A Comprehensive Approach for Maximizing Flexibility Benefits of Electric Vehicles

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***Abstract*—Increasing variability and uncertainty coming from both sides of the power system equilibrium equation, such as wind energy on the generation side and increasing share of new consumers such as electric vehicles on the demand side, entail higher reserve requirements. While traditional approaches of assigning conventional generation units to maintain system stability can increase operational costs, greenhouse gas emissions, or give signals for new investments, utilizing intelligent control of distributed sources might mitigate those negative effects. This can be achieved by controllable charging of domestic electric vehicles. On the other hand, increasing number of public charging stations gives final users the opportunity to fast charge, making their vehicles an additional source of uncertainty rather than a provider of flexibility. This paper brings a full system assessment of combined effect of slow home charging of electric vehicles together with fast charging stations (both with and without integrated energy storage systems), cast as mixed integer linear programming unit commitment model. The contributions of this paper look into optimal periods when fast charging is beneficial for the system operation, as well as assess the benefits of integrating battery storage into fast charging stations to mitigate the negative effects to power system operation.**

***Index Terms*—Ancillary services, battery storage system, electric vehicles (EVs), fast charging stations (FCS), power system flexibility, reserve provision.**

Nomenclature

Abbreviations

CPD Conventional power demand.
EPS Electrical power system.
ESS Energy storage system.
EV Electric vehicles.
FCS Fast charging stations.
G2V Grid to vehicle.
G2S Grid to station.
HPP Hydropower plants.
PRP Primary reserve provision.
RES Renewable energy sources.
S2G Station to grid.
SEV Slow electric vehicle (charging).
SOC State-of-charge.
SRP Secondary reserve provision.
TPP Thermal power plants.
TSC Total system cost.
TSE Total system emissions.
UFC Uncontrolled fast charging.
USC Uncontrolled slow charging.
V2G Vehicle to grid.
V2S Vehicle to station.
WPC Wind power curtailment.
WPP Wind power plants.

I. Introduction

Fossil fuel depletion and increasing environmental awareness are pushing modern societies to change their modus operandi by reducing nonrenewable energy consumption. Currently, more than 80% of total energy supply in the world relays on fossil fuels, where electricity generation and transportation systems are the biggest consumers [1]. Transition to nonfossil fuel driven economy is, therefore, seen through integration of renewable energy sources (RES) and society's willingness to accept lifestyle revisions such as transportation behavior changes. Although variable RES are a key factor in building environmentally efficient electrical power system (EPS), they introduce new challenges to traditional EPS operation. Variability and uncertainty of their primary source (wind speed, solar radiation) force conventional units to operate in nonoptimal operating points with higher number of intraday cycles. Additionally, integration of RES increases reserve requirements, which leads to higher total operational costs and emissions [2]. To fully exploit the benefits of RES, future power systems need to be flexible enough to cope with generation variations. Flexibility of EPS can be defined as the competence of EPS to balance power supply and demand through minimum cost provision of different services on multiple time scales. This capability of EPS is traditionally provided by conventional units and constrained by their technical characteristics. Nowadays, the focus is shifting to new concepts and technologies [3], [4] to provide required flexibility. A number of papers have been published analyzing the flexibility potential of energy storage systems (ESS) [5], [6], demand response [7], microgrids [8], multigeneration [9], EPS interconnection [10], and electric vehicles (EV).

This paper provides a comprehensive analysis of EV integration, focusing on mitigating negative effects of uncontrollable EV charging, in particular that of fast charging stations (FCS). Poorly designed EV charging infrastructure and management can generate new sources of imbalances and magnify system's flexibility requirements. The paper models EV behavior considering multiservice EPS with focus on a longer time scales (week, year) and different conditions/scenarios. The novelty of

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the proposed approach is in modeling simultaneously both effects of slow, controllable charging and uncertain and variable FCS (not shown before). Similar analyses could be done for other demand response technologies, but due to the specific requirements of EV and succinctness of the paper, they are omitted from consideration. Specifically, this paper analyses how FCS impact the system operation and looks into different aspects of (non)coincidence of RES production and FCS operation. With this in mind, integrating ESS into FCS could mitigate larger reserve requirements of uncontrollable FCS but also act as an additional service provider.

It should be mentioned that analyzes in this paper do not attempt to provide a full economic benefits assessment of ESS integration (by incorporating their investment costs) and cost benefit analyses of such implementation, only operational aspects and benefits are the focus.

II. Literature Review and Relevant Contributions

The concept of smart EV integration is, in recently published literature, usually seen through coordinated operation of EV and RES [11], [12], mitigation of variable and stochastic RES impact on the system operation [13], or through EV grid impacts [14], [15]. In the case where unit commitment of the entire system is considered, including the impact of EV on the provision of different services and, in particular, ancillary services as one of critical aspects of low carbon power system, FCS are neglected and their potentially negative impacts are not included in the modeling [16], [17]. To the authors' best knowledge, FCS have been analyzed only focusing on impacts on technical distribution grid constraints [18], [19] or included in models developed for distribution network planning, siting, and sizing [20], [21]. Additionally, FCS have been considered in the aggregators business concepts, maximizing revenues and defining business models for large FCS deployment [22], [23].

Potential of EV participation in ancillary services provision is discussed in [24] where authors conclude that providing negative secondary control is economically most beneficial for EV. In [25] and [26], EV aggregator model is proposed for participation in energy and reserve markets. Coordinated, aggregated participation of EV (slow charging) and battery storage stations along with conventional units in automatic frequency regulation is proposed in [27]. A new model for primary frequency control assessment is proposed in [28]. It was shown that PEVs can effectively improve system's frequency response following a disturbance. Another paper, [29], proposes EV as frequency controllers with goal to utilize more wind power. Papers listed in this paragraph describe the potential of EVs to provide ancillary services, however they do not consider the whole EPS operation nor the impact of both flexible slow or fast charging of EVs.

Stochastic optimization method has been developed in [30] for wind balancing using EV. Stochasticity of EV gri connection (unexpected EV interruptions) is modeled in [31]. Faria *et al.* [32] analyze EV charging impact on daily load diagram as well as detailed impact on local emissions of various particles. Detailed forecast tool for EV demand is provided in [33]; the presented model is very useful for both generation and demand side management of EV. Research in [34] provides stochastic UC MILP model used for study on slow charging EV impact on EPS flexibility under different charging patterns.

Work in [35] proposes day-ahead hourly unit commitment model in a power system composed of large-scale generators and aggregated EV. The model described in this paper is a short-term dispatch model and observes only slow charging of EVs without considering the need for ancillary services. Shortt and O'Malley [36] and Ramirez *et al.* [37] propose interesting long-term planning models where EV impact on system expansion has been observed. Mathematical models are very detail, however EVs are once again modeled only as slow charging without considering EV participation in ancillary services provision.

None of the papers published focuses on the entire power systems modeled with all technical and economic constraints, analyzing both SEV and FSC impacts, and considering both energy and ancillary services. This paper continues authors' prior research in [38] and [39], where detailed analyses of SEV contribution to system flexibility are provided. Mentioned papers handle only SEV charging as a potential flexibility provider, whereas model in this paper adds up FCS both as flexibility sink and source. It is very important to point out that this paper uses the same input parameters and the same energy balance equation for both SEV and FCS (all research so far observed only one of them). Interaction of the two methods can suppress or enhance the total EV impact. Therefore, the main contributions of this paper can be defined as follows.

1) Design of multiservice (energy plus reserve provision) unit commitment model considering technical constraints and forecasts of conventional units, RES and EVs, cast as mixed integer linear program.
2) EVs are, for the first time, mathematically described as both slow charging (at home) and fast charging (at FCS) in the same model using the same driving patterns and the same fleet's SOC equation.
3) Assessment of combined slow and fast EV charging impact on EPS flexibility through different charging modes.
4) Finding the "optimal time window" for FCS charging with regards to SEV charging and other technical constraints.
5) Optimal SEV and FCS charging strategy selection in regards to EPS flexibility.
6) Defining the role of integrated ESS as a technology to mitigate the negative effects of FCS integration and as additional contributor to systems flexibility.

III. Problem Formulation

Described model captures techno-economic aspects of large-scale thermal and hydro generators, wind generators, conventional demand, and EVs. Even though the entire EPS is modeled, contributions of this paper are in EVs modeling. Therefore, only EV's (both SEV and FCS in Sections III-C, III-D, and III-E) formulations are explained. Details of the remaining mathematical formulations (Sections III-A and III-B) are for the most part omitted. Only the most relevant equations are provided. Readers are encouraged to find related papers where additional information can be found.

A. Electric Power System Model

EPS is based on power generation-demand balance (1) and reserve provision-requirements balance (2)–(6). Considered EPS with service provision of different entities is illustrated in Fig. 1. Generation side, left side of (1), consists of the following.

1) Conventional units.
   a) Thermal power plants (TPP)—denoted as $p^{g_{TP}}$:
      i) nuclear power plants;

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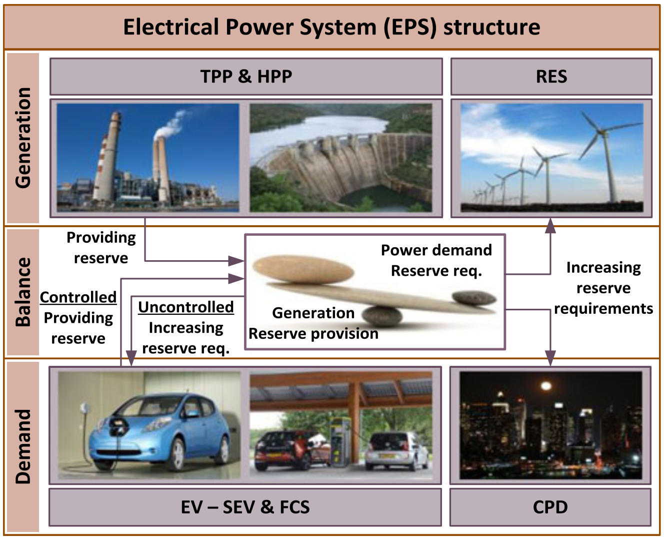

Fig. 1. Structure of observed EPS.

ii) coal fueled power plants;
iii) combined cycle gas turbines;
iv) open cycle gas turbines.

b) Hydropower plants (HPP)—denoted as $p^{\text{g\_HP}}$:
   i) run-of-river;
   ii) conventional HPP;
   iii) pump storage—denoted as $p^{\text{p\_PS}}$.

2) Renewable energy sources.
   a) Variable renewable energy:
      i) wind power plants (WPP)—denoted as $p^{\text{g\_WP}}$.

On the other hand, the right side of (1) consists of the following.

3) Conventional power demand (CPD)—denoted as P^{d}.
4) Electric vehicles:[1]
   a) slow EV (SEV) charging ($p^{\text{c\_EV}}$) and dis. ($p^{\text{d\_EV}}$);
   b) FCS charging ($p^{\text{c\_FCS}}$) and discharging ($p^{\text{d\_FCS}}$).[2]

$$\sum_{i=1}^{\text{Ni\_TP}} \left(p_{t,i}^{\text{g\_TP}}\right) + \sum_{i=1}^{\text{Ni\_HP}} \left(p_{t,i}^{\text{g\_HP}}\right) + \sum_{i=1}^{\text{Ni\_PS}} \left(p_{t,i}^{\text{g\_PS}} - p_{t,i}^{\text{p\_PS}}\right) + p_t^{\text{g\_WP}} = \text{P}_t^{\text{d}} + \sum_{i=1}^{Ni\_EV} \left(p_{t,i}^{\text{c\_EV}} - p_{t,i}^{\text{d\_EV}}\right) + \sum_{i=1}^{\text{Ni\_FCS}} \times \left(p_{t,i}^{\text{c\_FCS}} - p_{t,i}^{\text{d\_FCS}}\right). \tag{1}$$

Ancillary services are the supporting services provided to EPS to enable continuous and stable flow of electricity from producer to consumer. Even though the term is used to refer to variety of operations, in this paper it refers to spinning reserve provision only. Reserve provision-requirements equations are defined for five different services as follows:

1) primary reserve up (2) and down (3);
2) secondary reserve up (4) and down (5); and
3) tertiary reserve up (6).

$$\sum_{i=1}^{\text{Ni\_TP}} f_{t,i}^{\text{up\_TP}} + \sum_{i=1}^{\text{Ni\_HP}} f_{t,i}^{\text{up\_HP}} + \sum_{i=1}^{\text{Ni\_EV}} f_{t,i}^{\text{up\_EV}} + \sum_{i=1}^{\text{Ni\_FCS}} f_{t,i}^{\text{up\_FCS}} \geq \text{F}_t^{\text{up}} \tag{2}$$

$$\sum_{i=1}^{\text{Ni\_TP}} f_{t,i}^{\text{dn\_TP}} + \sum_{i=1}^{\text{Ni\_HP}} f_{t,i}^{\text{dn\_HP}} + \sum_{i=1}^{\text{Ni\_EV}} f_{t,i}^{\text{dn\_EV}} + \sum_{i=1}^{\text{Ni\_FCS}} f_{t,i}^{\text{dn\_FCS}} \geq \text{F}_t^{\text{dn}} \tag{3}$$

$$\sum_{i=1}^{\text{Ni\_TP}} r_{t,i}^{\text{up\_TP}} + \sum_{i=1}^{\text{Ni\_HP}} r_{t,i}^{\text{up\_HP}} + \sum_{i=1}^{\text{Ni\_EV}} r_{t,i}^{\text{up\_EV}} + \sum_{i=1}^{\text{Ni\_FCS}} r_{t,i}^{\text{up\_FCS}} \geq \text{R}_t^{\text{up}} \tag{4}$$

$$\sum_{i=1}^{\text{Ni\_TP}} r_{t,i}^{\text{dn\_TP}} + \sum_{i=1}^{\text{Ni\_HP}} r_{t,i}^{\text{dn\_HP}} + \sum_{i=1}^{\text{Ni\_EV}} r_{t,i}^{\text{dn\_EV}} + \sum_{i=1}^{\text{Ni\_FCS}} r_{t,i}^{\text{dn\_FCS}} \geq \text{R}_t^{\text{dn}} \tag{5}$$

$$\sum_{i=1}^{\text{Ni\_TP}} q_{t,i}^{\text{up\_TP}} \geq \text{Q}_t^{\text{up}}. \tag{6}$$

The left side of equations (2)–(6)[3] models all technologies capable of providing specific reserve (variables), while right side is calculated in advance and refers to deterministic reserve requirements (input time vectors).

Primary reserve requirements are usually fixed values defined by the loss of the largest generator in the system (or the largest loss of load), while secondary and tertiary reserve requirements depend on demand, wind, and EV forecasts (both SEV and FCS charging), shown in (7)–(11). $\text{R}_t^{\text{0,5h\_EV}}/\text{R}_t^{\text{0,5h\_FCS}}$ represent SEV/FCS share in secondary reserve requirements, while $\text{R}_t^{\text{4h\_EV}}/\text{R}_t^{\text{4h\_FCS}}$ represent their share in tertiary reserve. Please note that deterministic forecasts are used for future SEV and FCS power requirements (as well as for CPD and WPP); therefore, σ represents prediction error or deviation from the expected forecasted values, thus capturing the uncertainty of forecasts. Further explanations are provided in sections below.

$$\text{R}_t^{\text{0,5h\_EV}} = \sum_{i=1}^{\text{Ni\_EV}} \left(3,5 \cdot \sigma_t^{\text{0,5h\_EV}} \cdot \text{P}_i^{\max\_EV} \cdot \sum_{\tau=t}^{(t-C_i^{\text{UCH\_EV}}+1)} \text{N}_{\tau,i}^{\text{arr\_EV}}\right) \tag{7}$$

[1] In mathematical expressions, SEVs charging and discharging is denoted as EV in the superscript not SEV.

[2] It should be noted that, with no additional storage, FCS do not actually provide V2G service and $p^{\text{d\_FCS}}$ variable takes the value of zero.

[3] In the paper, tertiary reserve requirements are assumed to be provided only by offline TPPs.

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$$\mathrm{R}_t^{0,5\mathrm{h\_FCS}} = \sum_{i=1}^{\mathrm{Ni\_FCS}} \left(\begin{array}{l} 3,5 \cdot \sigma_t^{0,5\mathrm{h\_FCS}} \cdot \dfrac{\mathrm{P}_i^{\max\mathrm{\_FCS}}}{3} \cdot \\ \left(\mathrm{G}_i^{\mathrm{\_EV}} - \mathrm{N}_{\tau,i}^{\mathrm{arr\_EV}}\right) \cdot \dfrac{p^{\mathrm{perf\_EV}}}{100} \end{array} \right) \tag{8}$$

$$\mathrm{R}_t^{\mathrm{up}} = \mathrm{P}^{\mathrm{gmax}} + \sqrt{\begin{array}{l} (3 \cdot \sigma^{\mathrm{d}} \cdot \mathrm{P}_t^{\mathrm{d}})^2 + (3,5 \cdot \sigma_t^{(0,5\mathrm{h})\mathrm{\_WP}} \cdot \mathrm{P}_t^{\mathrm{\_WP}})^2 \\ + \left(\mathrm{R}_t^{0,5\mathrm{h\_EV}}\right)^2 + \left(\mathrm{R}_t^{0,5\mathrm{h\_FCS}}\right)^2 \end{array}} \tag{9}$$

$$\mathrm{R}_t^{dn} = \sqrt{\begin{array}{l} \left(3 \cdot \sigma^{\mathrm{d}} \cdot \mathrm{P}_t^{\mathrm{d}}\right)^2 + \left(3,5 \cdot \sigma_t^{(0,5\mathrm{h})\mathrm{\_WP}} \cdot \mathrm{P}_t^{\mathrm{\_WP}}\right)^2 \\ + \left(\mathrm{R}_t^{0,5\mathrm{h\_EV}}\right)^2 + \left(\mathrm{R}_t^{0,5\mathrm{h\_FCS}}\right)^2 \end{array}} \tag{10}$$

$$\mathrm{Q}_t^{\mathrm{up}} = \mathrm{P}^{\mathrm{gmax}} + \sqrt{\begin{array}{l} \left(3 \cdot \sigma^{\mathrm{d}} \cdot \mathrm{P}_t^{\mathrm{d}}\right)^2 + \left(3,5 \cdot \sigma_t^{(4\mathrm{h})\mathrm{\_WP}} \cdot \mathrm{P}_t^{\mathrm{\_WP}}\right)^2 \\ + \left(\mathrm{R}_t^{4\mathrm{h\_EV}}\right)^2 + \left(\mathrm{R}_t^{4\mathrm{h\_FCS}}\right)^2 \end{array}}. \tag{11}$$

Uncontrollable EV charging increases the reserve requirements due to uncertainty and variability of their arrival time at charging points and energy/power requirements; on the other hand, if EV charging is controlled/dispatchable, they are capable to provide reserve services. While TPP and HPP are conventional reserve providers, uncertain and variable CPD and WPP enhance the reserve requirements. Some papers have even considered WPP as reserve providers [40]. However, in the presence of flexible demand, such as controllable SEV, it has been shown that WPP are not preferred reserve providers since such concept does not fully utilize the renewable energy generation potential [39]. Additional information about reserve requirements and modeling can be found in [41].

The objective function of the UC model is the minimization of the operational costs, as shown in (12). Thermal unit's operational costs (startup, shutdown, fuel, greenhouse gas emissions), as well as those of hydro unit costs (O&M), are included. Thermal fuel consumption curve is modeled as three segments piecewise linear function as it is used in the U.S. electricity markets. For better understanding of the objective function, the reader is directed to [42]

$$\min \mathrm{COST} = \sum_{t=1}^{\mathrm{Nt}} \left[\sum_{i=1}^{\mathrm{Ni\_TP}} \left(c_{t,i}^{\mathrm{TP}}\right) + \sum_{i=1}^{\mathrm{Ni\_HP}} \left(c_{t,i}^{\mathrm{HP}}\right) \right]. \tag{12}$$

B. Generation Side Model

TPP and HPP models within unit commitment optimization are most commonly cast as binary problems. In order to improve computational efficiency of the UC model, TPP and HPP in this paper are clustered by technology type as in [43].

TPP generation is bounded by the following:

1) power generation constraints (three segment piecewise linear cost curve);
2) minimum up and down times;
3) ramping constraints;
4) reserve provision constraints;
5) greenhouse gas emission cost function.

HPP generation is subjected to:

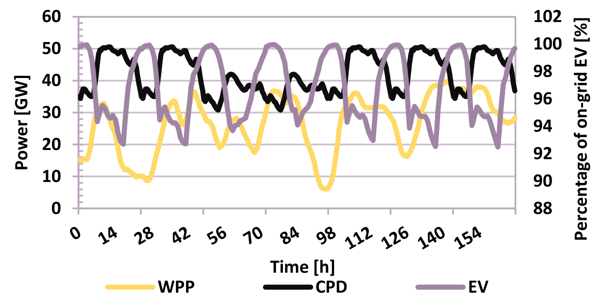

Fig. 2. WPP and CPD forecasts and EV's driving behavior.

1) water balance equation;
2) generation power constraints;
3) reservoir constraints;
4) hydro turbine constraints;
5) spillage constraint;
6) reserve provision constraints.

WPP generation is defined by real historical wind generation data (it can be seen as maximum wind power generation). Curtailment of WPP generation is allowed (production can be lower than historical/deterministic data). CPD has also been modeled as historic data, but it cannot be curtailed (strict constraint). Both WPP and CPD curves used in this paper are depicted in Fig. 2.

Due to the succinctness of this paper, mathematical formulations of UC operation are omitted from the paper but can be found in large number of recent publications [44]. Additional information (such as conventional units' technical data) can also be found in previous publications [38], [39]; the UC model presented in those papers is further expanded in the proposed contribution as shown in the following sections.

C. EVs Model

Integration of EVs might result in increase of peak power demand or reserve requirements. On the other hand, availability to provide services to the system mostly depends on their driving/parking/charging curves. This main constraint for EV charging/discharging is based on real historical driving behavior curves. The main input parameters, such as the number of EV arriving to the charging spots ($N_{t,i}{}^{\mathrm{arr\_EV}}$), number of EV leaving them ($N_{t,i}^{\mathrm{leav\_EV}}$), and number of EV currently connected to the charging spots ($N_{t,i}^{\mathrm{g\_EV}}$) are derived from the curves in report [45]. (13) presents energy balance equation where energy of the entire EV fleet ($s_{t,i}^{\mathrm{\_EV}}$) depends on fleet's energy in previous time step (*t–1*), energy of vehicles arriving ($s_{t,i}^{\mathrm{arr\_EV}}$)/leaving ($s_{t,i}^{\mathrm{leav\_EV}}$) charging spots, energy used for slow charging ($p_{t,i}^{\mathrm{c\_EV}}$), energy injected back into the grid in the V2G mode ($p_{t,i}^{\mathrm{d\_EV}}$), and energy used for fast charging/discharging ($s_{t,i}^{\mathrm{add\_FCS}}$). (14) and (15) present initial and final charging conditions. Minimum and maximum capacity of EV fleet is constrained with (16). (17) and (18) present boundaries for EV energy upon arrival and departure from the charging spot (state of charge of the fleet); $\mathrm{S}^{\mathrm{cons\_EV}}$ is energy of one EV when arriving to the charging spot, $\mathrm{S}^{\mathrm{minc\_EV}}$ is minimum energy of EV when leaving it, while $\mathrm{S}^{rm\max\_EV}$ is the maximum battery capacity of one EV

$$\begin{aligned} s_{t,i}^{\mathrm{\_EV}} &= s_{t-1,i}^{\mathrm{\_EV}} + s_{t,i}^{\mathrm{arr\_EV}} - s_{t,i}^{\mathrm{leav\_EV}} + p_{t,i}^{\mathrm{c\_EV}} \cdot \eta_i^{\mathrm{c\_EV}} \cdot \Delta \mathrm{t} \\ &\quad - p_{t,i}^{\mathrm{d\_EV}} / \eta_i^{\mathrm{d\_EV}} \cdot \Delta t + s_{t,i}^{\mathrm{add\_FCS}} \end{aligned} \tag{13}$$

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TABLE I
SEV OPERATION MODES

SEV – SLOW EV CHARGING			
CHARGING\ RESERVE		**NR** – No Reserve	**YR** – Yes Reserve
Uncontrolled A	**USC** – Uncon. Slow Charging	- EV slow charge at rated power from the moment they plug in until fully charged - EV do not impact reserve requirements	- EV slow charge at rated power from the moment they plug in until fully charged - EV causing increase in reserve requirements
Controlled – **Unidirectional B**	**G2V** – Grid to Vehicle	- EV optimal slow charging (in regards to EPS) - no EV discharging - no EV reserve provision	- EV optimal slow charging (in regards to EPS) - no EV discharging - EV provide reserve
Controlled – **Bidirectional C**	**V2G** – Vehicle to Grid	- EV optimal slow charging & discharging (in regards to EPS) - no EV reserve provision	- EV optimal slow charging & discharging (in regards to EPS) - EV provide reserve

$$s_{1,i}^{\mathrm{EV}} = \mathrm{S}_i^{0\_\mathrm{EV}} + s_{1,i}^{\mathrm{arr\_EV}} - s_{1,i}^{\mathrm{leav\_EV}} + p_{1,i}^{\mathrm{c\_EV}} \cdot \eta_i^{\mathrm{c\_EV}} \cdot \Delta \mathrm{t} - p_{1,i}^{\mathrm{d\_EV}}/\eta_i^{\mathrm{d\_EV}} \Delta t + s_{1,i}^{\mathrm{add\_FCS}} \tag{14}$$

$$s_{Nt,i}^{\mathrm{EV}} \geq \mathrm{S}_i^{0\_\mathrm{EV}} \tag{15}$$

$$\mathrm{N}_{t,i}^{\mathrm{g\_EV}} \cdot \mathrm{S}_i^{\min\_\mathrm{EV}} + s_{t,i}^{\mathrm{arr\_EV}} - s_{t,i}^{\mathrm{leav\_EV}} + s_{t,i}^{\mathrm{add\_FCS}} \leq s_{t,i}^{\mathrm{EV}} \leq \mathrm{N}_{t,i}^{\mathrm{g\_EV}} \cdot \mathrm{S}_i^{\max\_\mathrm{EV}} + s_{t,i}^{\mathrm{arr\_EV}} - s_{t,i}^{\mathrm{leav\_EV}} + s_{t,i}^{\mathrm{add\_FCS}} \tag{16}$$

$$\mathrm{N}_{t,i}^{\mathrm{leav\_EV}} \cdot \mathrm{S}_i^{\mathrm{minc\_EV}} \leq s_{t,i}^{\mathrm{leav\_EV}} \leq \mathrm{N}_{t,i}^{\mathrm{leav\_EV}} \cdot \mathrm{S}_i^{\max\_\mathrm{EV}} \tag{17}$$

$$0 \leq s_{t,i}^{\mathrm{arr\_EV}} \leq \mathrm{N}_{t,i}^{\mathrm{arr\_EV}} \cdot \mathrm{S}_i^{\mathrm{cons\_EV}}. \tag{18}$$

As elaborated in previous sections, charging of EVs can be done in two different ways: 1) SEV charging, denoted with EV superscript and 2) fast EVs charging denoted with superscript FCS in all equations. Unified modeling approach shown in the above equations enables different analyses of these charging regimes.

D. SEV Charging Model

Slow charging of EVs corresponds to charging at home, in garage, at workplace, at road curbs, parking lots, etc. These locations offer charging at lower power rates but require longer charging times (up to 10 h). However, the impact of SEV charging on EV battery is less degrading and service should be cheaper than in the case of FCS. To investigate all possible impacts on EPS, SEV charging is modeled through six operating modes as follows (see Table I).

1) *Operating mode A*: Uncontrolled slow charging (USC; also in the literature known as dumb, plug-in, passive). This mode is analyzed in two scenarios: 1) where such mode has no impact on the reserve requirements (marked USC-NR), this is the most frequent approach in the available literature; 2) with impact/increase of the reserve requirements (marked USC-YR), thus capturing unknown times of EV arrival/departure and energy/power requirements.
2) *Operating mode B*: Controlled unidirectional EV operation (G2V, only charging) where EV can provide only energy and no reserve services (denoted as G2V-NR) and multiple services, energy, and reserve (denoted as G2V-YR);
3) *Operating mode C*: Controlled bidirectional operation of EV (called V2G) where EV can be both charged and discharged. Again, the operating mode not only considers energy arbitrage participation (V2G-NR) but also energy and reserve provision by EV (V2G-YR).

In USC mode, power demand of EV passively and directly follows parking behavior of EV. EVs begin their charging immediately after they plug-in and charge until specific level of their battery's SOC has been reached. Discharging is not possible during USC as modeled by (19). $C_i^{\mathrm{UCH\_EV}}$ in (20) corresponds to time required to fully charge EV at rated power.

$$p_{t,i}^{\mathrm{d\_EV}} = 0 \tag{19}$$

$$C_i^{UCH\_\mathrm{EV}} = \mathrm{round}\left\{\frac{\mathrm{S}_i^{\max\_\mathrm{EV}} - \mathrm{S}_i^{\mathrm{cons\_EV}}}{\mathrm{P}_i^{\max\_\mathrm{EV}} \cdot \Delta \mathrm{t} \cdot \eta^{\mathrm{c\_EV}}}\right\}. \tag{20}$$

EVs in USC modes charge within the range of 90–100% of their rated power, as shown in (21) and (22). (21) presents initial conditions for time steps $1,\ldots,\mathrm{C}_\mathrm{i}^{\mathrm{UCH\_EV}}$.

$$\sum_{(\tau=Nt+t-C^{\mathrm{UCH\_EV}}+1)}^{Nt} \left(\mathrm{N}_{\tau,i}^{\mathrm{arr\_EV}} \cdot \mathrm{P}_i^{\max\_\mathrm{EV}} \cdot 0,9\right) + \sum_{\tau=1}^{t} \left(\mathrm{N}_{\tau,i}^{\mathrm{arr\_EV}} \cdot \mathrm{P}_i^{\max\_\mathrm{EV}} \cdot 0,9\right) \leq p_{t,i}^{\mathrm{c\_EV}} \leq \sum_{(\tau=Nt+t-C^{\mathrm{UCH\_EV}}+1)}^{Nt} \left(\mathrm{N}_{\tau,i}^{\mathrm{arr\_EV}} \cdot \mathrm{P}_i^{\max\_\mathrm{EV}}\right) + \sum_{\tau=1}^{t} \left(\mathrm{N}_{\tau,i}^{\mathrm{arr\_EV}} \cdot \mathrm{P}_i^{\max\_\mathrm{EV}}\right). \tag{21}$$

Equation (22) presents EV charging for a period of $C_i^{\mathrm{UCH\_EV}},\ldots,Nt$

$$\sum_{(\tau=t-C^{\mathrm{UCH\_EV}}+1)}^{\mathrm{t}} \left(\mathrm{N}_{\tau,i}^{\mathrm{arr\_EV}} \cdot \mathrm{P}_i^{\max\_\mathrm{EV}} \cdot 0,9\right) \leq p_{t,i}^{\mathrm{c\_EV}} \leq \sum_{(\tau=t-C^{\mathrm{UCH\_EV}}+1)}^{\mathrm{t}} \left(\mathrm{N}_{\tau,i}^{\mathrm{arr\_EV}} \cdot \mathrm{P}_i^{\max\_\mathrm{EV}}\right). \tag{22}$$

Controlled unidirectional charging (G2V) of operational mode B is a flexible way of charging, EVs charge according to signals from the system/market operator, as shown in (24). EV discharging is not permitted in this mode (23). G2V mode, due to its controllability, allows primary reserve provision (PRP), $f^{\mathrm{up\_EV}}$ and $f^{\mathrm{dn\_EV}}$ in (27) and (28), and secondary reserve provision (SRP), $r^{\mathrm{up\_EV}}$ and $r^{\mathrm{dn\_EV}}$ in (25) and (26). EV can provide secondary upward/downward reserve with decease/increase in their scheduled charging power. PRP is defined in the same manner, but it considers already allocated SRP

$$p_{t,i}^{\mathrm{d\_EV}} = 0 \tag{23}$$

$$\mathrm{P}_i^{\min\_\mathrm{EV}} \cdot \mathrm{N}_{t,i}^{\mathrm{g\_EV}} \leq p_{t,i}^{\mathrm{c\_EV}} \leq \mathrm{P}_i^{\max\_\mathrm{EV}} \cdot \mathrm{N}_{t,i}^{\mathrm{g\_EV}} \tag{24}$$

$$r_{t,i}^{\mathrm{up\_EV}} \leq p_{t,i}^{\mathrm{c\_EV}} \tag{25}$$

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$$r_{t,i}^{\mathrm{dn\_EV}} \leq \mathrm{P}_i^{\max\mathrm{\_EV}} \cdot \mathrm{N}_{t,i}^{\mathrm{g\_EV}} - p_{t,i}^{\mathrm{c\_EV}} \tag{26}$$

$$f_{t,i}^{\mathrm{up\_EV}} \leq p_{t,i}^{\mathrm{c\_EV}} - r_{t,i}^{\mathrm{up\_EV}} \tag{27}$$

$$f_{t,i}^{\mathrm{dn\_EV}} \leq \mathrm{P}_i^{\max\mathrm{\_EV}} \cdot \mathrm{N}_{t,i}^{\mathrm{g\_EV}} - p_{t,i}^{\mathrm{c\_EV}} - r_{t,i}^{\mathrm{dn\_EV}}. \tag{28}$$

In operational mode C, controlled bidirectional mode (V2G), EVs are charged (30) and discharged (31) when they bring benefits to power system operation. Integer variable $x_{t,i}^{\mathrm{c\_EV}}$ in (29) corresponds to the number of EV currently charging, while $(\mathrm{N}_{t,i}^{\mathrm{g\_EV}} - x_{t,i}^{\mathrm{c\_EV}})$ corresponds to the number of EV discharging

$$0 \leq x_{t,i}^{\mathrm{c\_EV}} \leq \mathrm{N}_{t,i}^{\mathrm{g\_EV}} \tag{29}$$

$$\mathrm{P}_i^{\min\mathrm{\_EV}} \cdot x_{t,i}^{\mathrm{c\_EV}} \leq p_{t,i}^{\mathrm{c\_EV}} \leq \mathrm{P}_i^{\max\mathrm{\_EV}} \cdot x_{t,i}^{\mathrm{c\_EV}} \tag{30}$$

$$\mathrm{P}_i^{\min\mathrm{\_EV}} \cdot \left(\mathrm{N}_{t,i}^{\mathrm{g\_EV}} - x_{t,i}^{\mathrm{c\_EV}}\right) \leq p_{t,i}^{\mathrm{d\_EV}} \leq \mathrm{P}_i^{\max\mathrm{\_EV}} \cdot \left(\mathrm{N}_{t,i}^{\mathrm{g\_EV}} - x_{t,i}^{\mathrm{c\_EV}}\right). \tag{31}$$

Similar to G2V, bidirectional V2G operational model can contribute to PRP, modeled as $f^{\mathrm{up\_EV}}$ and $f^{\mathrm{dn\_EV}}$ in (34) and (35), and SRP, modeled as $r^{\mathrm{up\_EV}}$ and $r^{\mathrm{dn\_EV}}$ in (32) and (33), respectively. SRP up can be provided by decrease in EV charging power or by increase in EV discharging power. On the other side, downward reserve can be provided by EV charging power increase or discharging power decrease. PRP is defined in the same manner, but it also takes already allocated SRP into account

$$r_{t,i}^{\mathrm{up\_EV}} \leq \mathrm{P}_i^{\max\mathrm{\_EV}} \cdot \left(\mathrm{N}_{t,i}^{\mathrm{g\_EV}} - x_{t,i}^{\mathrm{c\_EV}}\right) - p_{t,i}^{\mathrm{d\_EV}} + p_{t,i}^{\mathrm{c\_EV}} - \mathrm{P}_i^{\min\mathrm{\_EV}} \cdot x_{t,i}^{\mathrm{c\_EV}} \tag{32}$$

$$r_{t,i}^{\mathrm{dn\_EV}} \leq p_{t,i}^{\mathrm{d\_EV}} - \mathrm{P}_i^{\min\mathrm{\_EV}} \cdot \left(\mathrm{N}_{t,i}^{\mathrm{g\_EV}} - x_{t,i}^{\mathrm{c\_EV}}\right) + \mathrm{P}_i^{\max\mathrm{\_EV}} \cdot x_{t,i}^{\mathrm{c\_EV}} - p_{t,i}^{\mathrm{c\_EV}} \tag{33}$$

$$f_{t,i}^{\mathrm{up\_EV}} \leq \mathrm{P}_i^{\max\mathrm{\_EV}} \cdot \left(\mathrm{N}_{t,i}^{\mathrm{g\_EV}} - x_{t,i}^{\mathrm{c\_EV}}\right) - \mathrm{P}_{t,i}^{\mathrm{d\_EV}} + p_{t,i}^{\mathrm{c\_EV}} - \mathrm{P}_i^{\min\mathrm{\_EV}} \cdot x_{t,i}^{\mathrm{c\_EV}} - r_{t,i}^{\mathrm{up\_EV}} \tag{34}$$

$$f_{t,i}^{\mathrm{dn\_EV}} \leq p_{t,i}^{\mathrm{d\_EV}} - \mathrm{P}_i^{\min\mathrm{\_EV}} \cdot \left(\mathrm{N}_{t,i}^{\mathrm{g\_EV}} - x_{t,i}^{\mathrm{c\_EV}}\right) + \mathrm{P}_i^{\max\mathrm{\_EV}} \cdot x_{t,i}^{\mathrm{c\_EV}} - p_{t,i}^{\mathrm{c\_EV}} - r_{t,i}^{\mathrm{dn\_EV}}. \tag{35}$$

E. FCS Model

Integration of FCS is gaining momentum in recent years. Many distribution system operators, or private investors, are installing public FCS with high rated power. The main issue concerning FCS is not their consumed energy throughout day but their high peak demand. Fast charging service should be more expensive than SEV regime due to higher impact on grid's technical constraints (such as voltage congestions) and peak generation scheduling. Some recent research suggests that there are benefits of integrating ESS with FCS; in these conditions, the service for the final consumer remains fast, while the impact on the gird and the system is reduced. As mentioned before, this paper does not attempt to find economic justification for investments in ESS, it provides an insight in its positive impact on the system operation. Following on this, this paper considers ESS as integrated part of FCS, but it can be used or omitted depending on the services and scenarios analyzed. FCS is modeled by six potential operating modes (see Table II)

TABLE II
FCS OPERATION MODES

FCS – FAST CHARGING STATIONS				
CHARGING\ RESERVE			**NR** – No Reserve	**YR** – Yes Reserve
Uncontrolled D		**UFC** – Uncon. Fast Charging	- EV fast charge directly from the grid - FCS providing charging spot only - no FCS impact on reserve requirements	- EV fast charge directly from the grid - FCS providing charging spot only - FCS causing increase in reserve requirements
Controlled	**Unidirectional E**	**G2S** – Grid to Station	- EV fast charge through ESS integrated in FCS - FCS/ESS optimal charging (from the grid) - no FCS/ESS discharging to the grid - no FCS reserve provision	- EV fast charge through ESS integrated in FCS - FCS/ESS optimal charging (from the grid) - no FCS/ESS discharging to the grid - FCS provide reserve
	Bidirectional F	**S2G** – Station to Grid	- EV fast charge through ESS integrated in FCS - FCS/ESS optimal charging & discharging - no FCS reserve provision	- EV fast charge through ESS integrated in FCS - FCS/ESS optimal charging & discharging - FCS provide reserve

1) *Operating mode D*: Uncontrolled fast charging (UFC) without reserve requirements impact (UFC-NR) and increasing the reserve requirements (UFC-YR). The explanations are similar to the mode A of SEV, however the potential impact on requirements is much higher.
2) *Operating mode E*: Controlled unidirectional grid-to-station mode (called G2S, where fast charging is conducted by using ESS as a buffer to mitigate large power requirements). Again, two cases are analyzed: 1) FCS with reserve provision capability in G2S-YR scenario (capability of ESS to provide reserve services); and 2) without reserve provision capability in G2S-NR;
3) *Operating mode F*: Controlled bidirectional station-to-grid operation (called S2G, where FCS use ESS as interface with the grid, reducing the charging/discharging impact). Similar to the first two, this operating mode is analyzed for concepts when ESS can provide only energy arbitrage (S2G-NR) and energy arbitrage and reserve services (S2G-YR).

Modeling of FCS needs to be observed through three stages: 1) availability and the number of EV to be charged by FCS; 2) modeling ESS as a potential buffer of FCS and grid/system (if used); and 3) operating mode (both uncontrollable and controllable through integrated ESS).

EV fast charging requirements are modeled with (36) and (37). In (36), the minimum expected fast charging power is defined, as expected percentage of on-road fast charging EV. It is modeled using $p_{\mathrm{t}}^{\mathrm{perf\_EV}}$, which can either be a constant value or a decision variable (when used in the scenarios for determining the optimal fast charging time window) as modeled in (37). Opposite to SEV charging, where upper boundary for EV charging power is defined by the number of EVs parked, the requirements for EV to be fast charged are defined by the number of on-road EV $(\mathrm{G}_i^{\mathrm{EV}} - \mathrm{N}_{\mathrm{t},i}^{\mathrm{g\_EV}})$

$$p_{t,i}^{\mathrm{f\_EV}} \geq p_t^{\mathrm{perf\_EV}} \cdot \mathrm{P}_i^{\mathrm{fmax\_EV}} \cdot \left(\mathrm{G}_i^{\mathrm{EV}} - \mathrm{N}_{t,i}^{\mathrm{g\_EV}}\right) \tag{36}$$

$$\mathrm{P}_i^{\mathrm{perfmin\_EV}} \leq p_t^{\mathrm{perf\_EV}} \leq \mathrm{P}_i^{\mathrm{perfmax\_EV}}. \tag{37}$$

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Additionally, optional constraint for optimal fast charging is modeled by (38) where fast charging during a particular period (of length N_p) is defined by a minimum percentage of total EV energy demand ($\mathrm{P}^{\mathrm{enf\_EV}}$), meaning that a certain percentage of EV must be fast charged. This needs to be satisfied during periods *k*, ensuring minimum customer satisfaction if fast charging is allowed only during "optimal" periods in the day

$$\sum_{T=1+\mathrm{Np}*k}^{\mathrm{Np}*(k+1)} \begin{pmatrix} \mathrm{p}_{t,i}^{\mathrm{c\_EV}} \cdot \eta_i^{\mathrm{c\_EV}} \cdot \Delta t \\ -\mathrm{p}_{t,i}^{\mathrm{d\_EV}} \cdot \eta_i^{\mathrm{d\_EV}} \cdot \Delta t + s_{t,i}{}^{\mathrm{add\_FCS}} \end{pmatrix} \cdot \mathrm{P}^{\mathrm{enf\_EV}} \leq \sum_{T=1+\mathrm{Np}*k}^{Np*(k+1)} \left(s_{t,i}{}^{\mathrm{add\_FCS}}\right). \tag{38}$$

If EV can be charged by fast chargers, the decision variable $s_{t,i}^{\mathrm{add\_FCS}}$, in (13) and (14), contributes to total EV energy demand. The energy and the time of use of fast charging is defined with the duration of EV travel time $T_i^{\mathrm{dur\_EV}}$, modeling the connection between FCS requirements and energy of EV battery. (39) presents initial conditions and is valid for time steps $1, \ldots, \mathrm{arr}_i^{\mathrm{EV}}$. (40) defines additional energy for FCS in the remaining time steps

$$s_{t,i}{}^{\mathrm{add\_FCS}} \leq \eta_i{}^{\mathrm{f\_EV}} \cdot p^{\mathrm{f\_EV}}_{(Nt+t-T^{\mathrm{dur\_EV}}{}_i),i} \cdot \Delta t \tag{39}$$

$$s_{t,i}{}^{\mathrm{add\_FCS}} \leq \eta_i{}^{\mathrm{f\_EV}} \cdot p^{\mathrm{f\_EV}}_{(t-T^{\mathrm{dur\_EV}}{}_i),i} \cdot \Delta t. \tag{40}$$

(41)–(44) model storage (ESS) integrated in FCS. Integrated ESS prevents large power spikes in peak demand periods. From the system/grid point of view storage provides energy arbitrage and acts as a flexibility provider, while on the EV side it provides fast charging and thus satisfies customers' requirements for fast service. Equation (41) presents energy balance equation for FCS with ESS. $c_{t,i}^{\mathrm{FCS}}$ is the current state of charge of ESS. It is equal to energy in previous *(t–1)* state $c_{t-1,i}^{\mathrm{FCS}}$ plus energy "fast charged" to EV, $p_{t,i}^{\mathrm{f\_EV}}$, and energy exchanged by ESS and the system/grid expressed through ESS charging ($p_{t,i}^{\mathrm{c\_FCS}}$) and discharging ($p_{t,i}^{\mathrm{d\_FCS}}$)

$$\begin{aligned} \sum_{i=1}^{\mathrm{Ni\_FCS}} c_{t,\mathrm{i}}{}^{\mathrm{FCS}} \leq & \sum_{i=1}^{\mathrm{Ni\_FCS}} c_{t-1,i}{}^{\mathrm{FCS}} \cdot k_i{}^{\mathrm{loss\_FCS}} \\ & - \sum_{i=1}^{\mathrm{Ni\_FCS}} p_{t,i}{}^{\mathrm{f\_FCS}} / \eta_i{}^{\mathrm{fc\_EV}} \cdot \Delta t \\ & + \sum_{i=1}^{\mathrm{Ni\_FCS}} p_{t,i}{}^{\mathrm{c\_FCS}} \cdot \eta_i{}^{\mathrm{c\_FCS}} \cdot \Delta t \\ & - \sum_{i=1}^{\mathrm{Ni\_FCS}} p_{t,i}{}^{\mathrm{d\_FCS}} / \eta_i{}^{\mathrm{d\_FCS}} \cdot \Delta t. \end{aligned} \tag{41}$$

Equations (42) and (43) present initial and final conditions of ESS FSC

$$\begin{aligned} \sum_{i=1}^{\mathrm{Ni\_FCS}} c_{1,i}{}^{\mathrm{FCS}} \leq & \sum_{i=1}^{\mathrm{Ni\_FCS}} C_i{}^{\mathrm{0\_FCS}} \cdot k_i{}^{\mathrm{loss\_FCS}} \\ & - \sum_{i=1}^{\mathrm{Ni\_FCS}} p_{1,i}{}^{\mathrm{f\_FCS}} / \eta_i{}^{\mathrm{fc\_EV}} \cdot \Delta t \\ & + \sum_{i=1}^{\mathrm{Ni\_FCS}} p_{1,i}{}^{\mathrm{c\_FCS}} \cdot \eta_i{}^{\mathrm{c\_FCS}} * \Delta t \\ & - \sum_{i=1}^{\mathrm{Ni\_FCS}} p_{1,i}{}^{\mathrm{d\_FCS}} / \eta_i{}^{\mathrm{d\_FCS}} \cdot \Delta t \end{aligned} \tag{42}$$

$$c_{Nt,i}{}^{\mathrm{FCS}} \geq C_i{}^{\mathrm{0\_FCS}} \cdot \mathrm{G}_i^{\mathrm{FCS}} \tag{43}$$

FCS energy storage boundaries are defined as

$$C_i{}^{\mathrm{min\_FCS}} \cdot \mathrm{G}_i^{\mathrm{FCS}} \leq c_{t,i}{}^{\mathrm{FCS}} \leq C_i{}^{\mathrm{max\_FCS}} \cdot \mathrm{G}_i^{\mathrm{FCS}}. \tag{44}$$

In UFC mode, EVs are directly connected to grid (there is no ESS). Power for EV fast charging ($p^{\mathrm{f\_FCS}}$) is equal to the power withdrawn from the grid/system ($p^{\mathrm{c\_FCS}}$), shown in (45). If there is no ESS, the EV have no capability of discharging, as shown by (46). This operating mode depends only on EV driving/charging behavior; thus, it becomes an uncontrollable stochastic value. The impact of such charging regime on reserve requirements can only be negative, i.e., it increases reserve requirements as modeled in (8)–(11)

$$p_{t,i}{}^{\mathrm{c\_FCS}} = p_{t,i}{}^{\mathrm{f\_FCS}} \tag{45}$$

$$p_{t,i}{}^{\mathrm{d\_FCS}} = 0. \tag{46}$$

On the other hand, controlled unidirectional fast charging mode (G2S) requires ESS integration into FCS to alleviate unpredictable and variable behavior of EV fast charging demand. FCS are again used as platform for EV fast charging but EVs are not directly connected to the grid. The ESS acts as a mediator and charges during periods when it brings benefits to the EPS (47). By doing so, it allows EV to fast charge whenever they prefer, maintaining EV owners' comfort. Reserve modeling is similar as in SEV reserve provision and shown by (48)–(51)

$$\mathrm{P}_i{}^{\mathrm{min\_FCS}} \cdot \mathrm{G}_i^{\mathrm{FCS}} \leq p_{t,i}{}^{\mathrm{c\_FCS}} \leq \mathrm{P}_i{}^{\mathrm{max\_FCS}} \cdot \mathrm{G}_i^{\mathrm{FCS}} \tag{47}$$

$$r_{t,i}^{\mathrm{up\_FCS}} \leq p_{t,i}^{\mathrm{c\_FCS}} \tag{48}$$

$$r_{t,i}^{\mathrm{dn\_FCS}} \leq \mathrm{P}_i^{\mathrm{max\_FCS}} \cdot \mathrm{G}_i^{\mathrm{FCS}} - p_{t,i}^{\mathrm{c\_FCS}} \tag{49}$$

$$f_{t,i}^{\mathrm{up\_FCS}} \leq p_{t,i}^{\mathrm{c\_FCS}} - r_{t,i}^{\mathrm{up\_FCS}} \tag{50}$$

$$f_{t,i}^{\mathrm{dn\_FCS}} \leq \mathrm{P}_i^{\mathrm{max\_FCS}} \cdot \mathrm{G}_i^{\mathrm{FCS}} - p_{t,i}^{\mathrm{c\_FCS}} - r_{t,i}^{\mathrm{dn\_FCS}}. \tag{51}$$

Controlled bidirectional fast charging mode (S2G) is similar to G2S mode, modeled with (52), adding the exception of FCS discharging as in (53). Integer variable $x_{t,i}^{\mathrm{c\_FCS}}$ corresponds to the number of FCS currently charging, while expression ($\mathrm{G}_i^{\mathrm{FCS}} - x_{t,i}^{\mathrm{c\_EV}}$) corresponds to the number of FCS currently discharging. Reserves are modeled in the same manner

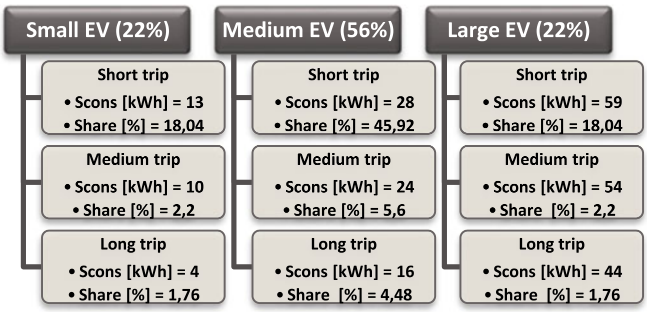

Fig. 3. EV types.

as SEV reserve provision

$$\mathrm{P}_i{}^{\min\_\mathrm{FCS}} \cdot x_{t,i}^{c\_\mathrm{FCS}} \leq p_{t,i}{}^{\mathrm{c\_FCS}} \leq \mathrm{P}_i{}^{\max\_\mathrm{FCS}} \cdot x_{t,i}^{c\_\mathrm{FCS}} \quad (52)$$

$$\mathrm{P}_i{}^{\min\_\mathrm{FCS}} \cdot (G_i^{\mathrm{FCS}} - x_{t,i}^{\mathrm{c\_FCS}}) \leq p_{t,i}{}^{\mathrm{d\_FCS}} \leq \mathrm{P}_i{}^{\max\_\mathrm{FCS}} \cdot (G_i^{\mathrm{FCS}} - x_{t,i}^{\mathrm{c\_FCS}}). \quad (53)$$

IV. Case Studies

The value of the proposed model will be shown using two case studies. The first analysis attempts to find an optimal time window for EV fast charging. The goal of these simulations is to analyze if an optimal charging time for fast charging of EV, without integrated ESS, exists.

In the second part, the analyses focus on determining the impact of fast charging EV on power systems flexibility. In these analyses, the flexibility will be evaluated through three flexibility metrics: total system cost (TSC), total system emissions (TSE), and wind power curtailment (WPC). General idea behind those three metrics is as follows: If flexibility of the system is decreasing then conventional system components work in nonoptimal operating points and have higher number of startups, consequently it means higher TSC and TSE. Lower flexibility also means the degraded capability of integrating wind power (WPC increases).

A. Simulation Parameters

Considered energy mix is similar to U.K. power system energy mix [38]. Vehicles driving behavior is taken from [45] and it has been used for calculation of number of vehicles arriving and leaving the charging stations (same as in [38]). Three different EV battery capacities and trip lengths have been modeled along with their different shares in total EV fleet, forming nine EV types (see Fig. 3). EV-type shares are calculated combining percentages of particular trip length (last row in Table III, coming from [45]) and future projections of EV types share in total EV fleet (highest priority row in Fig. 3, obtained from [46]). Energy conserved at the end of the trip is calculated using battery capacity, travel length, and average consumption.

The remaining EV technical characteristics are gathered from different publications and they are displayed in Table III (e.g., EV slow charging power used is 3.7 kW—IEC 61851 one phase ac connection, and fast charging power is 62.5 kW—ChadeMo). In this paper, EVs are leaving the grid fully charged, $\mathrm{S}^{\mathrm{minc\_EV}} = \mathrm{S}^{\max\_\mathrm{EV}}$. Initial energy of each EV type ($\mathrm{S}_i^{0\_\mathrm{EV}}$) is equal to 60% of battery capacity of initial on-grid EV.

Three different types/sizes of FCS have been observed as presented in Table II. Data for particular FCS type are calculated based on the number of EV that can be charged in every time step at full power (last row in Table IV). The total number of FCS ($\mathrm{G_i}^{\mathrm{FCS}}$) considers that all on-road EV can be fast charged (in other words, if it is "optimal for EPS," fast charging could be done without ESS). FCS/ESS capacities are calculated so they can fully recharge for eight hours at rated power.

The initial U.K. like power system (details are in [38]) energy mix is around 35% nuclear power plants, 45% coal power plants, 15% combined cycle gas turbines, and 5% open cycle gas turbines. For these analyses, a percentage of 40% WPP integration is used with peak net demand of around 60 GW. Percentage of EV integration is expressed as the share of EV in today's

TABLE III
EV Input Data

Power	$\mathrm{P}^{\min}$ [kW]	0,37	η^c, η^d, η^{fc}	0,95
	$\mathrm{P}^{\max}$ [kW]	3,7	$\mathrm{P}^{f\max}$ [kW]	50
EV size	$\mathrm{S}^{\min}$ [kWh]	Small		3,2
		Medium		6,4
		Large		12,8
	$\mathrm{S}^{\max}$ [kWh]	Small		16
		Medium		32
		Large		64
	Average consumption [kWh/km]	Small		0,15
		Medium		0,2
		Large		0,25
Trip	Trip length (km)	Short		20
		Medium		40
		Long		80
	Trip duration – Arr iv. (h)	Short		0,5
		Medium		1
		Long		1,5
	Percentage of the trips [%]	Short		82
		Medium		10
		Long		8

TABLE IV
FCS Input Data

Power energy loss		
η^c, η^d		0,95
k^{loss}		0,98
FCS type		
$\mathrm{P}^{\min}$ [kW]	Small	50
	Medium	150
	Large	500
P^{max} [kW]	Small	500
	Medium	1500
	Large	5000
S^{min} [kWh]	Small	200
	Medium	600
	Large	2000
S^{max} [kWh]	Small	1000
	Medium	3000
	Large	10000
FCS type share [%]	Small	50
	Medium	35
	Large	15
Max charg. number of EV (#)	Small	10
	Medium	30
	Large	100

TABLE V
OPTIMAL FAST CHARGING TIME WINDOW—FLEXIBILITY INDICATORS FOR UFC CHARGING MODE

Slow charging modes	USC-YR			G2V-YR		
Uncontrolled Fast Charging Scenarios UFC	**5%**	**0–12%**	**0–12 + 50% E**	**5%**	**0–12%**	**1–12 + 50% E**
Total System Cost TSC [%]	–0,31	–1,27	–1,04	0,61	0,02	0,22
Total System Emissions TSE [%]	–0,06	–0,83	–0,57	–0,55	–0,02	0,25
Wind Power Curtailment WPC [%]	0,87	–9,47	–2,33	0,00	0,00	0,00
Peak Demand Increase PDI [%]	–2,68	7,95	1,18	–7,43	0,00	–9,51
Energy supplied through FCS [%]	25,78	38,96	50,03	27,69	2,49	54,23

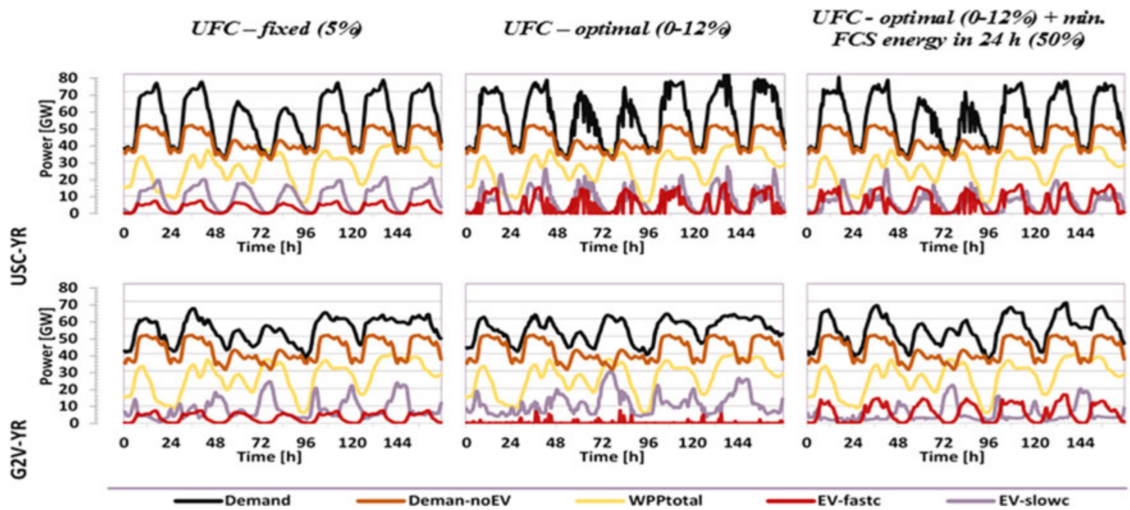

Fig. 4. Optimal fast charging time window—graphical result.

vehicle fleet in UK. It can be translated to EV maximum power; for example, total conventional vehicle fleet in U.K. today is around 30 million cars [47] and replacing 10% of them with EV increases U.K. peak power demand by 20% (if they all slow charged at daily peak power).

B. Optimal Fast Charging Time Window

This section will try to discover whether an optimal fast charging window ever exists, i.e., can the power system ever benefit from uncontrolled FCS (taking into account flexibility that is already consumed or brought to EPS by SEV charging). By allowing different shares of on-road EV to fast charge at each moment makes fast charging partially controllable but at the cost of EV drivers comfort. For example, it can be observed as discounts offered to FCS for charging at specific time ("happy hours") in order to change their behavior. On the other hand, controllable fast charging (G2S and S2G, or FCS with integrated ESS) provides controlled charging at FCS without any effect on EV drivers behavior.

Following on this, two SEV operational modes are analyzed in combination with FCS; USC-YR (operational mode A, increasing reserve due to uncontrollability, "dumb" charging), as inflexible operating regime, and G2V-YR, as source of additional flexibility (operational mode B, providing flexibility as reserve due to controllable charging).

Each of the two SEV modes is combined with fast charging, three different UFC scenarios have been simulated as follows.

1) Fixed percentage of on-road EV that are allowed to fast charge ($P_{tperf\_EV} = 5\%$), while the remaining 95% is using slow charging.
2) A certain percentage of up to 12% of on-road EV can fast charge (this is modeled by (37), variables $P_{perfmin\_EV} = 0\%$, $P_{perfmax\_EV} = 12\%$).
3) Variable percentage of EV is fast charged; however, there is a minimum required energy "assigned" for fast charging throughout the day (modeled with (37) and (38), $P_{enf\_EV} = 50\%$). In this section, 100% vehicles are considered electric.

Results of the simulations are shown in Table V and Fig. 4 for one-week time horizon. It can be noticed that in case with predefined fixed number of "dumb" fast charging EV (first column of Fig. 2), fast charging patterns are very similar for both SEV charging modes. As expected, such charging behavior results in peak demand increase, in case of uncontrollable slow charging, UCH-YR, the power demand increase (PDI) is around 54%, while in controllable slow charging regime, G2V-YR, PDI increases by 28%. The explanation is rather simple; controllable SEV charging is alleviating negative effects of FCS by shifting its charging during the night and using as much wind as possible during low demand periods (load leveling). This can be seen in Fig. 4, as slow charging EV curve and fast charging curve almost never occur at the same time. Comparing peak demands of the system with the case of only SEV charging (see Table V), introduction of FCS slightly decreases the peak demand in both USC-YR (−2.68%) and G2V-YR (−7,43%). On the other hand, its effect on other flexibility metrics is negligible (operational cost, greenhouse gas emissions, and wind curtailment). In the second case (second column of Fig. 4), the algorithm finds optimal fast charging time windows for fast charging. In case of uncontrollable slow charging mode, all flexibility metrics are slightly improved/decreased compared to fixed UFC; TSC, TSE around 1%, while WPC is reduced by 9.47%. It is interesting to notice that peak demand increases (by 7.95%). This happens because the objective function of the algorithm pushes the minimization of WPC and during the few specific peak demand moments, when there is an excess of wind, fast charging is deployed (total demand is increased). Since UCH-YR mode is inflexible, the capability of creating optimal fast charging windows brings additional flexibility. Fast charging will be a preferred option in those scenarios, encouraging all EV to fast charge, and, by doing so, increasing fast charging energy from 26% to 39% (FCS in Table V represents percentage of total required energy by EV provided through fast charging). It is interesting to notice that peak demand increases (by 7.95%). This happens since the objective function pushes the minimization of WPC and during the few specific peak demand moments when there is an excess of wind, fast charging is deployed (total demand is increased). UCH-YR mode is inflexible SEV charging mode and optimal fast charging provides new flexibility, meaning fast charging will be a preferred option in those scenarios increasing fast charging energy from 26% to 39% (FCS in Table V represents percentage of total required energy by EV provided through fast charging).

Due to high flexibility of the G2V-YR mode, there is no need for optimal fast charging windows and the end result is that all EVs have been controllably slow charged. In scenario where 50% of energy is being used for fast charging, both observed scenarios (third column of Fig. 4) show poorer results as system has been moved from its optimal point.

As a general conclusion, introduction of fast charging has minimal effect on defined flexibility metrics when comparing to flexible and inflexible SEV charging with 0% FCS. Uncontrollable charging, both slow in (USC-YR) and fast (UFC), depends on driving behavior of EVs and their charging occurs during peak daytime periods. Since they are both inflexible regimes, their effect on EPS is similar. On the other hand, G2V-YR incorporates high flexibility and can alleviate negative impacts of inflexible fast charging behavior.

C. Charging Station Impact on System's Flexibility

To evaluate the impact of fast charging on system's flexibility, the following analyses have been considered: 1) uncontrollable USC-YR with the addition of fixed 5% on-road vehicles fast charging and 2) controllable G2V-YR with the addition of fixed 5% on-road vehicles fast charging. Since there is a lack of real data on EV fast charging, we assume these percentages. In both analyses, six FCS operating modes and two EV shares have been used: 33% and 67%[4] (of total U.K. vehicle's fleet as EVs). The results are shown in Figs. 5 and 6, using 0% of fast charging EVs as base case for comparing (all EVs have been slow charged in base case).

Analyzing the results for uncontrollable SEV charging (see Fig. 5), USC-YR mode, it can be noticed that FCS coupled with ESS as a reserve provider (G2S-YR and S2G-YR) reduces all flexibility metric values, increasing the power system flexibility. In case of 67% of EVs, reduction of wind curtailment metric (WPC) is higher than for 33%, while the operating cost (TSC) and system emissions (TSE) reduction is lower. This suggests that larger share of USC-YR impacts EPS flexibility more than it gains from utilizing G2S and S2G reserve provision. Controlled

[4]The results for 100% are very similar as for 67%, therefore they are omitted from the paper.

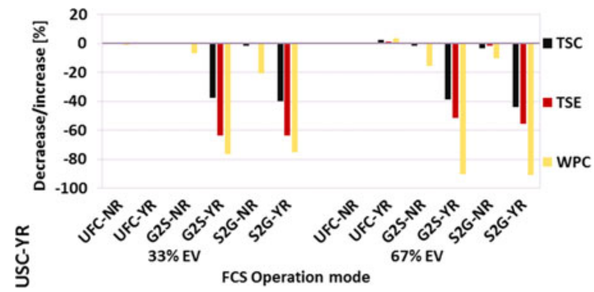

Fig. 5. FCS impact on EPS flexibility metrics USC-YR.

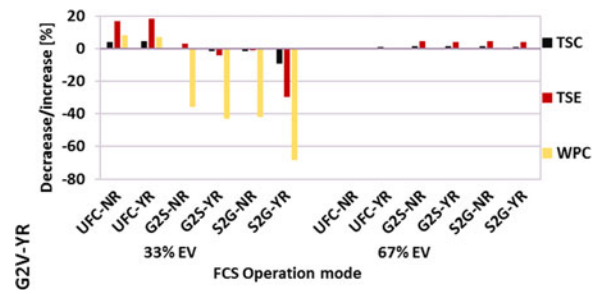

Fig. 6. FCS impact on EPS flexibility metrics G2V-YR.

fast charging modes without the capability of providing reserve (G2S-NR and S2G-NR) improves flexibility metrics; however, this is negligible compared to G2S-YR and S2G-YR modes. UFC-NR mode does not impact the metrics, while UFC-YR is the only mode negatively affecting EPS due to its increase in reserve requirements.

G2V-YR results (see Fig. 6) differ from those of USC-YR mode. When there is 33% share of EVs, UFC-NR and UFC-YR negatively impact flexibility metrics, as controllable slow charging does not provide enough flexibility to alleviate negative effects of uncontrollable fast charging. For higher EV share, i.e., 67% (meaning higher G2V-YR flexibility provision), fast charging impacts are completely mitigated. For 33% EV share, in all G2S and S2G modes, WPC is decreased. G2S-NR, G2S-YR, and S2G-NR have negligible effect on TSC and TSE, while S2G-YR provides far better results. For higher EV shares, all G2S and S2G modes act as TSC and TSE enhancers. A general conclusion can be made that unless fast chargers are coupled with ESS, they will have a negative impact on system operation, in terms of cost, emissions, and wind usage. Adding ESS to FCS can create additional benefits to the system operation by providing ancillary services, reducing the flexibility metrics.

V. Conclusion

This paper presents a multiple service unit commitment model for combined SEV and FCS operation, giving insight into the operational flexibility issues of integrating EV, respecting all technical constraints of conventional and low carbon technologies. A detailed model of EV behavior and their impact on power system operation, both in passive and active/controllable regime, demonstrates how increasing number of FCS, as providers of higher EV user comfort, can have a negative impact on power system operation; increasing the total operational cost, emissions, and reducing the level of used renewable energy. Even in cases where a certain percentage of EV can fast charge during "optimal" time windows, the negative effects are clearly visible. Issues arising from EVs integration can be efficiently mitigated and can turn into flexibility enhancement if adequate management plan is implemented. Uncoordinated fast and slow modes of charging will have severe negative effects on systems secure operation. If only controllable slow charging is enabled (for example at home), this could, to a significant level, mitigate negative effects of fast charging. ESS, as a part of FCS, can mitigate the negative effects caused by a large number of EVs being charged at FSC. Those effects are even more emphasized in case where a certain number of EVs are uncontrollably slow charged. In this paper, the role of storage is to act as a mediator between charging spot and power grid, also providing energy arbitrage and reserve services to the system operator. In general, FCS with integrated ESS can provide flexibility to power system by bidirectional power flow and by ancillary service provision. This paper revealed that ancillary services provision is more valuable as flexibility provider than the possibility of reinjecting the power back to grid.

Appendix

A. Decision Variables

$p_{t,i}^{\mathrm{g\_TP}}$	Thermal units generation.
$p_{t,i}^{\mathrm{g\_HP}}$	Hydro units generation.
$p_{t,i}^{\mathrm{g\_PS}}$, $p_{t,i}^{\mathrm{p\_PS}}$	Pump storage generation/pumping.
$p_t^{\mathrm{g\_WP}}$	Wind power generation.
$p_{t,i}^{\mathrm{c\_EV}}$, $p_{t,i}^{\mathrm{d\_EV}}$	EV slow charging/discharging.
$p_{t,i}^{\mathrm{c\_FCS}}$, $p_{t,i}^{\mathrm{d\_FCS}}$	FCS charging/discharging.
$p_{t,i}^{\mathrm{f\_EV}}$	EV fast charging.
$f_{t,i}^{\mathrm{up\_TP}}$, $f_{t,i}^{\mathrm{dn\_TP}}$, $r_{t,i}^{\mathrm{up\_TP}}$, $r_{t,i}^{\mathrm{dn\_TP}}$	Thermal units primary(f)/secondary(r) up/down reserve provision.
$f_{t,i}^{\mathrm{up\_HP}}$, $f_{t,i}^{\mathrm{dn\_HP}}$, $r_{t,i}^{\mathrm{up\_HP}}$, $r_{t,i}^{\mathrm{dn\_HP}}$	Hydro units primary(f)/secondary(r) up/down reserve provision.
$f_{t,i}^{\mathrm{up\_PS}}$, $f_{t,i}^{\mathrm{dn\_PS}}$, $r_{t,i}^{\mathrm{up\_PS}}$, $r_{t,i}^{\mathrm{dn\_PS}}$	Pump storage primary(f)/secondary(r) up/down reserve provision.
$f_{t,i}^{\mathrm{up\_EV}}$, $f_{t,i}^{\mathrm{dn\_EV}}$, $r_{t,i}^{\mathrm{up\_EV}}$, $r_{t,i}^{\mathrm{dn\_EV}}$	EV primary(f)/secondary(r) up/down reserve provision.
$f_{t,i}^{\mathrm{up\_EV}}$, $f_{t,i}^{\mathrm{dn\_EV}}$, $r_{t,i}^{\mathrm{up\_EV}}$, $r_{t,i}^{\mathrm{dn\_EV}}$	FCS primary(f)/secondary(r) up/down reserve provision.
$q_{t,i}^{\mathrm{up\_TP}}$	Thermal units tertiary up reserve provision.
$s_{t,i}^{\mathrm{EV}}$	Total energy in EV fleet of one EV type.
$s_{t,i}^{\mathrm{arr\_EV}}$	Total energy in cluster of EV arriving to the grid.
$s_{t,i}^{\mathrm{leav\_EV}}$	Total energy in a cluster of EV leaving the grid.
$s_{t,i}^{\mathrm{add\_FCS}}$	Additional energy brought to EV fleet due to fast charging.
$p_t^{\mathrm{perf\_EV}}$	Percentage of fast charging EV.
$x_{t,i}^{\mathrm{c\_EV}}$, $x_{t,i}^{c\_FCS}$	Number of EV/FCS charging.
$p_t^{\mathrm{sh\_WP}}$	Curtailed wind power.
$c_{t,i}^{\mathrm{TP}}$	Total thermal power plant cost.
$c_{t,i}^{\mathrm{HP}}$	Total HPP cost.
$c_{\mathrm{t,i}}{}^{\mathrm{\_FCS}}$	Energy conserved in FCS/ESS.

B. Input Parameters

$\mathrm{T^{dur\_EV}}_i$	EV-type trip duration.
$C_i{}^{\mathrm{0\_FCS}}$	Initial SOC of FCS/ESS.
$\mathrm{C}_i{}^{\mathrm{min\_FCS}}$, $\mathrm{C}_i{}^{\mathrm{max\_FCS}}$	Minimum/maximum capacity of FCS/ESS.
$\mathrm{k}_i{}^{\mathrm{loss\_FCS}}$	Storage efficiency of FCS/ESS.
$\mathrm{P}_t^{\mathrm{d}}$	Power demand.
$\mathrm{F}_t^{\mathrm{up}}$	Primary up reserve requirements.
$\mathrm{F}_t^{\mathrm{dn}}$	Primary down reserve requirements.
$\mathrm{R}_t^{\mathrm{up}}$	Secondary up reserve requirements.
$\mathrm{R}_t^{\mathrm{dn}}$	Secondary down reserve requirements.
$\mathrm{Q}_t^{\mathrm{up}}$	Tertiary up reserve requirements.
$\mathrm{P}_t^{\mathrm{WP}}$	Potential wind power generation.
$\mathrm{R}_t^{\mathrm{EV\_0,5h}}$, $\mathrm{R}_t^{\mathrm{EV\_4h}}$	Secondary/tertiary reserve requirements increase caused by uncontrolled EV charging.
$\mathrm{R}_t^{\mathrm{FCS\_0,5h}}$, $\mathrm{R}_t^{\mathrm{FCS\_4h}}$	Secondary/tertiary reserve requirements increase caused by uncontrolled FCS charging.
$\sigma_t^{\mathrm{sl(0,5h)\_EV}}$, $\sigma_t^{\mathrm{sl(4h)\_EV}}$	EV USC charging standard deviation for secondary/tertiary reserve.
$\sigma_t^{\mathrm{sl(0,5h)\_FCS}}$, $\sigma_t^{\mathrm{sl(4h)\_FCS}}$	FCS uncontrolled charging standard deviation for secondary/tertiary reserve.
$\sigma_t^{\mathrm{(0,5h)\_WP}}$, $\sigma_t^{\mathrm{(4h)\_WP}}$	Wind power standard deviation for secondary/tertiary reserve.
$\mathrm{N}_{\tau,i}^{\mathrm{arr\_EV}}$	# of EV arriving to the grid.
$\mathrm{N}_{t,i}^{\mathrm{g\_EV}}$	# of EV connected to the grid.
$\mathrm{N}_{t,i}^{\mathrm{leav\_EV}}$	# of EV leaving the grid.
Ni_TP	# of thermal technology types
Ni_HP	# of hydro technology types.
Ni_PS	# of pump storage technology types.
Ni_EV	# of electric vehicles types.
σ^{d}	Power demand standard deviation.
$C_i^{\mathrm{UCH\_EV}}$	Time required to recharge EV at full power.
$\eta_i^{\mathrm{c\_EV}}$, $\eta_i^{\mathrm{d\_EV}}$	EV charging/discharging efficiency.
$\eta_i^{\mathrm{fc\_EV}}$	EV fast charging efficiency.
$\eta_i^{\mathrm{c\_FCS}}$, $\eta_i^{\mathrm{d\_FCS}}$	FCS charging/discharging efficiency.
$\mathrm{S}_i^{\mathrm{0\_EV}}$	Initial energy conserved in EV fleet.
$\mathrm{S}_i^{\mathrm{min\_EV}}$	The lowest SOC value of one EV.
$\mathrm{S}_i^{\mathrm{max\_EV}}$	The highest SOC value of one EV.
$\mathrm{S}_i^{\mathrm{cons\_EV}}$	Energy conserved in one EV which arrives to the grid.
$\mathrm{S}_i^{\mathrm{minc\_EV}}$	The lowest allowed SOC in EV leaving the grid.
$\mathrm{P}_i^{\mathrm{fmax\_EV}}$	Fast charging power maximum.
$\mathrm{G}_i^{\mathrm{EV}}$	Total number of EV per type.
$\mathrm{G}_i^{\mathrm{FCS}}$	Total number of FCS per type.
$\mathrm{P}_i{}^{\mathrm{min\_FCS}}$, $\mathrm{P}_i^{\mathrm{max\_EV}}$	FCS charging (discharging) power minimum/maximum.
$\mathrm{P}_i{}^{\mathrm{min\_FCS}}$, $\mathrm{P}_i{}^{\mathrm{max\_FCS}}$	EV charging (discharging) power min/max.
$\mathrm{P}_i^{\mathrm{perfmin\_EV}}$, $\mathrm{P}_i^{\mathrm{perfmax\_EV}}$	Minimum/maximum percentage of fast charging

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