

Modeling the Operation of Electric Vehicles in an Operation Planning Model

Andres Ramos, Jesús M. Latorre, Fernando Báñez, Ángel Hernández, Germán Morales-España,
Kristin Dietrich, Luis Olmos
Universidad Pontificia Comillas
Madrid, Spain
Andres.Ramos@upcomillas.es

Abstract – This paper presents a short-term power system operation model where the electric vehicle management is being considered. Electric vehicles are considered as loads depending on the usage pattern. The operation model resorts to a mixed integer programming problem to determine the optimal system operation. We also evaluate vehicle to grid generation and power reserve service provision. Different EV share scenarios and V2G capabilities are evaluated for the mainland Spanish electric system. The contribution of electric vehicles on the integration of renewable sources is also determined.

Keywords: *electric vehicles, short-term operation planning, operating reserves, V2G services, renewable sources integration*

1 INTRODUCTION

One of the priorities of the EU policy is achieving a high share of overall energy consumption coming from renewable energy sources (RES) in the long-term. Strong incentives to the integration of RES have been given. Thus, solar photovoltaic and, mainly, wind generation power have strongly increased their production in many European countries, see [1] and [2]. A drawback of these generation resources is their intermittency (variability and uncertainty), hard to predict and to control, specially for high shares of wind generation, see [3] and [4].

Electric vehicles (EV) can play an important role in increasing the participation of RES into the system. They can adapt their load and generation profile to different system conditions and even provide some other services to the system [5].

Few papers deal with the integration of EVs in power system operation models. For instance, authors in [6] model it from the point of view of an energy services company. In [7] some regulatory issues related to the optimal rates of EV load for effective energy shifting are analyzed. In [8, 10] Plug-in Hybrid Electric Vehicles (PHEV) are modeled into a unit commitment model. In [9] the electric system is represented using an agent-based simulation model to determine spot prices taking into account EV management and wind generation. In [10] a particle swarm algorithm is used to achieve the optimal solution of a unit commitment model that includes EVs. An investment model that considers PHEV is presented in [11]. However, this model does not consider the different EV states and the operating reserve services provided by EVs.

This paper presents a short-term operation model that allows determining the technical and economic impact of EVs, see [12]. This short-term operation model is a day-ahead perfect market operation (unit commitment) where specific changes have been made to consider EV operation. In particular, EVs are modeled as potential providers of energy and operating reserve services through the efficient management of the charge and discharge (V2G) of their batteries.

The main contributions of the paper are the specific constraints modeling of the state-of-charge (SOC) of the batteries considering several states where EVs can be (either, connected or disconnected from the grid or moving), therefore requiring different inventory equations. Besides, the provision of operating reserves by the EVs and its impact on the battery SOC. These constraints are necessary to consider the impact of the EVs in the operation of the system on an hourly-based unit commitment. The application of the model to the large-scale Spanish system and the results obtained are also a contribution of the paper.

The paper is structured as follows: in section 2 we present the notation of the mathematical model we have developed. Section 3 includes the formulation of a day-ahead perfect market operation model that determines the optimal operation of the system including thermal, hydro, pumped storage hydro, wind generation and concentrated solar power plants as generating resources. The changes introduced in this model due to considering EVs are presented in section 4. Section 5 analyzes a realistic case study and determines the economic impact of smart charging and of the use of the V2G capability of EVs. Finally, in section 6 the main conclusions of this paper are presented.

2 NOTATION

In this section, the notation used in the paper is presented. Upper-case letters have been used for denoting parameters and lower-case letters for variables. The indexes have been defined with lower-case letters too, but they appear as sub/upper-indexes.

Table 1: Indexes.

P	Periods (hours)
$\mathcal{G}$	Generators
t	Thermal units ($\{t\} \subset \{g\}$)

h	Hydro plants (reservoirs) ($\{h\} \subset \{g\}$)
b	Pumped storage hydro plants ($\{b\} \subset \{h\}$)
i	Concentrated solar power (CSP) plants ($\{i\} \subset \{g\}$)

Table 2: Parameters.

		Unit
D_p	Demand for period p	MW
WG_p	Wind and other RES generation (small hydro, CHP, solar, biomass) for period p	MW
UR_p, DR_p	Upward and downward reserve in period p	MW
$\overline{GP}_p^g$	Maximum output of generator g in period p	MW
RU^t, RD^t	Ramp-up and ramp-down of thermal unit t	MW/h
I_p^h	Inflows in reservoir h for period p	MWh
EfP_h	Efficiency of pumping process in generator h	p.u.
In_p^i	Energy received in CSP plant i in period p	MWh
IRC^i, IRD^i	Charging and discharging hourly ramp of storage of CSP plant i	MWh/h
LsF_i	Energy loss factor of CSP plant i	p.u.
EfC_i	Efficiency in the charging process of CSP plant i	p.u.
URC, DRC	Upward and downward reserve deficit cost	€/MWh
$NSEC$	Non-supplied energy cost	€/MWh
FC^t	Fixed cost of thermal unit t	€/h
VC^t	Variable cost of thermal unit t including fuel cost and O&M	€/MWh
SC^t	Start-up cost of thermal unit t	€

Table 3: Variables.

		Unit
$opcost$	Total system operation cost	€
nse_p	Non-supplied power in period p	MW
sp_p	Power spillage (i.e., wind curtailment) in period p	MW
$urdef_p, drdef_p$	Upward and downward reserve deficit in period p	MW
st_p^t, sh_p^t	Start-up and shut-down of thermal unit t in period p	[0,1]
c_p^t	Commitment of thermal unit t in period p	{0,1}

gp_p^g	Output of generator g in period p	MW
gc_p^h	Consumption of pumped storage hydro plant $h \in b$ in period p	MW
r_p^h, s_p^h	Reservoir level and spillage of hydro reservoir h in period p	MWh
gur_p^g, gdr_p^g	Upward and downward power reserve of generator $g \notin b$ in period p	MW
pur_p^h, pdr_p^h	Upward and downward power reserve of pumped storage hydro plant $h \in b$ in period p	MW
ie_p^i, is_p^i	Energy stored and spilled in CSP plant i in period p	MWh
ic_p^i, id_p^i	Charging and discharging power for the storage of CSP plant i in period p	MW

3 OPTIMIZATION MODEL DESCRIPTION

In this section, the optimization model that is responsible for determining the scheduled daily program for all generators' is described. This model determines the unit commitment and daily economic dispatch, considering the demand and wind power generation forecasted (expected) one day in advance. Subsequently, these estimations may be altered by realizations in the values of the uncertain parameters (electricity demand, intermittent generation, availability of the generators) that are taken into account by a simulation model. It reproduces the real-time operation of the system by considering these stochastic events.

The optimization model has a yearly scope with a daily time frame and an hourly time unit for determining the system unit dispatch, since this is required to appropriately represent the time variation of consumption and output of EVs and the other technologies (including RES). As we consider the system operation constant in the hour, power is just converted into energy by multiplying by one hour and, therefore, they are equivalent. The chronology of operation decisions for the whole year is kept. So the initial states of the generating units, for every day, are those of the last hour of the previous day.

3.1 Objective function

The objective function minimizes the operation costs plus some deficit costs introduced for violating some constraints:

$$opcost = \sum_p \left[\sum_t (FC^t c_p^t + SC_t st_p^t + VC^t gp_p^t) + NSEC nse_p + URC urdef_p + DRC drdef_p \right] \quad (1)$$

Model constraints are described in the following sections. Note that the duration of all periods is one hour and therefore the formulation is simplified.

3.2 Demand and reserve constraints

The equation that ensure the balance of generation and demand for each period is presented as follows:

$$D_p - WG_p - nse_p + sp_p = \sum_g gp_p^g - \sum_h gc_p^h \quad \forall p \quad (2)$$

Where the set of generators g includes thermal units, hydro plants, pumped storage hydro plants and concentrated solar power plants. WG_p considers the next-day forecasted wind production (and other RES):

The total upward and downward reserve for each period p is provided by thermal units, hydro and pumped storage hydro plants. A deficit variable is introduced that is penalized in the objective function.

$$\begin{aligned} \sum_{g \in b} gur_p^g + \sum_{h \in b} pur_p^h + urdef_p &\geq UR_p \\ \sum_{g \in b} gdr_p^g + \sum_{h \in b} pdr_p^h + drdef_p &\geq DR_p \end{aligned} \quad \forall p \quad (3)$$

3.3 Thermal unit constraints

The commitment, start-up and shut-down of thermal units is controlled by the following logical relation where only the commitment variable needs to be defined as binary.

$$c_p^t - c_{p-1}^t = st_p^t - sh_p^t \quad \forall p, t \quad (4)$$

The output offered in the energy market plus the power reserve offered as operating reserve of each thermal unit is bounded by the maximum output of the unit.

$$gp_p^g + gur_p^g \leq \overline{GP}_p^g \quad \forall p, g \in t \quad (5)$$

The unit variation output, including the upward and downward power reserves, are limited by up and down hourly ramps in consecutive hours:

$$\begin{aligned} (gp_p^g + gur_p^g) - (gp_{p-1}^g - gdr_{p-1}^g) &\leq RU^g \\ (gp_{p-1}^g + gur_{p-1}^g) - (gp_p^g - gdr_p^g) &\leq RD^g \end{aligned} \quad \forall p, g \in t \quad (6)$$

As a difference with respect to the classical ramp constraints the former ones include also the power offered as up or down operating reserve, gur_p^g and gdr_p^g respectively, given that if the unit is called upon to provide reserve ramp rates must be satisfied.

The generators have a minimum time that, once the generator has been switched on (off), it must be kept running (stopped). These constraints are also included in the model.

3.4 Hydro plant constraints

The model ensures that a hydro plant cannot be generating while is pumping.

The output, including the power reserve, for each hydro plant is bounded by the maximum output of the plant.

$$gp_p^g + gur_p^g \leq \overline{GP}_p^g \quad \forall p, g \in h \quad (7)$$

The balance of the hydro reservoir level is managed with the following constraint that includes consumption and generation of the storage hydro plant and spillage and natural inflows:

$$r_p^h - r_{p-1}^h = -gp_p^h + Efp_h \cdot gc_p^h - s_p^h + I_p^h \quad \forall p, h \quad (8)$$

3.5 CSP plant constraints

CSP power plants behave as pumped storage hydro plants with daily management when they have some storage capability. Otherwise they act as intermittent generation.

The irradiation energy received is transformed in either CSP plant generation or charging or discharging power of the storage:

$$In_p^i - gp_p^i - ic_p^i + id_p^i = 0 \quad \forall p, i \quad (9)$$

The balance of the CSP plant storage is presented as follows:

$$ie_p^i - LsF_i \cdot ie_{p-1}^i = Efc_i \cdot ic_p^i - id_p^i - is_p^i \quad \forall p, i \quad (10)$$

Hourly ramp constraints in the charge and discharge of the CSP plants:

$$-IRD^i \leq ie_p^i - ie_{p-1}^i \leq IRC^i \quad \forall p, i \quad (11)$$

4 EV REPRESENTATION

First, the additions of indexes, parameters and variables that have been necessary to include the EV in the model are in the tables below. Afterwards, the new constraints included in the model are described.

4.1 New indexes and parameters

Table 4: Indexes.

e	Types of EV
s, s'	State of the EV (sc , sd and sm)

Two new indexes have been added: the type of EV that can exist in the system and the EVs state. The type of EV is used to represent different uses of cars, van, trucks, etc. The EV state can be: parked and connected to the grid (sc), parked and disconnected from the grid (sd) and moving (sm). These states, similar to those

found in [12], make possible three different situations in the use of the batteries of the EVs, depending whether the vehicle is connected, disconnected or moving:

- The connected ones can be charging or discharging their batteries. Note that the charging and discharging process have different efficiencies, $EEfGtB^e$ and $EEfBtG^e$ respectively.
- It is assumed that the disconnected vehicles, as mentioned previously, which are stopped, do not have energy losses.
- The moving EVs have a pattern of distance and driving time (in fact, the energy consumed) given by a parameter. The energy transformation from battery to wheel has a different efficiency, $EEfBtW^e$.

In order to model the impact of a massive use of EV, some data are needed: i) mobility patterns, ii) the characterization of different uses of EVs corresponding to different segments of them and iii) battery characteristics of each EV segment. Mobility patterns specify the daily distance to be covered, the SOC at the beginning of the day, the hourly usage of the EV and vehicle connection profiles of the EV. These detailed characteristics allow distinguishing among EV states previously mentioned. The set of EVs is segmented according to the combination of mobility patterns of these vehicles. Finally, battery characteristics consider maximum and minimum SOC, efficiencies in the possible processes (Grid-To-Battery, Battery-To-Wheel, Battery-To-Grid), maximum charging and discharging rates and maximum power output. The symbols for the parameters presented previously are summarized in the next table.

Table 5: Parameters.

	Unit
$\overline{EC}_p^e, \overline{ED}_p^e$	Maximum power charged and discharged by EV e in the period p MW
$\underline{EE}^e, \overline{EE}^e$	Minimum and maximum energy charged by EV e MWh
ERC^e, ERD^e	Battery charge and discharge ramp of EV e within a period MWh/h
$EP_p^{e,s}$	Percentage of EV of type e and in the state s for each period p p.u.
$EPT_p^{e,s,s'}$	Percentage of EV of type e and in the state s' that move to the state s for each period p p.u.
$ET_p^{e,s}$	Battery energy used in transport of each type of EV e in each state s for each period p MWh
$EEfGtB^e$	Grid to battery efficiency for each type of EV e p.u.
$EEfBtG^e$	Battery to grid efficiency for each type of EV e p.u.

$EEfBtW^e$	Battery to wheel efficiency for each type of EV e p.u.
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Variables

	Unit
$ee_p^{e,s}$	State of charge (SOC) of the battery of EV e at the end of period p in each state s MWh
$ep_p^{e,s}, ec_p^{e,s}$	Generation and consumption of EV e in state s in period p MW
eur_p^e, edr_p^e	Upward and downward power reserve available for EV e in period p MW
$eurc_p^e, eurd_p^e, edrc_p^e, edrd_p^e$	Upward and downward power reserve of charging and discharging available for EV e in period p MW
ch_p^e	EV e discharging or charging indicator in period p {0,1}

It is assumed that the EV charging and discharging process is managed by demand aggregators (or energy services providers) responding to the market price. From the point of view of the system operator (SO) they behave as in a perfect market optimizing simultaneously power system operations and the timing of EV charging and discharging (including provision of V2G services), also known as smart charging. Vehicle owners decide when they drive, as given by mobility patterns, but SO decides when EVs can be recharged, taking into account the connection profile. Smart charging of EVs may improve the power system efficiency, by increasing off-peak loads and thus allowing higher penetration of WG.

It follows the adaptations in the formulation of the day-ahead market operation.

4.2 Objective function

The objective function of the optimization model remains the same as before. The SO is assumed to minimize the total variable generation cost including vehicle charging requirements, subject to the same previous generation constraints and EV batteries being charged in time for every trip demanded; and serving all vehicle charging and utility electricity loads, and reserve requirements.

4.3 Demand and reserve constraints

The balance of generation and demand for each period includes production and consumption of the EVs:

$$D_p - WG_p - nse_p + sp_p = \sum_g gp_p^g + \sum_{e,s} (ep_p^{e,s} - ec_p^{e,s}) \quad \forall p \quad (12)$$

EVs can provide energy storage by charging the vehicle battery when electricity is less expensive and discharging when it is more expensive,

Furthermore, the total upward and downward reserve for each period p also takes into consideration the contribution of the EV to the reserves:

$$\begin{aligned} \sum_{g \in b} gur_p^g + \sum_{g \in b} pur_p^g + \sum_e eur_p^e + urdef_p &\geq UR_p \\ \sum_{g \in b} gdr_p^g + \sum_{g \in b} pdr_p^g + \sum_e edr_p^e + drdef_p &\geq DR_p \end{aligned} \quad \forall p \quad (13)$$

EVs can also provide ancillary services: such as operating reserves. Unlike generators, vehicle batteries have faster response times without the need to incur in spinning costs.

4.4 EV constraints

The battery energy inventory constraint keeps track of the SOC in each period p for all EVs as a function of the energy charged and discharged into and from the battery, and the SOC at the end of the previous hour. When EVs become disconnected or begin moving they take their battery energy out from the connected state as represented by the last term of the equation.

$$\begin{aligned} ee_p^{e,s} - ee_{p-1}^{e,s} &= ec_p^{e,s} EEfGtB^e - \frac{ep_p^{e,s}}{EEfBtG^e} \\ &\quad - \frac{ET_p^{e,s}}{EEfBtW^e} + \sum_{s' \neq s} ee_{p-1}^{e,s'} EPT_{p-1}^{e,s,s'} \end{aligned} \quad \forall p, e, s \quad (14)$$

This is a simplified energy inventory equation that approximates the different energy movements between connected and disconnected vehicles. This inventory equation by EV state considering the effect of the disconnected EVs is a contribution of the paper.

The logical EV constraints of charge, discharge and movement during period p are presented as follows:

$$\begin{aligned} ec_p^{e,s} = ep_p^{e,s} &= 0 \quad \forall s \notin sc \\ ET_p^{e,s} &= 0 \quad \forall s \notin sm \end{aligned} \quad \forall p, e, s \quad (15)$$

The maximum power that EV type e can charge and discharge for the state s during period p is limited by the maximum charge and discharge of an individual battery times the number of EVs in that state, and taking into account the logical condition that an EV cannot charge and discharge in the same period:

$$\begin{aligned} ec_p^{e,s} &\leq (1 - ch_p^e) \overline{EC}^e EP_p^{e,s} \\ ep_p^{e,s} &\leq ch_p^e \overline{ED}^e EP_p^{e,s} \end{aligned} \quad \forall p, e, s \quad (16)$$

The maximum power that EV type e can consume and generate for each state s during each period p is constrained by the amount of energy stored in the battery:

$$\begin{aligned} ec_p^{e,s} &\leq EP_p^{e,s} (\overline{EE}^e - ee_p^{e,s}) \\ ep_p^{e,s} &\leq EP_p^{e,s} (ee_p^{e,s} - \underline{EE}^e) \end{aligned} \quad \forall p, e, s \quad (17)$$

Hourly charging and discharging power ramps of the EV batteries have to be bounded for each state s during each period p :

$$\begin{aligned} ec_p^{e,s} - ec_{p-1}^{e,s} &\leq RC^e \\ ep_{p-1}^{e,s} - ep_p^{e,s} &\leq RD^e \end{aligned} \quad \forall p, e, s \quad (18)$$

The next equation represents the provision of battery energy for mobilizing power reserves. If EV type e is providing (up and down) power reserves during period p , then some energy has to be kept in the battery in case this energy is actually required by the system:

$$\begin{aligned} ee_p^{e,s} &\geq \underline{EE}^e + \sum_{p' \leq p} \left(\frac{eur_{p'}^e}{EEfBtG^e} + eurc_p^e EEfGtB^e \right) \\ ee_p^{e,s} &\leq \overline{EE}^e - \sum_{p' \leq p} \left(\frac{edr_{p'}^e}{EEfBtW^e} + edrc_p^e EEfGtB^e \right) \end{aligned} \quad \forall p, e, s \quad (19)$$

The total upward and downward power reserve for an EV type e during period p is the amount of upward and downward power reserve of charging and discharging processes:

$$\begin{aligned} eur_p^e &= eurc_p^e + eurd_p^e \\ edr_p^e &= edrc_p^e + edrd_p^e \end{aligned} \quad \forall p, e \quad (20)$$

The maximum amount of power that can be provided to the upward and downward power reserves by an EV type e during period p is:

$$\begin{aligned} eur_p^e &\leq EP_p^{e,s} (\overline{EC}^e + \overline{ED}^e) \\ edr_p^e &\leq EP_p^{e,s} (\overline{EC}^e + \overline{ED}^e) \end{aligned} \quad \forall p, e, s \in sc \quad (21)$$

4.5 Mathematical problem

The operation planning problem has the structure of a mixed-integer optimization problem. Results of the model include, among others, generation output, wind surplus, pumped storage hydro usage, system marginal costs, fuel consumption and CO2 emissions as well as charging and discharging profiles of the EVs.

5 CASE STUDY

A case study based on the mainland Spanish system is analyzed to observe the operational and economic impact of different EVs shares in the system. The contribution of the EV to the integration of RES is also determined.

The case study is based on the electric system preview by the Ministry of Industry for 2016 [14]. We have

studied four different scenarios of EV share, namely with 100000 and 250000 EVs that correspond to almost 0.5 % and 1 % of the total vehicle fleet and the same cases with V2G capability. Smart charging and discharging processes are considered in the case study.

The following table summarizes the main attributes of the case study.

Demand and reserve		
Yearly Energy	323.4	TWh
Winter Peak	59135	MW
Summer Peak	44511	MW
Minimum Load	18385	MW
Peak/Off-Peak Ratio	3.2	p.u.
Max Upward Reserve Required	5974	MW
Max Downward Reserve Required	1774	MW
Net installed capacity		
Nuclear	7000	MW
Coal	6338	MW
CCGT	25026	MW
Gas Turbines	2100	MW
Hydro	16500	MW
Pure Pumped Storage Hydro	2432	MW
Combined Pumped Storage Hydro	2985	MW
Wind Generation	29778	MW
CHP	9008	MW
Other RES	10758	MW
Yearly Natural Hydro Inflows	28.5	TWh
Price		
Nuclear	0.002	€/Mcal
Coal	0.014	€/Mcal
Natural Gas	0.025	€/Mcal
CO2	30	€/t CO2

Table 6: Main attributes of the electric system.

We are assuming a mix of EVs with an average specific energy consumption of approximately 0.15 kWh/km, 25 kWh as battery capacity and 90 % as efficiencies, grid-to-battery and battery-to-wheel [15]. With these characteristics, an average vehicle has a range of approximately 75 km using half of the battery capacity.

The change in the energy produced by the different technologies can be seen in the following figure. As it can be observed in the first two bars, CCGT thermal units increase their generation due to EVs use while coal units decrease generation. However, when V2G services are provided by EVs, coal units' output is not affected. Pumped storage hydro plants (either pure or mixed) decrease generation in the four scenarios because EVs now play a similar storage role. The efficiency of pumped storage hydro plants is 70 % while EVs have an energy efficiency around 80 % [15], therefore EV substitutes some use of the pumped storage hydro plants under this smart charging process. Degradation by use of the EV batteries can reduce their efficiency and, therefore, change the use of pumped storage hydro plants.

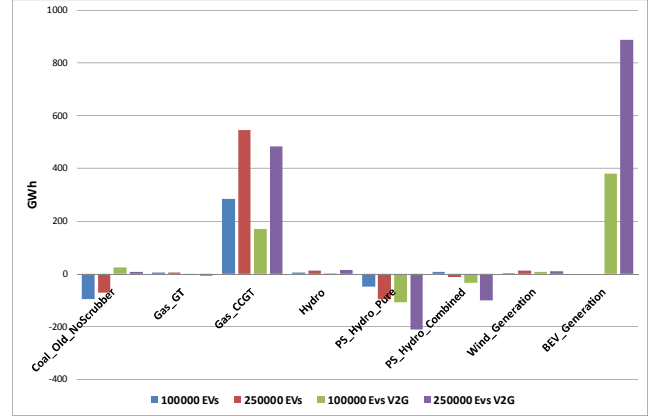


Figure 1: Impact on energy for the different scenarios.

The global impact of EVs in the system can be monitored in the following table.

	0 EVs	100000 EVs	250000 EVs	100000 EVs V2G	250000 EVs V2G
Average cost of total demand [€/MWh]	26.03	26.06	26.10	26.01	26.00
Marginal cost of energy consumed by EV [€/MWh]		71.25	66.08	33.68	38.72
Yearly incremental cost per EV [€]		140	130	66	76
Value of V2G per EV [€]				74	54

Table 7: Impact in costs for the different scenarios.

Average cost of the energy increases somewhat with increasing number of EVs and decreases when V2G is allowed, given that we allow more flexibility to the system. If we consider that the energy used by the EVs is the last energy produced, the marginal price will be around 71.25 or 66.08 €/MWh without V2G, and 33.68 or 38.72 €/MWh with V2G, again due to this V2G possibility. The incremental total system operation cost per year per EV is shown in the third row. That is, less than 0.4 €/day and represents the charging cost for each EV without V2G and half of it when EVs provide V2G services. The last row shows the value of the V2G services per EV.

The amount of WG that can be integrated by increasing the number of EVs is shown in the following table. We can observe that each EV is able to integrate, to the electric system, from 38 up to 69 kWh of WG, depending on the scenario, from a total of 2000 kWh that approximately requires an EV for driving every year.

	0 EVs	100000 EVs	250000 EVs	100000 EVs V2G	250000 EVs V2G
WG curtailment [GWh]	27	23	14	20	15
WG integrated by each EV [kWh]		38	51	69	45

Table 8: Impact on WG integration for the different scenarios.

The charging and discharging daily profiles for the 100000 EVs' scenario are shown in the following figure. Charge is mainly done at off-peak hours and between peak hours in the afternoon. The maximum charging demand is around 230 MW and the maximum

generation, in case of V2G is provided, is around 190 MW.

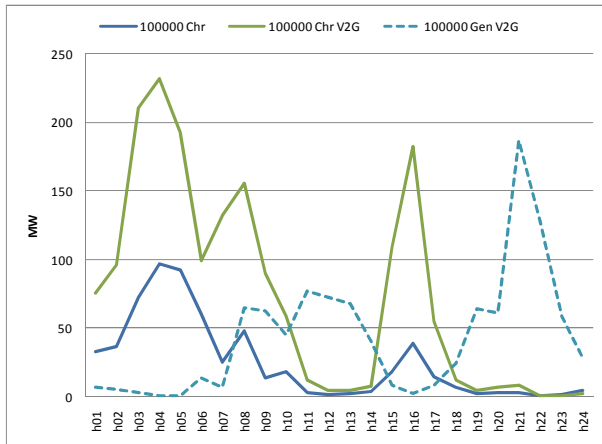


Figure 2: Average charging and discharging profiles.

6 CONCLUSIONS

This paper has presented a day-ahead operation model where EV management is considered. Special attention is paid to the EV representation into the system operation and the contribution of the EV to energy services, vehicle to grid generation and power reserve service provision. Different EV share scenarios and V2G capabilities are evaluated for the mainland Spanish electric system in 2016. The contribution of electric vehicles on the integration of renewable sources has also been determined showing in summary that EV allows higher amounts of WG integration especially when V2G services are provided.

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