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Leveraging smart meter data for economic optimization of residential photovoltaics under existing tariff structures and incentive schemes

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HIGHLIGHTS

- Hourly smart meter data is used to determine the optimal PV system for each customer.
- Mixed-integer particle swarm optimization with a penalty function is used.
- The algorithm is tested using real-world energy data from 120 households.
- PV systems are found to be not universally viable for all customers.
- Optimal systems are found to be highly dependent on the customer's energy profile.

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ABSTRACT

The introduction of smart grid technologies and the impending removal of incentive schemes is likely to complicate the cost-effective selection and integration of residential PV systems in the future. With the widespread integration of smart meters, consumers can leverage the high temporal resolution of energy consumption data to optimize a PV system based on their individual circumstances. In this article, such an optimization strategy is developed to enable the optimal selection of size, tilt, azimuth and retail electricity plan for a residential PV system based on hourly consumption data. Hourly solar insolation and PV array generation models are presented as the principal components of the underlying objective function. A net present value analysis of the potential monetary savings is considered and set as the optimization objective. A particle swarm optimization algorithm is utilized, modified to include a penalty function in order to handle associated constraints. The optimization problem is applied to real-world Australian consumption data to establish the economic performance and characteristics of the optimized systems. For all customers assessed, an optimized PV system producing a positive economic benefit could be found. However not all investment options were found to be desirable with at most 77.5% of customers yielding an acceptable rate of return. For the customers assessed, the mean PV system size was found to be 2 kW less than the mean size of actual systems installed in the assessed locations during 2015 and 2016. Oversizing of systems was found to significantly reduce the potential net benefit of residential PV from an investor's perspective. The results presented in this article highlight the necessity for economic performance optimization to be routinely implemented for small-scale residential PV under current regulatory and future smart grid operating environments.

1. Introduction

Over the last decade, the solar photovoltaics (PV) industry has undergone significant technological improvement and enormous growth in installed capacity. As market penetration increases for PV, primarily driven by the continued reduction in technology costs, installation incentive schemes will be reduced or removed altogether. In an Australian context, the Solar Bonus Scheme (SBS) and the Small-scale Renewable Energy Scheme (SRES) incentivized the installation of PV through generous feed-in tariffs (FiT) and a cost rebate mechanism respectively. Historically, these incentive schemes encouraged investors to install large PV systems aiming to generate as much energy as possible during peak solar insolation hours. However the SBS in

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Nomenclature

$\alpha(\cdot), \lambda(\cdot), h(\cdot), \psi(\cdot)$	penalty function components
β	PV array tilt angle
χ	constriction factor
δ	solar declination and latitude
η_e	balance of plant efficiency
$\eta_{mpp}, \eta_{mpp,stc}$	maximum power point efficiency at operating and standard test conditions
γ	PV array azimuth angle
μ_{mpp}	maximum power point temperature coefficient
ω, ω_s	solar hour and sunset hour angles
ϕ	latitude
ρ_g	ground reflectance
θ, θ_z	beam irradiance angle of incidence and zenith angle
A_c	PV module area
c_1, c_2	acceleration coefficients
$C_{base,q}, C_{pv,q}$	electricity cost in period q without (lowest cost plan) and with PV installed
C_{cert}	cost of SRES certificates
d, h, q	day, hour and billing period
D_k	degradation factor
$E_{load,qdh}, E_{pv,qdh}$	load energy and PV generated energy
E_{year}	yearly energy consumption
$g_k(\boldsymbol{x})$	optimization constraint functions
G_T, I_T	irradiance and hourly insolation on tilted plane
$G_n^j, P_{i,n}^j$	global and personal best positions of particle i in dimension j & iteration n
H, H_b, H_d	daily global, beam and diffuse insolation
I, I_b, I_d, I_o	hourly global, beam, diffuse & extra-terrestrial insolation
i, j, n	particle number, particle dimension and iteration number
J, K, N	dimensionality of problem, number of problem constraints, number of interations in the solution algorithm
M_{life}, M_{loc}	SRES contribution length and location multipliers
$P_{pv}, P_{pv,rat}$	PV output and rated powers
R_b	ratio of tilted-plane versus horizontal beam irradiance
r_g	effective real electricity price growth
r_{deg}	degradation rate
r_{eff}, r_{real}	effective and real annual discount rates
$r_{i,n}^j, R_{i,n}^j$	sequence of uniformly distributed random numbers
S_{pv}	PV system cost
t	number of discounting periods per year
T_c, T_a, T_{NOCT}	PV module, ambient and nominal operating cell temperatures
$T_{feed,qdh}$	PV feed-in tariff
$T_{grid0,qdh}, T_{grid,qdh}$	grid-imported tariff under lowest cost and alternative plans
$T_{sc0,qd}, T_{sc,qd}$	daily supply charge under lowest cost and alternative plans
U_{inv}, U_{pv}	unit cost of inverter replacement and PV system ($/W)
$v_{i,n}^j, x_{i,n}^j$	velocity and position of particle i in dimension j & iteration n
y	year number
Z	number of PV modules
CDO	Climate Data Online
CER	Clean Energy Regulator
FiT	feed-in tariff
LCOE	levelized cost of electricity
MIRR	modified internal rate of return
NOCT	nominal operating cell temperature
NPV	net present value
PSO	particle swarm optimization
PV	photovoltaics
SBS	Solar Bonus Scheme
SGSC	'Smart Grid, Smart City' project
SRES	Small-scale Renewable Energy Scheme
STC	standard test conditions
TOU	time-of-use

Australia, under which the FiT was initially set to be 60 c/kWh and later reduced to 20 c/kWh, was closed to new customers in 2011 and officially ended in 2016. Current Australian FiTs are no longer mandated but rather set by individual retailers. As an example, the benchmark range for FiTs in New South Wales was 4.7–6.1 c/kWh in 2015–2016 increased to 5.5–7.2 c/kWh in 2016–2017 [1], significantly less than those offered under the SBS.

An assessment of the Australian Government Clean Energy Regulator (CER) database [2] revealed a relatively large national average size of 5.11 kW for new systems installed between January 2015 and August 2016. However due to closure of the SBS, the newly installed large systems are ineligible for the high mandated FiTs under the SBS and subsequently the payback period is increasingly reliant on the cost savings achieved through self-consumption of PV generated energy.

Current policy is to retain the SRES in the medium term, however the magnitude of the effective rebate will be gradually reduced between 2017 and 2030 [3]. Consequently, a shift in industry practice is required, moving from large PV systems to more economically efficient ones.

The reduction and removal of incentive schemes are not the only disrupting factor to the small-scale PV industry. The penetration and system characteristics of residential PV systems have the potential to be significantly influenced by the introduction of smart meters and other smart grid technologies. Enabled by smart meters, the implementation of new dynamic tariff structures will require due consideration of a customer's temporal energy consumptions habits.

The 'Smart Grid, Smart City' (SGSC) project [4] undertaken between 2012 and 2014, was commissioned by the Australian Government to trial a wide range of smart grid technologies, becoming one of the largest trials to have been conducted in the world to date [4]. From a national cost-benefit perspective, the SGSC project and other independent research conducted by the Grattan Institute [5] in 2015, found a real and immediate business case for the introduction of dynamic tariffs focusing on temporal energy demand in order to remove the cross-subsidies existing between non-PV owners and PV owners. Under such an environment, the uptake of small-scale PV in Australia was projected to exhibit continued growth. However in response to the recommended tariff restructures, a reduction in average size of new residential systems was forecasted to occur [4].

The removal of government incentive schemes and the introduction of dynamic tariffs will increase the complexity of the business case for small-scale rooftop PV systems. The findings of the SGSC project and the Grattan Institute highlight the need for a comprehensive assessment tool to inform prospective investors and establish the economic efficiency of new PV systems.

An optimization strategy for residential PV systems is developed in this research. The maximization of the net benefit achieved through reduced imported energy costs is set as the underlying objective. Within a competitive retail electricity market with various tariff structures including flat and dynamic time-of-use (TOU) rates, the best plan is not self-evident. The research presented in this article is principally focused towards leveraging temporal energy consumption data facilitated by smart meters to develop