o^r = \eta_r P_{ac} \tag{6}$$

where, P_o^i is the power output from the inverter (kWh), P_o^r is the rectified inverter output to the battery, P_{dc} and P_{ac} are the DC and AC powers respectively, η_i and η_r are the inverter and rectifier efficiencies respectively.

F. Utility Grid:

It represents the local utility company that supplies electricity to the residential load. The tariff rates, demand charge, consumption charges for which are considered as per the standard UK energy rates [12].

III. Optimisation Problem Formulation

In this section, the optimisation problem is formulated using MILP (multi-integer linear programming) to determine the optimal size of wind turbines, solar panels and energy storage required to meet the energy demand. The objective is to minimise the total cost of the system with more penetration of RESs to reduce the carbon emissions while ensuring reliable and sustainable power supply. The decision variables in this MILP optimisation problem are the number of solar panels (β), wind turbines (α) and batteries (γ) needed for the optimal operation to minimise the system annual cost (SAC) of the residential buildings over the time period T. The objective function can be formulated as:

$$\min(SAC) = \sum_{t=1}^{T}(\beta C_{pv}(t) + \alpha C_w(t) + \gamma C_b(t) + P_o^i C_{in}(t)) \tag{7}$$

where α, β and γ are integers subjected to

- Power Balance Constraint

$$\sum_{t=1}^{T}(P_{pv}(t) + P_w(t) + P_b(t) + P_g(t)) \geq P_l(t) \tag{8}$$

- Capacity Constraints

$$P_{pv}^{min} \leq P_{pv}(t) \leq P_{pv}^{max} \tag{9}$$

$$P_w^{min} \leq P_w(t) \leq P_w^{max} \tag{10}$$

$$SOC^{min} \leq SOC(t) \leq SOC^{max} \tag{11}$$

- Economic Constraints

$$\sum_{t=1}^{T}(\beta C_{pv}(t) + \alpha C_w(t) + \gamma C_b(t) + P_o^i C_{in}(t)) \leq B \tag{12}$$

TABLE I: Abbreviation Table for optimisation problem

Abbreviation	Description
C_{pv}	Solar power generation cost
C_w	Wind power generation cost
C_b	Battery operational cost
C_{in}	Invertor operational cost
$P_{pv}^{min}, P_{pv}^{max}$	Lower and upper solar power capacity
P_w^{min}, P_w^{max}	Lower and upper wind power capacity
SOC^{min}, SOC^{max}	Lower and upper state of charge (SOC) of battery
B	Budget for the installation
CE_{sys}	System Carbon emissions
CE_{per}	Permissible carbon emissions

- Environmental Constraints

$$\sum_{t=1}^{T} CE_{sys}(t) \leq CE_{per}(t) \tag{13}$$

The description of these variables is presented in Table I. The values of C_{pv}, C_w, C_b and C_{in} include the capital, replacement, salvage, operational and maintenance costs of solar panels, wind turbines, battery units and inverters respectively.

IV. Results & Discussion

In this paper, results were obtained for different configurations of energy generation sources (Grid, Solar and Wind) using MILP optimisation and then validated using HOMER (hybrid optimisation of multiple energy resources) for the residential load consisting of 200 households in London, UK [11]. The overall process to simulate the system was divided into three parts as (also shown in Fig. 3):

- **Data Collection**: The data was collected based on the individual energy demand for 200 households. The data was then aggregated to create the total electricity demand of the complete residential sector. Further, the weather profiles and economic attributes of the residential area were collected, which along with the energy data were fed to the energy model.
- **Hybrid Energy Optimiser**: The hybrid energy model was designed by connecting solar panels, wind turbines, battery, converter and utility grid to the residential load. The collected data was fed to this model according to which the simulation parameters (such as load demand, weather conditions, geographical conditions, energy rates and tariff etc.) were set and finally, the MILP optimisation was carried out for different combinations of the energy sources to meet the load demand.
- **Decision Making**: The key concept used to decide the feasibility of result was that at every time step, the load demand was being met under the specified conditions. The technical, economical and environmental parameters were calculated to compare different simulation results. This could help the consumer to choose between cost and emissions of the electricity for their homes.

Out of the various feasible solutions obtained after simulating the energy system with distinct combination of energy resources, three best possible solutions (or cases) were selected

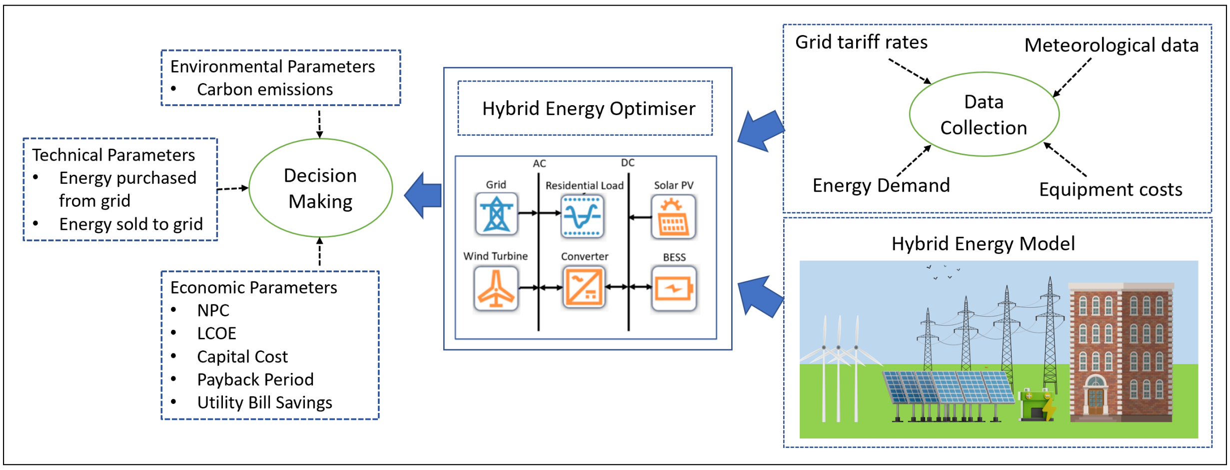

Fig. 3: Techno-economic-environmental analysis process

and discussed based on carbon emissions, utility bill savings, energy sold and energy purchased (shown in Table II) These cases were a) grid, b) grid, solar PV, wind, BESS, and c) grid and wind, connected to the residential load.

A. Case A: Grid only

In this scenario, there was no renewable generation to avoid the initial capital investment and the residential load was solely dependent on utility grid to meet its load demand. There was only one way flow of energy, i.e., electricity was purchased from the grid. Although with the zero capital investment in this case, there were no savings in the total utility bills and it contributed to over 240 tonnes/yr of carbon footprints.

B. Case B: Wind+Solar+BESS+Grid

This was a zero-emissions case that considered a low carbon energy system having both solar and wind in addition to the grid connectivity as a backup. In Table II, it can be seen that it was possible to generate revenue by saving the electricity bills of upto £0.2M/yr with negligible carbon emissions. However, the initial investment was approximately £9M, which is quite high for a normal household. There are government support schemes available for increasing renewable penetration by giving subsidies to install more renewable plants locally.

C. Case C: Wind+Grid

As reflected in Table II, this case discussed a trade-off between cost and emissions, to provide a practical solution for solving the energy needs in the present scenario of rising energy prices. In this system, the total savings on total utility bills were upto £0.1M/yr having less initial capital investment (than Case B) with the payback period of 6.2 yrs. This would also help in decarbonisation efforts of the residential sector with significantly less emissions as compared to Case A. Moreover, with the continuous upgrades in the power electronic devices, the cost of installing on-shore and off-shore wind turbines is becoming cheaper.

The above-mentioned cases highlight the fact that reduction in the carbon emissions can be achieved by increasing the renewable energy penetration in the existing energy systems, resulting in increasing the investment costs. In contrast, with the existing grid, the load demand can be met, however, the target of zero emissions can not be achieved. Therefore, a trade-off between emissions and cost provides an optimal solution (as discussed in Case C) while designing the capacity of renewable plants in a residential sector (as shown in Fig. 4). Figure 5 shows the contribution of different sources of energy to meet the demand under the optimal conditions (Case C) obtained after MILP optimisation. As winds were stronger in London (as compared to solar irradiation), wind energy contributed the largest amount to meet the load demand. Therefore, the results obtained suggest that wind energy alone was able to supply the load, and the investment costs for installing other renewable energy plants (such as solar panels, BESS) should be avoided. However, there is a need for backup (either grid or other RES) to meet the load demand whenever winds are not strong to generate enough energy. Furthermore, the energy sold by the households was higher than the energy purchased from the grid (as depicted from Fig. 6) resulting in the overall profit to the energy user and simultaneously contributing towards the greener environment.

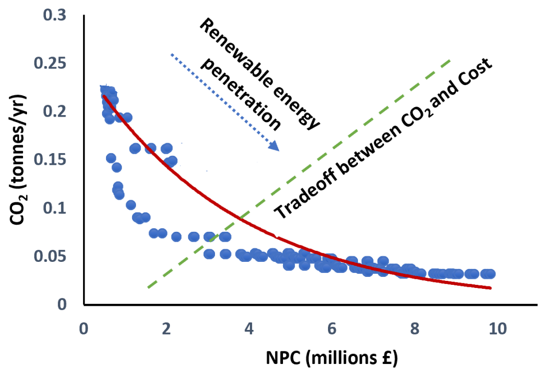

Fig. 4: Relationship between carbon emissions and NPC

TABLE II: Techno, Economic and Environmental parameters of a UK's residential complex

		Case A: Grid only	**Case B: Solar+Wind +BESS+Grid**	**Case C: Wind+Grid**
Architecture			PV capacity- 1046 kW Wind Capacity - 600 kW BESS - 580 strings each 1kWh	Wind Capacity - 800 kW
Technical Parameters	Energy purchased (kWh/yr)	381,516	4,000	84,000
	Energy Sold (kWh/yr)	0	3,544,514	1,991,185
Economic Parameters	NPC (£)	0.5M	8.2M	3.1M
	LCOE (£/kWh)	0.35	0.11	0.187
	Capital Cost (£)	0	8.95M	1.8M
	Payback Period (yr)	–	18	6.2
	Utility Bill Savings (£/yr)	-38,151	176,285	91,159
Environmental Parameters	Carbon Emissions (Kg/yr)	241,118	3870	53,000

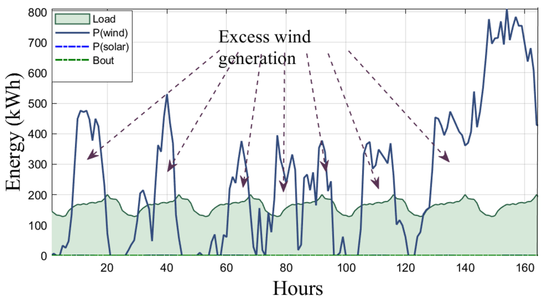

Fig. 5: Energy generation by RESs to meet demand

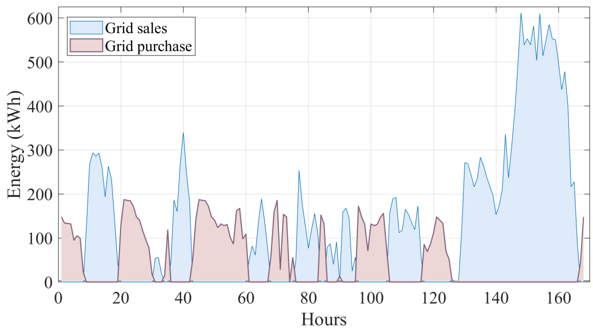

Fig. 6: Hourly energy sold and purchased from the grid

V. Conclusion

The techno-economic-environmental analysis presented in this paper highlighted different feasible combinations of distinct energy sources that could be employed to power the UK's residential sector. Given the renewable energy penetration in the energy systems and the cost associated to replace the existing energy system with the renewable energy systems, this paper presented an optimal planning solution – a trade-off between cost and emissions for the considered residential load. The environmental analysis carried out in this paper suggested the dominance of installing wind turbines based on the weather profile of the area. Technical analysis deduced the amount of energy exchange between the households and the grid, whereas economic parameters advised the energy users about the profit and the pay-back period for the optimal case.

In the future, we will focus on modelling the uncertainties in RESs to make the residential building energy model robust under the abnormal conditions.

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References

[1] H. Ritchie, M. Roser, and P. Rosado, "CO_2 and greenhouse gas emissions," *Our World in Data*, 2020. [Online]. Available: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

[2] P. Bojek, "Solar PV," 2022. [Online]. Available: https://www.iea.org/reports/solar-pv

[3] J. Ramanujam and U. P. Singh, "Copper indium gallium selenide based solar cells–a review," *Energy & Environmental Science*, vol. 10, no. 6, pp. 1306–1319, 2017.

[4] G. D'Amico, F. Petroni, and S. Vergine, "Ramp rate limitation of wind power: An overview," *Energies*, vol. 15, no. 16, p. 5850, 2022.

[5] O. Krishan and S. Suhag, "Techno-economic analysis of a hybrid renewable energy system for an energy poor rural community," *Journal of Energy Storage*, vol. 23, pp. 305–319, 2019.

[6] T. Ma and M. S. Javed, "Integrated sizing of hybrid PV-wind-battery system for remote island considering the saturation of each renewable energy resource," *Energy conversion and management*, vol. 182, pp. 178–190, 2019.

[7] N. M. Kumar, S. S. Chopra, A. A. Chand, R. M. Elavarasan, and G. Shafiullah, "Hybrid renewable energy microgrid for a residential community: A techno-economic and environmental perspective in the context of the SDG7," *Sustainability*, vol. 12, no. 10, p. 3944, 2020.

[8] A. Mostafaeipour, A. Bidokhti, M.-B. Fakhrzad, A. Sadegheih, and Y. Z. Mehrjerdi, "A new model for the use of renewable electricity to reduce carbon dioxide emissions," *Energy*, vol. 238, p. 121602, 2022.

[9] R. Chopra, C. Magazzino, M. I. Shah, G. D. Sharma, A. Rao, and U. Shahzad, "The role of renewable energy and natural resources for sustainable agriculture in ASEAN countries: Do carbon emissions and deforestation affect agriculture productivity?" *Resources Policy*, vol. 76, p. 102578, 2022.

[10] M. Butturi, F. Lolli, M. Sellitto, E. Balugani, R. Gamberini, and B. Rimini, "Renewable energy in eco-industrial parks and urban-industrial symbiosis: A literature review and a conceptual synthesis," *Applied Energy*, vol. 255, p. 113825, 2019.

[11] G. Piggott, "Electricity consumption in a sample of london households," 2015. [Online]. Available: https://data.london.gov.uk/blog/electricity-consumption-in-a-sample-of-london-households

[12] Energy & Industrial Strategy, "Energy bills support factsheet," *Department for Business*, Nov 2022. [Online]. Available: https://www.gov.uk/government/publications/energy-bills-support