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Flexibility of electric vehicles and space heating in net zero energy houses: an optimal control model with thermal dynamics and battery degradation

Jyri Salpakari *, Topi Rasku, Juuso Lindgren, Peter D. Lund

New Energy Technologies Group, Department of Applied Physics, School of Science, Aalto University, P.O.Box 15100, FI-00076 AALTO (Espoo), Finland

HIGHLIGHTS

- A new optimal control model of a microgrid with smart PEVs and space heating.
- Battery degradation and thermal dynamics of PEVs and buildings included.
- A case study on 1–10 houses with empirical data from Southern Sweden.
- 8–33% cost savings with optimal control compared to energy-efficient baseline.
- Battery degradation cost significantly decreases the added value of vehicle-to-grid.

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ABSTRACT

With the increasing penetration of distributed renewable energy generation and dynamic electricity pricing schemes, applications for residential demand side management are becoming more appealing. In this work, we present an optimal control model for studying the economic and grid interaction benefits of smart charging of electric vehicles (EV), vehicle-to-grid, and space heating load control for residential houses with on-site photovoltaics (PV). A case study is conducted on 1–10 net zero energy houses with detailed empirical data, resulting in 8–33% yearly electricity cost savings per household with various electric vehicle and space heating system combinations. The self-consumption of PV is also significantly increased.

Additional benefits through increasing the number of cooperating households are minor and saturate already at around 3–5 households. Permitting electricity transfer between the houses and EV charging stations at workplaces increases self-sufficiency significantly, but it provides limited economic benefit. The additional cost savings from vehicle-to-grid compared to smart charging are minor due to increased battery degradation, despite a significant self-sufficiency increase. If the optimization is conducted without taking the battery degradation cost into account, the added monetary value of vehicle-to-grid can even be negative due to the unmanaged degradation. Neglecting battery degradation completely leads to overestimation of the vehicle-to-grid cost benefit.

1. Introduction

Concerns about climate change drive the use of variable renewable energy (VRE) in electricity production, most notably solar and wind generation [1]. Without additional flexibility, large scale VRE generation cannot be fully utilized without compromising power system reliability and safety [1].

Demand side management (DSM) can compensate for lack of flexibility by establishing control of the consumption. Ideal DSM appliances have a lot of idle time and are shiftable, i.e. the exact timing of their power draw is irrelevant to the end user. Therefore, space heating and heating domestic hot water (DHW) with heat pumps and thermal energy storage (TES), and charging plug-in electric vehicles (PEVs) are promising candidates for DSM applications [2]. Moreover, they fit with electrification of transport and heating sectors, and energy efficiency of buildings, which are seen as key pathways to low-carbon energy systems along with increase in VRE use [3]. Heat pumps are a well-established technology

* Corresponding author.
E-mail address: jyri.salpakari@aalto.fi (J. Salpakari).

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Nomenclature

Abbreviations

A/C	air conditioning
BEV	battery electric vehicle
CHP	combined heat and power
COP	coefficient of performance
DHW	domestic hot water
DOD	depth of discharge
DSM	demand side management
E10	ethanol-fuel mixture with 10% ethanol
GSHP	ground-source heat pump
HVAC	heating, ventilation, and air conditioning
ICE	internal combustion engine
LMO	lithium manganese oxide
LP	linear programming
MG	microgrid
MILP	mixed-integer linear programming
net-ZEB	net zero energy
NMC	nickel manganese cobalt
PDF	probability density function
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
PV	photovoltaic
RE	renewable energy
SC	smart charging
SEA	Swedish Energy Agency
SHLC	space heating load control
SOC	state of charge of battery
TRNSYS	Transient System Simulation Tool
V2G	vehicle-to-grid
VRE	variable renewable energy

Symbols

A	surface area, heat transfer and capacity matrix
a_c	capacity severity factor in battery ageing model
B	heat transfer and capacity matrix
b	battery ageing model fitting parameter
C	heat capacity
c	specific heat capacity, battery ageing model fitting parameter
D	power draw required by EV driving
E	energy
F	fuel energy
f	probability density function
G	grid or market interaction power
g	vehicle grid-connection indicator
H	heat transfer coefficient
h	height
i	general integer index
J	ampere-hour throughput
j	general integer index
k	general integer index
L	battery capacity loss ratio
N	number
P	electric power
p	price, cost
Q	ampere-hour capacity of battery
R_g	universal gas constant
r	driving mode parameter in PEV battery ageing model
S	electric power for vehicle charging or discharging in home grid
SOC	state-of-charge
T	temperature
t	time
U	voltage, U-value
V	volume
w	indicator of vehicle location at workplace charging station
y	electricity transmission to workplace indicator
z	battery ageing model fitting parameter
α	coefficient of performance
α_c	battery ageing model fitting parameter
$\boldsymbol{\beta}$	matrix in analytic solution of differential equation
β_c	battery ageing model fitting parameter
$\boldsymbol{\gamma}$	matrix in analytic solution of differential equation
γ_c	battery ageing model fitting parameter
$\boldsymbol{\epsilon}$	matrix in analytic solution of differential equation
$\boldsymbol{\zeta}$	matrix in analytic solution of differential equation
η	efficiency
κ	supply water temperature coefficient of the heating system
Λ	effective surface area of vehicle cabin
μ	air exchange rate
ν	battery self-discharge rate
τ	supply water temperature constant of the heating system
$\bar{\upsilon}$	total heat transfer factor to interior from radiant floor
Φ	total thermal power
ϕ	thermal power
φ	passive heat gain
Ψ	total electric power in electric heating or cooling
ψ	electric power in electric heating or cooling

Subscripts and superscripts

0	reference value
$+$	charging, heating
$-$	consumption, cooling, discharging
ac	activation
app	appliance
b	battery, buy
c	cabin
cell	cell
Ca	Carnot
d	degradation
do	door
dhw	domestic hot water
e	exterior (ambient air)
F	fuel
f	fee, floor
fl	floor
g	ground, going to work
HVAC	heating, ventilation and air conditioning
h	house
i	interior
in	inlet
m	market
max	maximum
min	minimum
ppl	people
r	retail, returning from work
ro	roof
s	sell
sol	solar
sup	supply
system	system
ref	reference value
v	vehicle
w	work
wa	wall
wi	window