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Optimal battery storage operation for PV systems with tariff incentives ☆

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HIGHLIGHTS

- PV – Battery system under FiT incentive is modelled to maximise revenue streams.
- Optimisation model is developed to optimise power flows in the PV-Battery system.
- Real residential PV and demand data is used to simulate the optimisation model.
- Sensitivity analysis on the impact of battery capacity on the model is carried out.
- Impact of unit cost on the adoption of battery storage for PV under FiT is studied.

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ABSTRACT

Many efforts are recently being dedicated to developing models that seek to provide insights into the techno-economic benefits of battery storage coupled to photovoltaic (PV) generation system. However, not all models consider the operation of the PV – battery storage system with a feed-in tariff (FiT) incentive, different electricity rates and battery storage unit cost. An electricity customer whose electricity demand is supplied by a grid connected PV generation system benefiting from a FiT incentive is simulated in this paper. The system is simulated with the PV modelled as an existing system and the PV modelled as a new system. For a better understanding of the existing PV system with battery storage operation, an optimisation problem was formulated which resulted in a mixed integer linear programming (MILP) problem. The optimisation model was developed to solve the MILP problem and to analyse the benefits considering different electricity tariffs and battery storage in maximising FiT revenue streams for the existing PV generating system. Real data from a typical residential solar PV owner is used to study the benefit of the battery storage system using half-hourly dataset for a complete year. A sensitivity analysis of the MILP optimisation model was simulated to evaluate the impact of battery storage capacity (kWh) on the objective function. In the second case study, the electricity demand data, solar irradiance, tariff and battery unit cost were used to analyse the effect of battery storage unit cost on the adoption of electricity storage in maximising FiT revenue. In this case, the PV is simulated as a new system using Distributed Energy Resources Customer Adoption Model (DER-CAM) software tool while modifying the optimisation formulation to include the PV onsite generation and export tariff incentive. The results provide insights on the benefit of battery storage for existing and new PV system benefiting from FiT incentives and under time-varying electricity tariffs.

1. Introduction

Energy policy incentives across the globe have supported the installation of distributed energy resources at different levels of the energy system [1,2]. From 2010 it was recorded significant increase of PV installation due to the decrease of the module cost and the implementation of incentive-based programmes like the FiT policies [3,4]. The recent changes in the FiT policies for example in the UK and the closure of the Renewable Obligation scheme applied to a small-scale solar PV with a capacity less than or equal to 5 MW will drastically affect the scale of domestic PV installations [5,6]. In some countries, for example, Germany, a FiT scheme that favours installation of battery storage to maximise self-consumption is already in place [7]. The intermittent nature of solar PV and the mismatch between customer-sited solar PV power

☆ Information about the data underpinning the research work reported here which can be made available can be found in the Cardiff University data catalogue at http://doi.org/10.17035/d.2017.0038094155.

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Nomenclature

Sets
d day = 1–365.
t hour = 1–48 (30 min timestep)

Parameters
$P\_pv(d,t)$ generated PV Power at every time step (kW)
$P\_dmd(d,t)$ electricity demand at each time step
p_FIT generation FiT (pence/kWh)
p_export export FiT (pence/kWh)
p_retail standard retail electricity tariff (pence/kWh)
Δt optimisation time step: half-hourly
$P\_dmd\_unmet(d,t)$ unmet electricity demand at each time step (kW)
$P\_pv\_excess(d,t)$ excess electricity from PV at each time step (kW)
$P\_pv\_onsite(d,t)$ PV power output used for self-consumption (kW)
$Pch\_\min$ minimum battery charging power (kW)
$Pch\_\max$ maximum battery charging power (kW)
$Pdis\_\min$ minimum battery discharging power (kW)
$Pdis\_\max$ maximum battery discharging power (kW)
e^c battery charging efficiency
e^d battery discharging efficiency
$Ebatt\_\min$ battery minimum energy state of charge (kWh)
$Ebatt\_\max$ battery maximum energy state of charge (kWh)
M an arbitrary number that should be big enough to ensure a feasible solution

$TotalPV\_generated$ the total kWh generated by the PV system that is eligible for the export tariff
$TotalPV\_exported$ the amount of kWh exported to grid that is eligible for the export tariff

Variables
$P\_pv\_\text{export}(d,t)$ PV power sold to the grid at each time step (kW)
$P\_grid(d,t)$ Grid Electricity Imported at each time step (kW)
$P\_charge(d,t)$ the power used to charge the battery from excess PV (kW)
$P\_charge\_grid(d,t)$ the power used to charge the battery from the grid (kW)
$X(d,t)$ a binary variable that prevents buying and selling of electricity simultaneously at each time step
$Y(d,t)$ binary variable at each time steps that constraints charging power to prevent charging and discharging simultaneously
$Z(d,t)$ binary variable at each time steps that constraints discharging power to prevent charging and discharging simultaneously
$P\_discharge(d,t)$ the power discharged by the battery to meet unmet demand (kW)
$E\_s(d,t)$ battery energy state of charge at each time step (kWh)
$E\_s(d,t-1)$ battery energy state of charge at the previous time step (kWh)

output and the residential electricity load profiles makes battery storage a potential option to maximise savings [8–10].

The cost of battery packs is falling, about 25% reduction for lithium-ion battery between 2009 and 2014 according to [1]. The domestic electricity storage battery could provide support to an existing customer-sited PV enrolled in FiT incentivised schemes. According to [11], the value of the California's Public Utilities Commission policy on supporting affordable solar PV installations in multi-family housing could be enhanced by battery storage systems. This means that the value proposition for solar PV owners in respect to changes in the electricity rates and tariffs could be improved considerably with a well-managed battery energy storage system. In Spain for example, the parliament have signed an agreement to remove the decree against self-consumption [12,13]. This shows a clear opportunity for the deployment of battery energy storage in existing and new PV systems benefiting from FiT schemes. Maximising the use of battery storage for grid connected residential solar PV applications has been studied and the benefit to distribution network operators has been demonstrated in [7,14–16]. By optimising the operation of battery storage coupled to a residential PV the effect of variable PV output is minimised. Smart tariffs have the potential to encourage the adoption of distributed energy systems, as it has been widely used in California and Australia for managing high demand charges [17,18]. In the UK the economy 7 and 10 tariffs are used as a two-tier tariff for customers with storage heaters [19–21]. A triad peak energy demand predicting model for buildings was developed in [22], which is relevant because electricity customers are becoming sensitive to electricity tariffs at hours with low price/kWh periods. Linear programming and MILP methods using optimisation software tools have been proposed for maximising the scheduling of distributed energy resources with battery storage systems in [23–25]. In [26–29], an optimal power flow management scheme was proposed for a standalone backup generator. The objective of the work in [28] is to minimise the fuel costs of a backup generator for a residential building using battery energy storage coupled to a grid connected solar PV. In [14,15], a low voltage distribution network operator owned battery storage was used to control the power flows in the network. In [13], smart time of use tariffs was used to maximise daily revenue streams for a residential solar PV connected to a battery storage, however, no FiT incentive was considered in the optimisation process. The work in [7], investigated the use of battery storage in residential low voltage network to defer costly network upgrades, and a multi-objective optimisation formulation to evaluate the trade-offs between voltage regulation, peak power reduction and the annual cost of electricity supply was developed. In [30], an optimisation based approach that maximises daily operational savings for grid connected solar PV customers was presented. An optimal power flow management framework for a grid connected PV with battery storage in order to maximise the peak shaving service is presented in [31]. Another study [32] simulated the impact of using a combination of solar PV, battery storage, Stirling Engine Combined Heat and Power on electricity self-sufficiency, intermittent grid demand and customer economic costs. Other studies [30,33,34] have considered the optimisation of battery storage operation under specific tariff structures. Others have looked into large scale operational planning of renewable energy sources (PV and wind power) in combination with battery energy storage [35–38]. The references (for example, [26–29,31,39]) focused on using time-varying tariff structures to optimise the operation of customer-owned solar PV in combination with battery storage system over a 24 hour period. In [39], the optimal benefit of battery energy storage was only computed for a typical day in summer and winter and then computed for the year using projected estimates. Maximisation of FiT revenue streams at the customer premises for existing and new PV generating systems benefiting from FiT incentive (generation and export tariff) and under time-varying electricity tariff schemes can be achieved by using battery storage. To the extent of the author's knowledge, no literature reviewed has developed an optimisation