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Integrated optimisation of photovoltaic and battery storage systems for UK commercial buildings

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HIGHLIGHTS

- Optimal model for selection and operation of photovoltaic and battery systems.
- Building features and attributes are considered in the analysis.
- Preferred design and operation influenced by real-time price models of electricity.
- Revenues can be derived from providing Firm Frequency Response services.
- Model provides financial indicators to reduce real-world investment uncertainty.

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ABSTRACT

Decarbonising the built environment cost-effectively is a complex challenge public and private organisations are facing in their effort to tackle climate change. In this context, this work presents an integrated Technology Selection and Operation (TSO) optimisation model for distributed energy systems in commercial buildings. The purpose of the model is to simultaneously optimise the selection, capacity and operation of photovoltaic (PV) and battery systems; serving as a decision support framework for assessing technology investments. A steady-state mixed-integer linear programming (MILP) approach is employed to formulate the optimisation problem. The virtue of the TSO model comes from employing granular state-of-the-art datasets such as half-hourly electricity demands and prices, irradiance levels from weather stations, and technology databases; while also considering building specific attributes. Investment revenues are obtained from reducing grid electricity costs and providing fast-frequency response (FFR) ancillary services. A case study of a distribution centre in London, UK is showcased with the goal to identify which technologies can minimise total energy costs against a conventional system setup serving as a benchmark. Results indicate the best technology configuration is a combination of lithium-ion batteries and mono-crystalline silicon PVs worth a total investment of £1.72 M. Due to the available space in the facility, the preferred PV capacity is 1.76 MW, while the battery system has a 1.06 MW power capacity and a 1.56 MWh energy capacity. Although PV performance varies across seasons, the solution indicates almost 30% of the energy used on-site can be supplied by PVs while achieving a carbon reduction of 26%. Nonetheless, PV and battery systems seem to be a questionable investment as the proposed solution has an 8-year payback, despite a 5-year NPV savings of £300k, implying there is still a performance gap for such systems to be massively deployed across the UK. Overall, the TSO model provides valuable insights into real-world project evaluation and can help to reduce the uncertainty associated with capital-intensive projects; hence proving to be a powerful modelling framework for distributed energy technology assessments.

1. Introduction

Growing concerns about climate change and the associated decarbonisation agenda, research for energy independence and geopolitical evolutions have led countries to rethink their energy consumption. In this context, carbon intensive organisations in the UK, such as food retailers with a complex supply chain and a large property portfolio, are investigating pathways to reduce their carbon footprint while making financially attractive investments.

Photovoltaic (PV) and battery systems are two technologies that hold great potential to positively impact energy use in buildings

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Nomenclature

Indices and sets

t	time intervals
d	day-types
y	years
p	PV technologies
b	battery technologies

Parameters

e^D_{tdy}	electricity demand at time interval t of day type d and year y (kWh)
U^P_p	binary used to define the user pre-selection of PV technology p
U^B_b	binary used to define the user pre-selection of battery technology b
A^r	roof area (m^2)
W^r	roof surface loading coefficient (kg/m^2)
C	coverage, percentage of the roof that can be covered by PV modules
A^P_p	size of module of PV technology p (m^2)
W^P_p	weight of module of PV technology p (kg)
A^P_p	size of module of PV technology p
I_{td}	irradiance (GHI) level at time interval t of day typed (kWh/m^2)
δ^P_y	influence of module degradation on PV production at year y (%)
η^{aux}	efficiency of PV auxiliary equipment (%)
η^{losses}	influence of losses (temperature, ohmic wiring, etc.) on PV production (%)
η^P_p	electrical efficiency of PV technology p (%)
p^{FiT}	price of FiT agreed at the start of the contract (£/kWh)
D_d	number of days in the day type group d in a year
Δ_y	discount Multiplier for year y (Present Value multiplier)
$p^{P,C}_p$	annualised capital expenditure of PV technology p (£/Wp/yr)
$p^{P,M}_p$	annualised maintenance cost of PV technology p (£/Wp/yr)
O^P_p	module nominal power of PV technology p (Wp)
V^r	volume available in the building for batteries (m^3)
$e^{vol,B}_b$	volumetric energy density of battery technology b (kWh/m^3)
SOC^c_{tdy}	portion of the battery SoC (State of Charge) that is charged at interval t of day type d and year y (%)
SOC^d_{tdy}	portion of the battery SoC that is discharged at interval t of day type d and year y (%)
α^B_b	percentage of battery energy capacity that can be used (maxSoC, maxDOD) for battery technology b (%)
RTE^B_b	Round-Trip Efficiency of battery technology b (%)
p^{FR}_y	price of providing FR during a day of year y (£/kW/day)
κ^B	availability of the battery to provide FR (%)
τ^B	reduction factor of FR earnings during FR + TOU days (%)
$p^{B,C}_b$	annualised capital expenditure of battery technology b (£/kWh/yr)
$p^{B,M}_b$	annualised maintenance cost of battery technology b (£/kW/yr)
$p^{B,R}_b$	annualised cost of replacing the battery to last 15 years for technology b (£/kWh/yr)
p^i_{tdy}	price of importing electricity at interval t of day type d and year y (£/kWh)
p^e_{tdy}	price of exporting electricity at interval t of day type d and year y (£/kWh)

Binary variables

β^P_p	defines the selection of PV technology p
β^B_b	defines the selection of battery technology b
β^{FR}_d	defines the selection of FR only for battery operation during day type d
β^{TOU}_d	defines the selection of FR + TOU for battery operation during day type d

Positive variables

e^i_{tdy}	electricity import at time interval t of day type d and year y (kWh)
e^e_{tdy}	electricity export at time interval t of day type d and year y (kWh)
e^P_{tdy}	electricity produced by PV at time interval t of day type d and year y (kWh)
e^d_{tdy}	electricity discharged by the battery at time interval t of day type d and year y (kWh)
e^c_{tdy}	electricity charge for the battery at time interval t of day type d and year y (kWh)
N	number of PV modules
E^B	battery energy capacity (kWh)
O^B	battery power capacity (kW)

Free variables

$C^{P,FiT}$	NPV (Net Present Value) of FiT earnings (negative costs) for the period (£)
$C^{P,C}$	NPV of PV capital costs for the period (£)
$C^{P,M}$	NPV of PV maintenance costs for the period (£)
$C^{B,FR}$	NPV of FR earnings (negative costs) for the period (£)
$C^{B,C}$	NPV of battery capital costs for the period (£)
$C^{B,M}$	NPV of battery maintenance costs for the period (£)
C^{GHG}	NPV of carbon costs for the period (£)
C^o	NPV of operating costs for the period (£)
C^i	NPV of importing costs for the period (£)
C^e	NPV of exporting earnings for the period (£)
f	objective function, sum of all NPVs (£)

[1–3]. Electricity produced by a photovoltaic system can be directly used on site, hence reducing the electricity imported by the business, decreasing its electricity bill and associated carbon costs. Similarly, the battery system can be used in different ways to maximise revenue streams; for example, by shifting electricity demand of the building to reduce costs or by providing grid services. Overall, such systems can be appealing to investors if the business case offers sensible returns. However, it is difficult for decision makers to assess the attractiveness of such investments, as identifying the appropriate technologies, capacities, energy yields, and operational strategies can be challenging and highly uncertain [4]. Furthermore, each building is different and there is no “one size” that fits all solutions. Due to these factors, it is commonplace to discourage technology investments without conducting a thorough analysis. This issue suggests there is a great need to develop robust and comprehensive models assessing the impact new technologies can have on buildings with a focus on providing business certainty before making an investment.

Different simulations and optimisation models have been developed in this field of research. These solutions range vastly in complexity and scope [4], with a more detailed overview of existing work provided in the following section. Simple models