Design Optimisation of Hybrid Photovoltaic and Energy Storage Systems through Smart Grid Technologies to Maximise Economic Benefit

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Certificate of Original Authorship

I, Jeremy Paul Every, declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Electrical and Data Engineering of the Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Nomenclature

α	Contraction-expansion coefficient (QPSO)
α	Solar altitude
$\alpha(\cdot), \lambda(\cdot), h(\cdot), \psi(\cdot)$	Penalty function components (PSO)
α_s	Sunset hour solar altitude ($-0.833°$)
β	Solar collector surface tilt angle
β_0,β_1,β_2,β_3,β_4,β_5	BRL parameter coefficients for
χ	Constriction factor (PSO)
Δ	Brightness index
δ	Maximum depth of discharge
δ	Solar declination
$\delta(m)$	Optical thickness
$\delta_R(m)$	Rayleigh atmosphere optical thickness
ϵ	Clearness index
η_e	Balance of plant efficiency
$\eta_{ac,wire}$	AC wiring efficiency
η_{batt}	BESS round-trip efficiency
$\eta_{dc,wire}$	DC wiring efficiency
η_{inv}	Inverter efficiency
η_{mm}	Module mismatch efficiency
$\eta_{mpp,STC}$	Maximum power point efficiency at standard test conditions
η_{mpp}	Maximum power point efficiency at operating conditions
η_{soil}	Soiling efficiency
γ	Solar collector surface azimuth angle
κ_b	Battery cost reduction rate
κ_{inv}	Inverter cost reduction rate
μ_{mpp}	Maximum power point temperature coefficient
μ_{P2P}	Sale margin of P2P participant
μ_T	P2P trader margin
$\omega, \omega_s, \omega_{z,s}$	Solar hour angle, sunset hour angle and sunset zenith angle ($90.833°$)
ω_1, ω_2	Solar hour angle 1 and 2

ϕ	Latitude
ψ	Persistence factor
ψ,ψ^2	Particle characteristic wave function and probability density (QPSO)
ρ_g	Composite ground reflectance factor
θ, θ_z,$\theta_{z,s}$	Direct irradiance angle of incidence, solar zenith angle and zenith angle at sunset
ζ_{batt}	Cycle degradation rate (kWh/cycle)
A_c	PV module area
A_i	Anisotropy index
AST	Apparent solar time
B_T	Direct irradiation on a tilted surface
$B_{BESSsell,qdh}$	BESS sell reservation price of hour h, day d, billing period q
$B_{BUY,qdh}$	Final successful buy reservation price in a P2P bidding hour h, day d, billing period q
$B_{buy,qdh}$	BESS sell reservation price of hour h, day d, billing period q
$B_{pvsell,qdh}$	PV sell reservation price of hour h, day d, billing period q
$B_{sell,qdh}$	P2P sell reservation price (either $B_{pvsell,qdh}$ or $B_{BESSsell,qdh}$)
c_1, c_2	Acceleration coefficients (PSO)
$C_{\max 0}$	Initial maximum capacity
$C_{\max,qdh}$	Maximum capacity at the start of hour h, day d, billing period q
$C_{base,q}$	Electricity cost in period q without PV installed (lowest cost plan)
$C_{c,qdh}$	Total BESS charge cost up to hour h, day d, billing period q
C_{degrad}	Battery degradation cost
C_{EOL}	End-of-life maximum capacity
$C_{i,n}^j$	Mean best position of particle i in dimension j at iteration n (QPSO)
$C_{pv,q}$	Electricity cost in period q with PV installed
C_{qdh}	Available capacity at the start of hour h, day d, billing period q
C_{STC}	Cost of STC certificates
d	Day number of billing period q
D_q	Days in billing period q
D_T	Diffuse irradiation on a tilted surface
D_y	PV module degradation factor in year y
E	Equation of time
E_{bal}	Energy balance after accounting for DER energy flows and losses
$E_{bd,qdh}$	BESS discharge energy at the end of hour h, day d, billing period q
$E_{bdbid,qdh}$	P2P BESS sell energy bid of hour h, day d, billing period q
$E_{bdloss,qdh}$	BESS energy loss during discharge in hour h, day d, billing period q

$E_{bg,qdh}$	BESS grid-charge energy at the end of hour h, day d, billing period q
$E_{bgloss,qdh}$	BESS energy loss during grid-charge in hour h, day d, billing period q
$E_{bloss,qdh}$	Total BESS energy loss in hour h, day d, billing period q
$E_{bpv,qdh}$	BESS PV-charge energy at the end of hour h, day d, billing period q
$E_{bpvloss,qdh}$	BESS energy loss during PV-charge in hour h, day d, billing period q
$E_{buybid,qdh}$	P2P Buy energy bid of hour h, day d, billing period q
E_{EOL}	Total energy throughput of BESS before reaching end-of-life
$E_{load,qdh}$	Load energy in hour h, day d, period q
$E_{P2P,qdh}$	P2P energy cleared of hour h, day d, billing period q
$E_{pv,qdh}$	PV generated energy in hour h, day d, period q
$E_{pvbid,qdh}$	P2P PV sell energy bid of hour h, day d, billing period q
$E_{through,qdh}$	Cumulative BESS energy throughput up to hour h, day d, billing period q
E_{year}	Yearly energy consumption
F	BESS loss factor
f	Horizon brightening modulating factor
F_1, F_2	Circumsolar and horizon brightening coefficients
F_{x-y}	View factors for each irradiation component
$g_k(\boldsymbol{x})$	Optimisation constraint functions (PSO)
G_T	Incident solar irradiance
$G_n^j, P_{i,n}^j$	Global and personal best positions of particle i in dimension j and iteration n (PSO)
G_o, G_{on}	Extra-terrestrial irradiance incident on a horizontal plane projected from Earth's surface and on the plane normal to propagation
G_{sc}	Solar constant (1367 W/m^2)
H	Daily global (total) irradiation on the horizontal plane
h	Hour number of day d
H_b, H_d	Daily direct and diffuse irradiation on the horizontal plane
H_o	Daily extra-terrestrial solar irradiation on a horizontal plane projected from Earth's surface
i	Particle number (PSO)
I, I_T	Hourly global (total) irradiation on the horizontal plane and a tilted plane
I_b, I_d	Hourly direct (beam) and diffuse irradiation on the horizontal plane
I_bn	Direct normal irradiation
I_o, I_{on}	Hourly extra-terrestrial solar irradiation incident on a horizontal plane projected from Earth's surface and on the plane normal to propagation
$I_{d,cs}$	Circumsolar diffuse irradiation
$I_{d,hz}$	Horizon brightening diffuse irradiation
$I_{d,iso}$	Isotropic diffuse irradiation

$I_{d,T}$	Diffuse irradiation on a tilted surface
I_{gc}, I_{dc}, I_{bnc}	Global, diffuse and direct normal clear-sky irradiation
$I_{op,qdh}$	Off-peak BESS charge/discharge control variable for hour h, day d, billing period q
$I_{pk,qdh}$	Peak BESS charge/discharge control variable for hour h, day d, billing period q
$I_{sh,qdh}$	Shoulder BESS charge/discharge control variable for hour h, day d, billing period q
J	Number of unique buy reservation prices in particular bidding hour
j, J	Particle dimension and dimensionality of the problem (PSO)
K	Number of problem constraints (PSO)
K	Number of unique sell reservation prices in particular bidding hour
K_T, k_T	Daily and hourly clearness indexes
$L_{i,n}^j$	Delta potential well characteristic length (QPSO)
L_{st}, L_{loc}	Longitudes of the standard meridian and the location in question
M	Particle swarm size (PSO)
m	Air mass
m	Comprehensive learning refreshing gap (CLQPSO)
M_x	BESS operation mode variable
M_{life}, M_{loc}	SRES contribution length and location multipliers
n	Day number of the year
n, N	Iteration number and maximum number of iterations (PSO)
P	Payback period
p, p_0	Mean site elevation and sea level atmospheric pressure
$P_{\max,pvbatt,q}$	Maximum power demand with a PV-BESS system
$P_{\max,q}$	Maximum power demand without a PV-BESS system
$P_{c,i}$	Learning probability of particle i (CLQPSO)
$P_{c,qdh}, P_{d,qdh}$	BESS charge and discharge permission control parameters of hour h, day d, billing period q
$p_{i,n}^j$	Local attractor of particle i in dimension j at iteration n (QPSO)
$P_{pv,rat}$	PV module rated power
P_{pv}	PV module output power
Q	Number of billing periods q in system lifetime
q	Billing period of year y
R^2	Coefficient of determination
R_b	Ratio of direct irradiance on a tilted plane versus the horizontal plane
r_e	Effective real electricity price growth
R_T	Ground-reflected irradiation on a tilted surface

$R_{\max}$	Maximum BESS charge/discharge rate
$R_{BUY,qdh}$	Supply and demand ratio at the final successful buy reservation price of hour h, day d, billing period q
$R_{buy,qdh}$	Supply and demand ratio for a particular P2P participant buying energy of hour h, day d, billing period q
r_{deg}	Degradation rate
r_d	Effective real discount rate per billing period
r_e	Effective real electricity price growth rate per billing period
$r_{i,n}^j, R_{i,n}^j$	Sequence of uniformly distributed random numbers (PSO)
r_{inf}	Rate of inflation
r_{nom}	Annual nominal discount rate
r_{real}	Annual real discount rate
$R_{SELL,qdh}$	Demand and supply ratio at the final successful sell reservation price of hour h, day d, billing period q
$R_{sell,qdh}$	Demand and supply ratio for a particular P2P participant selling energy of hour h, day d, billing period q
S_b	Total BESS cost
S_{pv}	PV system cost
t	Number of discounting (billing) periods per year
T_a	Ambient temperature
T_c	PV module temperature
$T_L(m)$	Linke Turbidity
$T_{\max,der,qd}$	Maximum power demand with DERs
$T_{\max}$,$T_{\min}$	Maximum and minimum daily temperatures
$T_{c,qdh}$	Moving average electricity tariff for BESS charging up to hour h, day d, billing period q
$T_{DC0,qd}, T_{DC,qd}$	Network demand charge under lowest cost and alternative plans
$T_{fit,qdh}$	PV feed-in tariff
$T_{luos,qdh}$	LUoS energy charge of hour h, day d, billing period q
T_{NOCT}	Nominal operating cell temperature
$T_{P2P,qdh}$	P2P clearing price of hour h, day d, billing period q
$T_{pv,qdh}$	PV feed-in tariff or power purchase agreement supply rate
$T_{ret0,qdh}, T_{ret,qdh}$	Retailer tariff under lowest cost and alternative plan
$T_{sc0,qd}, T_{sc,qd}$	Daily supply charge under lowest cost and alternative plans
$T_{tuos,qdh}$	TUoS energy charge of hour h, day d, billing period q
U_b	Per unit battery cost
U_{inv}	Unit inverter replacement cost (\$/W)
U_{pv}	Unit cost of PV system replacement(\$/$\mathrm{W_p}$)

$v^j_{i,n}, x^j_{i,n}$	Velocity and position of particle i in dimension j & iteration n (PSO)
W_q	Maintenance cost
X	Number of batteries
$x_{\rho,j}, y_{\rho,k}$	Unique buy and sell reservation prices in a particular bidding hour
$x_{\xi,j}, y_{\xi,k}$	Cumulative energy bids up to a unique buy and sell reservation price in a particular bidding hour
y	Year number
Y_{EOL}	Cycle life
Y_{qdh}	Operational cycles at the end of hour h, day d, billing period q
$Z, Z_{\max}$	Number of PV modules and maximum number of modules permitted
AEMC	Australian Energy Market Commission
AER	Australian Energy Regulator
AMI	Advanced metering infrastructure
AREMI	Australian Renewable Energy Mapping Infrastructure
ARENA	Australian Renewable Energy Agency
BAU	Business-as-Usual
BESS	Battery energy storage system
BoM	Australian Bureau of Meteorology
BRL	Boland–Ridley–Lauret diffuse fraction model
BSRN	Baseline Surface Radiation Network+
CDF	Cumulative distribution function
CDO	Climate Data On-line
CdTe	Cadmium telluride
CER	Australian Government Clean Energy Regulator
CIGS	Copper indium gallium selenide
CPI	Combined Performance Index
CPP	Critical peak pricing
CSV	Comma-separated variable
DAP	Day-ahead pricing
DER	Distributed energy resource
DG	Distributed generation
DHI	Diffuse horizontal irradiation
DLC	Direct load control
DLT	Distributed ledger technology
DNI	Direct normal irradiation
DNSP	Distribution Network Service Provider
DR	Demand response

DS	Distributed storage
DSM	Demand-side management
DUoS	Distribution use-of-system
ESRA	European Solar Radiation Atlas
ET	Extra-terrestrial
FiT	Feed-in tariff
GEBA	Global Energy Balance Archive
GHI	Global horizontal irradiation
GW	Gigawatt
GWh	Gigawatt hour
HDKR	Hay-Davies-Klucher-Reindl
HSI	Hourly Solar Irradiance Data
ICT	Information and communications technology
IWEC2	International Weather files for Energy Calculations (Second Generation)
KSI	Kolmogorov-Smirnov Integral
kW	Gigawatt
kWh	Kilowatt hour
LCOE	Levelised cost of energy
LGC	Large-scale generation certificate
LGNC	Local general network credit
LNC	Local network charge
LRET	Large-scale Renewable Energy Target
LRMC	Long-run marginal cost
LUoS	Local use-of-service
MBE	Mean bias error
MeAPE	Median absolute percentage error
MINLP	Mixed-Integer Non-Linear Programming
MIRR	Modified internal rate of return
MMR	Mid-market rate
MW	Megawatt
MWh	Megawatt hour
NASA	National Aeronautical and Space Administration
NEM	National Electricity Market
NOCT	Nominal operating cell temperature
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Resource Database

NUoS	Network use-of-system
OMS	One Minute Solar Data
OVER	Relative frequency of exceedence from KSI
P2P	Peer-to-peer
PPA	Power purchase agreement
PSO	Particle swarm optimisation
PTR	Peak-time rebates
PV	Photovoltaic
QDPSO	Quantum delta potential well-based particle swarm optimisation
QPSO	Quantum-behaved particle swarm optimisation
RET	Renewable Energy Target
rMBE	Relative mean bias error
RMSE	Root mean square error
rRMSE	Relative root mean square error
RTP	Real-time pricing
SAM	System Advisor Model
SBS	Solar Bonus Scheme
SDR	Supply and demand ratio
SGSC	Smart Grid, Smart City
SoDa	Solar Radiation Data
SRES	Small-scale Renewable Energy Scheme
SSE	Surface Meteorology and Solar Energy
STC	Small-scale technology certificate
STC	Standard test conditions
TMY	Typical Meteorological Year
TOU	Time-of-use
TSS	Tariff structure statement
TUoS	Transmission use-of-system
UTC	Coordinated Universal Time
W	Watt
WMO	World Meteorological Organisation
WRDC	World Radiation Data Centre

Abstract

ADVANCES in photovoltaic and battery energy storage system (BESS) technologies have made hybrid PV-BESS systems an attractive prospect for residential energy consumers. However, the process to select an appropriate system is non-trivial due to the relatively high cost of batteries, a multitude of available retail electricity plans, the removal of incentive schemes and the impending introduction of disruptive technologies such as peer-to-peer energy trading.

The introduction of Smart Grid technologies, particularly smart meters, enables consumers to leverage high temporal resolution energy consumption data to optimise system design based on an individual customer's circumstance. In this research, real-world energy consumption data for a large sample of homes are applied to an optimisation strategy developed to the select system size, tilt, azimuth and retail electricity plan for a residential PV-BESS based on a customer's temporal load profile. A case study examining a real world hybrid PV-BESS is presented to demonstrate the potential benefit of applying the optimisation process established in this research.

Particle swarm optimisation (PSO) is utilised as the underlying optimisation algorithm given its suitability to mixed integer non-linear programming problems, characteristic of the energy models developed in this research. To improve global search performance with minimal parameter adjustments, various forms of PSO are applied including quantum-behaved PSO and a modified version with a comprehensive learning component.

To facilitate energy yield modelling, accurate hourly solar irradiation and photovoltaic array generation models are critical to the optimisation process. Numerous models have been developed to estimate diffuse and direct irradiance components based on global irradiation measurements. The Boland–Ridley–Lauret (BRL) model consists of a single set of parameters for all global locations. There is scope to improve the BRL model to better match local climatic conditions. In this research, the Köppen-Geiger climate classification system is considered to develop a set of adjusted BRL models for Australian conditions, which are subsequently applied to the energy models developed in this research.

With the future application of peer-to-peer energy trading markets, prospective investors would benefit from prior consideration of market conditions and the penetration rates of participant PV-BESS systems when designing such systems. In this research, a lifetime assessment of PV-BESS systems is undertaken for a hypothetical peer-to-peer market of over 2,000 participants. Trader margin, participant margin, network tariff structures and PV-BESS penetration rate scenarios are considered to examine the impacts on the optimal PV-BESS design maximising the economic return.