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Estimation of Load Behaviour, Insulation Capacity and Designing an Optimal Photovoltaic System for Residential Consumption

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ABSTRACT: Harvesting energy from renewable sources could assist carbon emission reduction, limiting global warming and mitigate the growing energy demand. The research was set out to estimate the load behaviour, insulation capacity and design an optimal photovoltaic (PV) system for residential consumption, and to carry out an environmental techno-economic analysis of the PV system using cash flow analysis and environmental impact analysis using standard methods. In this research, a Solar PV net capacity of 1,839kWh was achieved for residential building with total energy consumption of 3258kWatt-year and the remaining load generated from the grid, due to the limitation posed by roof space. The system was designed for optimal solar energy generation and economic performance such as capital cost, net present value, internal rate of return (considering fuel escalation) and the overall cash flow on investment was established. An estimate of CO_2 emissions prevention was conducted to determine and evaluate the environmental impact of the system. Result showed that investing in a renewable energy alternative such as Solar PV yields comparative economic benefit.

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Energy demand for services to satisfy the social, economic, welfare and health development of humans have increased over time. Thus, the drive towards the generation of this needed energy from sources, such as fossil fuel, coal and gas-powered plants, at all costs, despite their obvious environmental challenges has gained corresponding increase (Edenhofer *et al*., 2011; Alami *et al*., 2022). Greenhouse gas emission from these dirty energy sources has been an issue of environmental concern over the years due to the excess utilization of fossil fuels thus affecting humans and endangering other living species. Anthropogenic Greenhouse gas such as Carbon dioxide currently accounts for the greatest portion of global warming associated with human activities (EPA, 2020). However, cubing these energy contributions to climate change as well as securing clean energy supply are the two major challenges of the energy sector towards attaining a sustainable future (Owusu and Asumadu-Sarkodie, 2016). Consequently, utilizing energy from renewable sources such as wind, solar, biomass, tides, waves and geothermal heat (Maka *et al*., 2021) can help in decarbonizing the environment, limiting global warming and mitigating the growing energy demand thus accelerating the drive towards carbon neutral goal by 2050 (Eid *et al*., 2022; U.N Secretary-general annual report, 2020). Solar energy potential has gained popularity due to the growing attention of the world's population in the development of renewable energy. It involves the utilisation of incident solar radiation to produce electricity without carbon dioxide (CO_2) emission (Maka *et al*., 2021). It is an efficient, clean, economical, sustainable and environmentally friendly source of energy (Alami *et al*., 2022). Solar PV system has gained the most global adoption compared to other renewable energy technologies with 98GW overall capacity growth in 2019 estimated to be 60% of other renewable types (IRENA 2020 as cited in Alami *et al*., 2022). Behind-the-meter (BTM) PV systems have been favoured for most residential and commercial use

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due to their low consumer costs, state-mandated renewable policies, trend towards decentralized grid and the need for innovative business models. However, some of its challenges include solar radiation fluctuation, shading, soiling, weather dependency (Alami *et al*., 2022; Erdener *et al*., 2022). Hence, this research is aimed at designing an environmental techno-economic PV system for home consumption and its sustainability. Energy security, sustainable development and wellbeing play key roles in driving energy policy throughout the world thus necessitating a fine balance of environmental sustainability with necessary economic development (Prasad *et al*., 2019; Awan, Imran and Munir, 2014; Goldthau, 2013). Hence, there is the two intertwined issues, i.e., meeting the rising energy demand and limiting its environmental impact, faced in the 21st century (Verbruggen, 2010 as cited in Owusu and Asumadu-Sarkodie, 2016). Consequently, various countries' leadership have been encouraging environmentally friendly renewable energy, conservation strategies and technological innovations by engaging in developing regulations and related policies (Lu *et al*., 2020). A strategically designed sequence of actions which includes both local and global policy level is necessary in achieving a systematic transition towards more efficient energy regime. Policy tools such as tradable emission rights, taxes, and subsidies, as well as regulation such as feed-in-tariffs for renewable energy production have been introduced (Goldthau, 2016 as cited in Lu *et al*., 2020). These initiatives by local authorities, towards implementing sustainable policies, includes mitigating carbon emission to less than 40% by 2030 (compared to baseline), climate change adaptation as well as access to secure, sustainable and affordable energy (Martins *et al*., 2022). Generally, the electricity markets serve as a powerful energy system integrator due to the diversity of power generation sources (such as wind, solar, hydro, biomass, geothermal, fossil fuel and gas) that produces exact same resource (electrons) (Goldthau, 2013). However, the rate of global commercial energy consumption of these renewable sources (particularly, solar energy) is thousands of times smaller than the energy flows from the sun to the earth (World Energy Assessment, 2000). The objectives of this work is to estimate the load behaviour, insulation capacity and design an optimal PV system for residential consumption, and to carry out an environmental techno-economic analysis of the PV system using cash flow analysis and environmental impact analysis.

MATERIALS AND METHODS

The methodology is structured as follows: Consumption Capacity, PV design, Techno-economic analysis and Environmental Impact assessment.

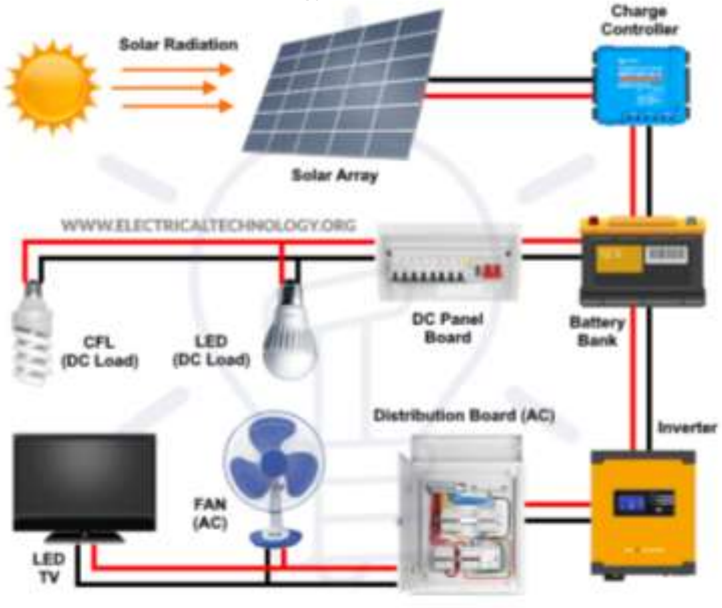

Fig 1: Off-grid Solar PV set up. Source: https://www.electricaltechnology.org

Electricity Consumption Capacity: Electricity consumption capacity represents the amount of electrical energy that will be consumed over a specific time, in units of Wh (or kWh). The Site Location for the electricity consumption capacity study was No7, Lord Nelson Street, Sneinton, Nottingham, United Kingdom. NG2 4FA

$$AEC\ (KWyr) = \left(Rating\ (KW\right) \times \left(Hour\ of\ use(h/day)\right) \times 365days/yr\Big) \quad (1)$$

Where AEC = Annual Electricity Consumption (KWyr)
Average Unit rate of electricity (p/kWh) = 20 p/kWh (www.gov.uk)
Annual Electricity Payment (£) = Total Annual Energy Consumption (KWyr) × Average Unit rate of electricity (p/KWh) × £0.01/p = 3258(KWyr) × 20(p/KWh) × £0.01/p= £651.6

Solar PV design: The Solar PV is designed as fixed roof-mounted smart grid type and it is represented by the design flowchart in figure 2.

Table 1: Electricity Consumption Capacity (www.electricitycalculator.net)

No	**Appliance**	**Qty**	**Rating (KW)**	**Hour of use (h/day)**	**daily Consumption (KWh)**	**Annual Energy (kWh/yr)**
1	Light bulb	10	0.007	10	0.07	26
2	Refrigerator	1	0.75	8	6	2190
3	Washing Machine	1	0.8	0.5	0.4	146
4	Blinder	1	1	0.5	0.5	183
5	Electric Kettle	1	1	0.5	0.5	183
6	Toaster	1	1	0.25	0.25	91
7	Tv	1	0.1	4	0.4	146
8	Laptop	4	0.06	8	0.48	175
9	Mobile phone charger	6	0.015	5	0.075	27
10	Microwave	1	1	0.25	0.25	91
Total Annual Energy Consumption						3258

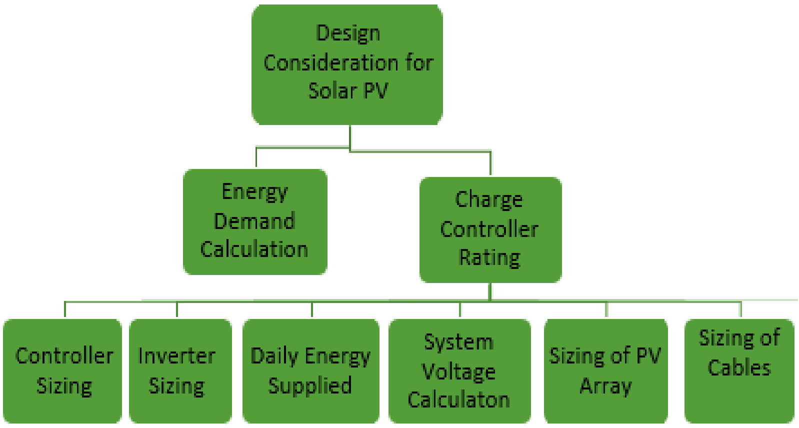

Fig 2: Solar PV design flow chart

Solar PV system Capacity = 2.4kWdc (16m²) > the calculated PV capacity.


System Capacity: 2.4 kWdc (16 m2)

Fig 3: System Capacity for Resident (7 Lord Nelson Street, Nottingham) Source: PVWatts Calculator (nrel.gov)

Table 2: Solar PV System Specification (PVWatts Calculator (nrel.gov)

Period	Average Solar Radiation (kWh/m²/day)	AC Energy (kWh/yr)
Annual	2.88	1,839
PV System Specification		
Location	7 Lord Nelson, Street, Nottingham	
DC System Size	2.15KW	
module Type	Standard	
array Type	Fixed (Rood Mount)	
array Tilt	20°	
array Azimuth	180°	
System Losses	14.08%	
Inverter Efficiency	96%	
DC to AC Size Ratio	1.2	
Capacity Factor	9.80%	

Solar PV Installation Price
According to Solar photovoltaic (PV) cost data - GOV.UK (www.gov.uk),
Installation Price of solar PV with capacity ranges 0-4KW= £1628/KW
Total Solar PV installation Price (£)
= PV system Capacity (kW, dc) × Installation Price of PV (£/KW)
= 2(kW, dc) × £1628/KW = £3,256
Annual Electricity Saved using PV (£):
Total Annual Energy Saved (KWyr) × Average Unit rate of electricity (p/KWh) × £0.01/p = 1839(KWyr) × 20(p/KWh) × £0.01/p= £367.8/yr

Techno-Economic Consideration
The annual Simple payback for PV installation (SPPV) may be computed as

$$\text{SPPV}\ (yr) = \frac{\text{Extra Fist cost(£)}}{\text{Annual Savings}(\frac{\text{£}}{\text{yr}})} \qquad (2)$$

$$= \frac{\text{£3,256}}{\text{£367.8/yr}} = 8.85yrs$$

Initial (Simple) Rate of Return (iROR): That is, it is the ratio of the annual savings to the extra initial investment:

$$\text{iROR} = \frac{\text{Annual Savings}(\frac{\text{£}}{\text{yr}})}{\text{Extra First Cost (£)}} \qquad (3)$$

$$= \frac{\text{£367.8/yr}}{\text{£3,256}} = 11\%yr^{-1}$$

Present Value Factor (PVF):

$$PVF(d,n) = \frac{(1+d)^n - 1}{d(1+d)^n} \qquad (4)$$

(Assuming a discount for best alternative investment earns 7.8% for a capital ΔP =£3,256 for n (Say 15yrs) period, the PVF (d, n) = 8.66 (Table 1).

NPV and IRR with Fuel Escalation (e)

Equivalent discount rate with fuel escalation (d')

$$d' = \frac{d-e}{1+e} \qquad (5)$$

IRR with fuel escalation, has a present value of the escalating series of annual savings equal to the extra initial principal (Gilbert, 2013)

$$NPV = \Delta\text{A} \times \text{PVF}(d',n) - \Delta\text{P} = 0 \qquad (6)$$

I.e. $PVF(d',n) = \frac{\Delta\text{P}}{\Delta\text{A}}$

$$IRR_e = IRR_0(1+e) + e \qquad (7)$$

Where IRR_0 = Internal Rate of return without fuel escalation, IRR_e = Internal Rate of return with fuel escalation
Assuming a Fuel Escalation (e) = 3% (Table 1).

Cash Flow Analysis: This is carried out using an excel spreadsheet in order to account for complicating factors such as fuel escalation, tax-deductible interest, depreciation, periodic maintenance costs, and disposal or salvage value of the solar PV at the end of its lifetime.

Capacity Factor

$$CFR = (i,n)\frac{i(1+i)^n}{(1+i)^n - 1} \qquad (8)$$

$$A = P \times CFR(i,n) \qquad (9)$$

Where, A represents annual loan payments (480.91£/yr), P is the principal borrowed (£3,256), i is the interest rate given as 7.8%, and n is the loan term (yrs) taken as 15yrs. Therefore, CRF (i, n) = 0.1154/yr by substitution in the formular above.

Environmental Impact Assessment
Amount of CO2 Emission Prevented:

According to Gilbert, 2013,
One Rosenfeld = Energy saving of 3billion KWyr and an annual Carbon reduction of 3million metric tons of CO2.
Given an annual energy saving of the solar PV as 1,839 KWyr.

Total number of similar Capacity of solar PV to achieve one (1) Rosenfeld

$$= \frac{3\text{billion KWyr}}{1839\text{KWyr}} = 1.6 million\ units$$

Capacity Factor (CF):

$$CF = \frac{\text{Annual energy}\left(\frac{\text{KWh}}{\text{yr}}\right)}{\text{Power Rating (KW)}\times\frac{8760\text{KWh}}{\text{yr}}} = \frac{1839\ \left(\frac{\text{KWh}}{\text{yr}}\right)}{2\text{KW}\times 8760\text{KWh/yr}} = 0.105(10.5\%)$$

RESULT AND DISCUSSION

Results from the electricity consumption capacity to the solar PV design show that the smart grid solar PV reduces on-grid energy demand from 3258kWyr to 1419kWyr thereby resulting in an annual saving of £367.8. It is observed that Simple Payback and Initial Rate of Return gives a simple estimation of the viability of the project while assessing the latter for its economic benefits. However, its information can be a little too trivial in order to either accept or reject the proposed project. Thus, there is the need to carry out further analysis such as the net present value estimation, internal rate of return (with and without fuel escalation) and the cash flow analysis for loan repayment (present value factor). The solar PV with an extra cost £3,256, saving £367.8/yr (i.e., simple payback of Simple Payback of 8.85) with a lifetime of 15 years has IRR without fuel escalation of value between 7% and 8% (Gilbert, 2013. Pp267) which gives approximately 7.8% by interpolation.

Table 3: NPV and IRR with and without fuel escalation for 7.8% discount

d (%)	ΔP/ ΔA	n (yr)	PVF (yr)	NVF (yr)	e (%)	d' (%)	PVF' (yr)	NPV' (£)
0.078	8.85	**15**	8.66	**-69.01**	0.3	0.0466	10.622	**650.85**

Table 3 above shows a comparative increase in NPV considering an assumed fuel escalation of 3%. Also, using the relationship $IRR_e = IRR_0 (1 + e) + e$, for $IRR_0 = 7.8\%$, IRR_e is 0.1103 (11%). Meaning NPV increases with increasing fuel escalation and reducing discount). From session 3.4.5, a cash flow analysis was conducted to analyse energy investment. Complicating factors such as fuel escalation, personal discount and salvage value of the equipment at the end of its lifetime was accounted for following global speculation. However, tax-deductible interest was not considered as same has become obsolete in UK's energy policy. Consequently, considering an investment of £3,256, 7.8% interest loan and assuming an electricity price escalation of 3%/yr, it was observed that the minimum loan term year that makes the cash flow positive from the beginning is 15yrs, as also observed from Figure 6 below. With a personal discount factor of 10%, result from excel spreadsheet showed that 15 annual payments of £375.76 is required.

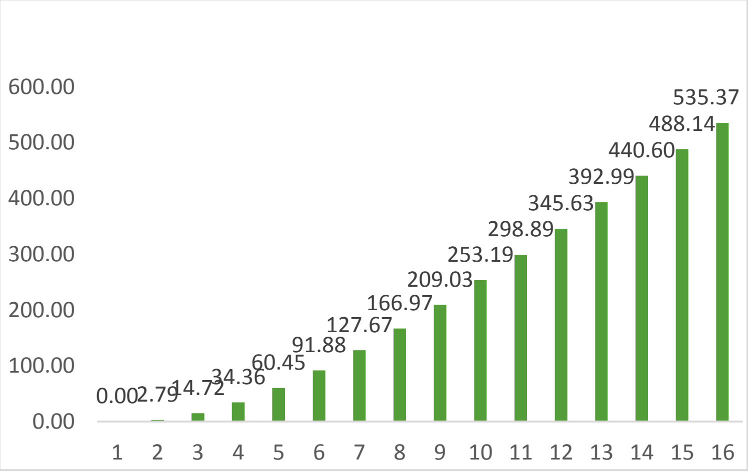

Fig 4: Cash Flow Graph

Result from session 3.5 show that One Rosenfeld (Energy saving of 3billion kWh/yr and an annual Carbon reduction of 3million metric tons of CO_2) can be achieved by installing about 1.6million units of 2kw Solar PV in UK. With an estimated 27.8million household in UK (www.ons.gov.uk), the above installation units represent about 5.8% of households in UK. Also, given that 1,000kWh of solar-generated electricity save 0.3 tonnes of CO_2 annually (www.theecoexperts.co.uk), thus the designed PV (1,839kWh) will save 0.55 tonnes of CO_2. Estimation of the system's capacity factor (session 3.5) is about 10.5% in same range as that achieved using PVWatts Calculator (9.8%) (www.nrel.gov) in Table 2.

Conclusion: Non-dependence on carbon fuel sources prove to play major role in reducing carbon emission. In this research, a solar PV smart grid system has been designed considering techno economic viability as well as environmental impact of the system. This work shows that solar PV remains one of the best alternatives for the future generation of electricity, due to the introduction of policies such as demand response and smart grid connection thus offering high energy resources.

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