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Impact of plug-in hybrid electric vehicles on thermal generation expansion with high wind penetration

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Abstract

By 2030, the Australian government intends to increase the market share of electric vehicles by at least 50%. This paper investigates the effect of the upcoming large-scale implementation of plug-in hybrid electric vehicles (PHEVs) in Australia on thermal power generation expansion decisions and integration of wind power into New South Wales (NSW), the largest regional market in the Australian National Electricity Market (NEM). Furthermore, seeking to understand whether optimizing and allocating PHEV charging loads can effectively decrease investments and operational costs of the power system with high wind penetration, we also evaluate the potential cost savings from the dedicated governmental charging strategy of PHEV fleets. To this end, we develop a Mixed Integer Linear Programming (MILP) optimization model for optimal power system investment decisions. The simulation results demonstrate that, grid-connected PHEVs obviously increase power system financial and operational burdens. When compared to the scenario with dumb charging strategy, smart charging strategy results in less investment in thermal generation and flatter load curve, as well as less wind curtailment.

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Keywords: Electricity markets; Generation capacity investment; Plug-in hybrid electric vehicles; Wind power

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1. Introduction

Over the last decade, the global installed capacity of renewable energy, such as wind power, has experienced a dramatic growth. Due to zero fuel cost and free emission, wind power offers both economic and environmental benefits. However, wind power varies depending on meteorological conditions, resulting in intrahourly fluctuations. To compensate the inherent variability and uncertainty of wind energy, the power system requires additional investment of expensive fast-responding gas combustion turbine units. Research has shown that such an approach can increase system operational costs by up to $5/MWh, as well as generate to a higher production of NOx and SO_2 emissions that harm human health and the environment [1,2].

Plug-in electric vehicles (PEVs), including plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), have the capacity to quickly adjust demand-side consumption, thereby promptly modifying the system load

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Nomenclature

A. Sets

I	Set of candidate thermal generators, indexed by i
J	Set of PHEV groups, indexed by j
L	Set of load seasons, indexed by l
M	Set of generation technologies, indexed by m
S^l	Set of wind generation scenarios in load season l, indexed by s
T^l	Set of hours for each load season, indexed by t

B. Binary Decision Variables

u_i	Binary capacity expansion decision variable

C. Continuous Decision Variables

$P_{j,t,s}^{EV}$	Charging power of PHEV group j in hour t under scenario s
$P_{i,t,s}^{thermal}$	Electricity generation from generator i in hour t under scenario s
$P_{t,s}^{wind}$	Wind power output in hour t under scenario s
$P_{t,s}^{wind\cdot curtail}$	Wind curtailment in hour t under scenario s
$SOC_{j,t,s}$	State of charge for the batteries of PHEV group j in hour t under scenario s

D. Parameters

F_i	Fixed annual cost for candidate thermal generator i
Inv_i	Annualized investment for candidate thermal generator i
P_i^{max}	Installed capacity for candidate thermal generator i
k_l	Number of weeks in load season l
c_i	Operational cost (incl. fuel cost and variable O&M cost) for candidate thermal generator i
Dec_i	Ramping down limit for candidate thermal generator i
Inc_i	Ramping up limit for candidate thermal generator i
$P_j^{EV\cdot max}$	Maximum charging power for PHEV group j
$P_{t,s}^{load}$	Non-PHEV load in hour t under scenario s
$P_{t,s}^{wind\cdot available}$	Available wind power in hour t under scenario s
SOC_j^{max}	Maximum battery state of charge for PHEV group j in hour t under scenario s
SOC_j^{min}	Minimum battery state of charge for PHEV group j in hour t under scenario s
$\lambda^{wind\cdot curtail}$	Maximum wind curtailment ratio
ω_s	Probability of scenario s.

profile. Previous studies have demonstrates that this flexibility of PEVs to the grid can not only accommodate the intermittence and uncertainty of wind power [3], but also improve grid stability [4], lower power system costs [5], and boost power system efficiency [6].

Despite electric vehicles' advantages, electric utilities have expressed concern over the growing battery charging load. In response to the ambitious target of the Australian government to increase, by 2030, the market share of electric vehicles by at least 50%, the present paper explores the prospective impact of the upcoming large-scale implementation of PHEVs on thermal generation investment decisions and integration of wind power into New South Wales (NSW), the biggest sub-electricity market in the National Electricity Market (NEM) of Australia. In addition, seeking to understand whether optimizing and allocating PHEV loads can effectively decrease capital and operational costs of the power system with high wind penetration, or whether smart charging strategy will only benefit system load shifting, we also evaluate the potential cost savings from the dedicated governmental charging strategy of PHEV fleets.

Using electric vehicles as a means to facilitate integration of wind power into power systems has been extensively discussed in the literature [3,7–10]. Furthermore, many previous researches evaluated the effect of electrifying vehicles on power system's capacity expansion and operational costs (e.g. [11–13]).

To the best of our knowledge, so far there have been no studies on grouping passenger vehicle driving behaviors to examine the interactive relationship between electric vehicles penetration, power system expansion, as well as wind power integration in Australia. In the context of the prospective large-scale introduction of PHEVs for a power system with high wind power penetration towards 2030, the present case study of the NSW power system quantitatively investigates a thermal generation capacity investment problem with consideration of a massive implementation of PHEVs for a power system with high wind power penetration.

2. Model

The present paper introduces a stochastic investment decision program with hourly unit commitment and economic dispatch. In the proposed optimization problem, total annualized system costs are to be minimized in some future years. Wind power scenarios are constructed to capture its uncertainty. The planning of generation expansion is formed as a Mixed Integer Linear Programming (MILP) problem.

$$min \sum_{i\in I} u_i (Inv_i P_i^{max} + F_i) + \sum_{l\in L} k_l \sum_{s\in S^l} \omega_s \sum_{t\in T^l} \sum_{i\in I} c_i P_{i,t,s}^{thermal} \tag{1}$$

$$\sum_{i\in I} P_{i,t,s}^{thermal} + P_{t,s}^{wind} = P_{t,s}^{load} + \sum_{j\in J} P_{j,t,s}^{EV} \qquad \forall i, j, t \in T^l, s \in S^l \tag{2}$$

$$P_{i,t,s}^{thermal} \leq u_i P_i^{max} \qquad \forall i, t \in T^l, s \in S^l \tag{3}$$

$$P_{i,t,s}^{thermal} \leq P_{i,t-1,s}^{thermal} + Inc_i \qquad \forall i, t \in T^l, s \in S^l \tag{4}$$

$$P_{i,t,s}^{thermal} \geq P_{i,t-1,s}^{thermal} - Dec_i \qquad \forall i, t \in T^l, s \in S^l \tag{5}$$

$$P_{t,s}^{wind} + P_{t,s}^{wind\cdot curtail} = P_{t,s}^{wind\cdot available} \qquad \forall t \in T^l, s \in S^l \tag{6}$$

$$P_{t,s,l}^{wind\cdot curtail} \leq \lambda^{wind\cdot curtail} P_{t,s,l}^{wind\cdot available} \qquad \forall t \in T^l, s \in S^l \tag{7}$$

$$P_{j,t,s}^{EV} \leq P_j^{EV\cdot max} \qquad \forall i, j, t \in T^l, s \in S^l \tag{8}$$

$$SOC_j^{min} \leq SOC_{j,t,s} \leq SOC_j^{min} \qquad \forall i, j, t \in T^l, s \in S^l \tag{9}$$

$$u_i \in \{0, 1\} \qquad \forall i \tag{10}$$

$$P_{i,t,s}^{thermal}, P_{t,s}^{wind\cdot curtail}, P_{j,t,s}^{EV} \geq 0 \qquad \forall i, t \in T^l, s \in S^l \tag{11}$$

The objective (1) is to maximize the annualized power system cost that consists of the annualized investment, the fixed costs of building new power plants, and the accumulated operational costs in a year. u_i is scenario-independent binary capacity expansion decision variable that represents which candidate units will be built to serve the power system. Constraints in Eq. (2) ensure that hourly energy is balanced for any hour t in scenario s during season l. To simplify calculation, we do not consider trans-state electricity trading. In (3), the generation output of generator i is limited by u_i and its rated installed capacity. Constraints in (4) and (5) limit the maximum ramping up and down rates for each generator i in any two consecutive hours. Here, we simplify the generator model by ignoring the constraints of the start-up/shutdown time, start-up cost, and minimum generation output. Eq. (6) imposes the balance of hourly wind power. Constraints (7) set a cap on the maximum wind curtailment. Considering that an excessively high charging power will damage PHEV batteries, constraints (8) regulate the maximum charging power so as to prolong the life cycle of batteries. Constraints (9) ensure that the ratio of the residual energy to the rated capacity of batteries remains within a certain range to protect the batteries. In constrains (10), binary investment decision variable is set to 1 if candidate thermal generator i will be built, and 0 otherwise. Constraints (11) ensure power generation and wind curtailment nonnegative.

Of note, in a fully deregulated electricity market, individual electricity generation companies usually make their own decentralized investment decisions. However, in the present study, we aim to explore to what extend the number of PHEVs and charging strategy influence the power system investment and operation. To this end, instead of modeling interactions between investors and examining the dynamic aspects of system investment decisions, we propose a one-period static centralized capacity expansion model. In addition, to obtain authorization to access battery charging, power system operators or utilities usually have to pay PHEV owners, which may affect driving patterns and consumer utilities. But the controlled charging strategies proposed in the present study involve only passenger vehicles that finish the last trip of the day, thus not decreasing any driving experience. Therefore, we do not consider the costs of compensating PHEV owners. In addition, we also assume that the expanded power system can ensure consistent electricity supply. Accordingly, load shedding and corresponding values of lost load are not included in the model.

3. Data description

3.1. Benchmark load

We develop the hourly load data for NSW by averaging the real 2018 half-hourly load profile obtained from the Australian Energy Market Operator (AEMO). Considering that, in 2030, the annual non-PHEV load is estimated to fluctuate within 1% as compared to that in 2018 [14], we use the 2018 demand data to represent the prospective 2030 data without any scaling. The hourly load data is profiled into three seasonal time slices, from which one week in March represents summer load season, one week in August represents winter load season, and one week in October represents other load season. These three typical weeks comprise a total of 504 h. To reduce computational complexity, we assume that each of the seasons (summer, winter, and other season) represents 1/3 of the year, and the multipliers k_l equal 52/3 to obtain the optimal economic dispatch on the annual basis.

3.2. PHEV load

In general, due to the limitations of battery capacity, the rated capacity and all-electric range of different PHEV models vary within a very narrow range. To efficiently model and schedule the behaviors of PHEV fleets, we use the parameters of Mitsubishi Outlander SUV, one of the most popular PHEV models in Australia, to represent all PHEV batteries (see Table 1). Relying on the growth trend in the number of registered passenger vehicles in NSW. we assume that, by then, there would be about 4,130,008 PHEVs on the NSW roads in 2030.

Table 1. Parameters of PHEV.

Type	Numerical value
Battery size (kWh)	12
All electric range (km)	54
Charging power limit (kW)	3.7
SOC min/max limit (%)	10/100
Energy efficiency (km/kWh)	4.5

The daily driving data of passenger vehicles are collected from Queensland (QLD) Household Travel Survey released by Department of Transportand Main Roads [15]. The data are grouped based on the daily accumulative driving distance and the last return time of day, as illustrated in Fig. 1. Due to limited data availability, we assume that NSW passenger vehicle owners' driving patterns are identical to those of owners from the neighboring state, QLD. The daily driving distances of passenger vehicles are concentrated in the range of 0–50 km, with very few people driving over 100 km accumulatively per day. Moreover, over 67.19% of the last return time occurs from 3 pm to 8 pm. If these PHEVs charge immediately after arriving home, this PHEV load, coupled with the existing non-PHEV peak load in the evening, will cause the so-called 'peak on peaking' phenomenon for the power system. Consequently, the supply side of the power system will face big operational burdens.

3.3. Wind uncertainty

We construct wind power scenarios based on the real hourly wind profiles of the years 2015–2017. These profiles are derived from 6 potential wind power sites in NSW from AEMO [16]. Each 7-day hourly wind power output is considered to be one scenario. We assume that, in 2030, wind penetration can reach 40%. We scale up total the exiting hourly wind profile and let $P_t^{wind\cdot available}*8760$ be equal to 40% of the annual load in NSW.

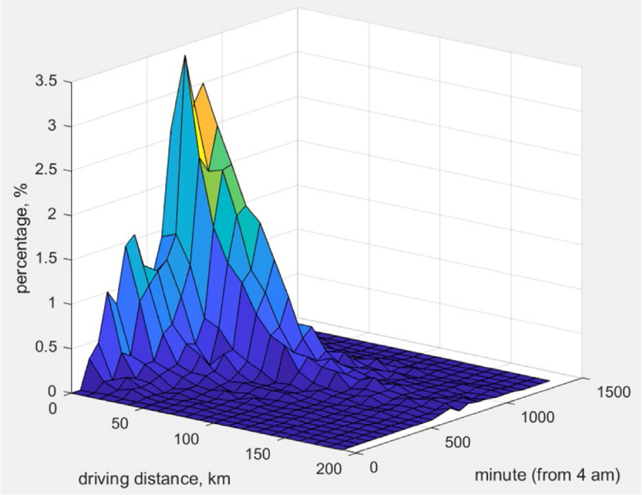

Fig. 1. Distribution of passenger vehicles based on last-trip ending time and daily accumulative driving distance.

Table 2. Parameters of candidate units.

Candidate unit	Base	Medium		Peak	
Technology	Black coal	CCGT	CCGT	OCGT (aero)	OCGT (frame)
Investment cost (AUD/year/MW)	325,257	198,407	94,325	78,062	65,051
Fixed cost of O&M (AUD/year/MW)	50,000	35,000	20,000	10,000	8,000
Variable cost of O&M (AUD/MW)	8	12	1.5	15	12
Fuel cost (AUD/MWh)	27	56	47	60	69

3.4. Candidate thermal units

The current NSW power system is assumed to have four coal units for baseload with the accumulated 8240 MW installed capacity, and three gas-fired power stations with the installed capacity over 200 MW, including one combined-cycle gas turbine (CCGT) power station and two open-cycle gas turbine (OCGT) power plants. We assume that investment decisions could be made in any of 15 candidate units, including 2 baseload units, 6 shoulder load units, and 7 peak load units. Table 2 lists the parameters of the candidate units based on Australian Power Generation Technology Report [17].

4. Results and discussion

4.1. Scenario description

To investigate the impacts of PHEV charging strategies on power system expansion, we consider the following two charging strategies:

- Dumb charging. It allows PHEVs to start charging as soon as the vehicle finishes the last trip of the day.
- Smart charging. In order to minimize system costs, charging of PHEVs can be flexibly allocated and dispatched under constrained conditions.

4.2. Results

Fig. 2 shows the main economic modeling results for the scenarios of dumb charging and smart charging in relation to annualized capital cost (i.e. investment), electricity generation cost (i.e. operational cost), and total cost in 2030. As compared to smart charging, dumb charging requires spending a total of 24.1% more to increase thermal

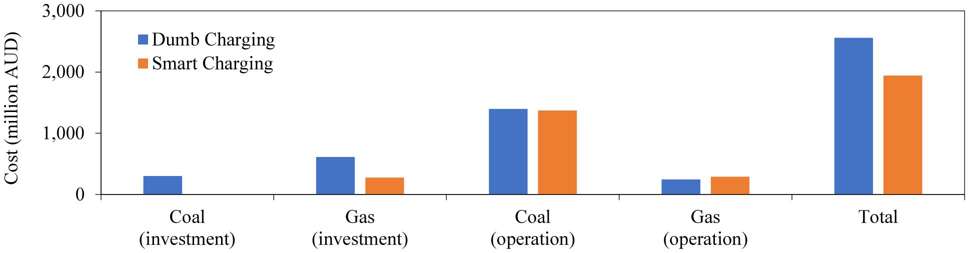

Fig. 2. Annualized capital cost, operational cost, and total yearly cost for gas-fired units and coal-fired units.

capacity and run thermal units for supporting PHEV battery charging. By contrast, smart charging effectively pushed down the investment in new thermal capacity to AUD 613 million, which corresponds to halving the capital cost of dumb charging scenario. Importantly, with smart charging, the power system reduces investment on coal-fired units to zero. The main reason underlying this reduction is that baseload units can be fully utilized almost all the time, as smart charging takes full advantage of fast ramping up/down characteristics of gas-fired units and shifts partial PHEV loads from peak to off-peak hours.

The power consumption of charging batteries causes a significant increase in the yearly load by 13.84%. The hourly load (incl. both the PHEV and the non-PHEV load) for three representative seasons is shown in Fig. 3. With dumb charging, due to the so-called 'peak on peaking' phenomenon caused by the overlap of the arriving-home time of passenger vehicles with the peak hours of the non-PHEV loads, system load burden significantly increases from 4pm to 8pm. However, with the smart charging strategy, the load peak is shaved through a shift from its original time position to the valley hours at around midnight (mainly from 11 pm to 5 am). This 'valley filling' effectively reduces the overall peak load by around 13.58%, 19.67% and 8.34%, in summer, winter, and other season, respectively.

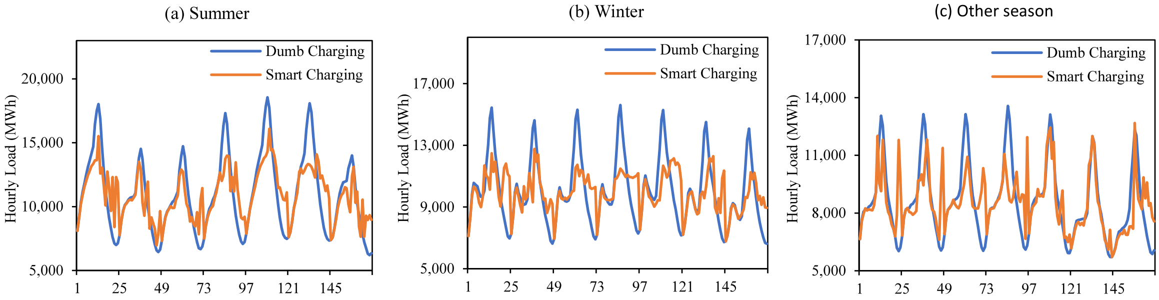

Fig. 3. Hourly load for the representative weeks of (a) summer; (b) winter; and (c) other season.

Table 3 summarizes the installed capacity of thermal generation for dumb charging and smart charging strategies. Applying smart charging hedges the capital cost of new coal-fired generators and decreases the required installed capacity of gas units from 8,423 MW to 5,075 MW. This reduction can be explained by the flexibility afforded by smart charging that evenly spreads the load over the evening hours. In addition, smart charging uses the maximum from the existing and to-be-built medium and peak gas-fired units, thereby reducing reliance on building new units.

Table 3. Total installed capacity at dumb charging and smart charging (MW).

	Coal-fired units	Gas-fired units
Dumb charging	9465	8423
Smart charging	8240	5075

Wind curtailment is typically defined as a condition when wind turbines can output more than the total system load. Table 4 compares the two charging scenarios regarding the ability of PHEVs to accommodate the fluctuation

Table 4. Expected wind curtailment at dumb charging and smart charging.

	Wind curtailment (MWh)	Wind curtailment (%)
Dumb charging	3,938,583	10.6
Smart charging	3,243,102	8.77

wind power into the power system. The results demonstrate that, owing to shifting the hours with surplus wind, smart charging facilitates the reduction of the expected wind curtailment percentage from 10.61% to 8.77%. In view of the Australian federal government's strong commitment to the development of renewable energy, the share of wind power in the NEM is expected to boom in the upcoming years. Consequently, along with the electrifying transition of vehicles, the smart charging strategy of PHEV fleets shows much promise in terms of fostering the system integration of wind power.

5. Conclusions

In the context of the prospective large-scale implementation of PHEVs, we quantitatively investigated the thermal generation capacity investment and operation problem based on a case study of the NSW power system in 2030. To evaluate how the massive penetration of PHEVs influence the costs of power system with a high wind penetration, we simulated the proposed MILP problem using two charging strategies—namely, dumb charging and smart charging.

Our simulation results showed that PHEVs can incur extra system costs of AUD 2,560 million for the scenario with dumb charging strategy. In contrast, with the smart charging strategy, the corresponding annual system cost would decrease to AUD 1,942 million. Due to the massive battery charging load, both the daily peak load and load variation would remarkably increase. In addition, a high wind power penetration incurs huge power system burden from the view of supply side. When compared to the scenario with dumb charging strategy, smart charging strategy results in less investment in thermal generation and flatter load curve, as well as less wind curtailment.

The limitation of the present study is that our simulations results are specific to NSW and largely depend on our assumptions such as the power system generation mix, PHEV charging, and wind generation profile. In further research, we intend to investigate the robustness of our optimization results upon release of some of the assumptions. We also plan an in-depth financial analysis in full consideration of different PHEV penetrations rates, smart charging acceptance, and other controlled charging strategies, such as delay charging.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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