Fast Charging Stations - Power and Ancillary Services Provision

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***Abstract*—High penetration of variable renewable sources act as a heavy burden on conventional power system management and operation. Uncertainty in power systems expanded from demand side to generation side as well. Since new sources of imbalances have entered power system, it should be reorganized, automated and modernized. New providers of flexibility should be recognized and used in future power system planning and design. One of the possible technologies that can be used for flexibility provision are electric vehicles. Numerous fast charging stations are installed all over the world and such trend will continue in future. Depending on their operation, charging stations can act as flexibility providers but they can also further degrade system's flexibility if installed without any kind of energy buffer. This paper will present mixed integer linear model for flexibility studies of modern power systems with high penetration of variable renewable sources and electric vehicles. Results clearly show that smart planning of fast charging infrastructure can bring huge benefits to power system concerning costs, emissions, and variable renewable power curtailment.**

Keywords-renewable energy sources; electric vehicles; fast charging stations; flexibility; ancillary services

I. INTRODUCTION

New technologies integrated in power system introduced new problems to conventional power system operation. Due to their variability and unpredictability renewable energy sources brought new stochastic variables on generation side [1], [2]. New electricity loads such as electric vehicles or heat pumps [3], when uncontrolled, can also intensify uncertainty of power demand and cause increase in peak demand. In order to balance mentioned new power system state with huge number of stochastic variables, new fast responding generating units should be installed. Installment of such units, usually expensive gas turbines, is contrary to the initial plan where renewable generation should replace fossil fueled units. Advanced methods for system flexibility increase can be recognized in energy storage installment [4] or in usage of demand response programs [5]. Interesting way to decrease stochastic impact of variable renewable sources (VRE) on power system is to balance their generation locally and to use rest of the grid just when local generation is insufficient – microgrids [6].

This paper aims to present mixed integer linear programming (MILP) model with VRE, conventional power plants and incorporated fast charging stations. Also, goal is to examine impacts of fast charging stations (FCS) on power systems operation and flexibility. Different operating regimes provide insight in wide range of impacts on power system.

Flexibility of the power system can be defined as a competence of system to adequately balance power supply and power demand. Ancillary services are supporting services required by power system 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 is referring to reserve provision only.

A lot of recent literature have been published with the topic of FCS impact on power system, short overview is presented in the following. A revenue model of FCS has been developed in [7]. Authors propose that FCS sets the limit on EV required state-of-charge (SOC) in order to boost its revenue. Control of FCS with bidirectional power capabilities is proposed in [8]. A multi-objective planning strategy for FCS is developed in [9] where the overall annual cost of investment and energy losses are minimized simultaneously with the maximization of the annual traffic flow captured by FCS. Research paper [10] presents FCS load behavior model and uses it to asses impacts of FCS on distribution system where high accuracy of model has been proven. Authors in [11] propose a multi-objective FCS planning method which can ensure charging service while reducing power losses and voltage deviations of distribution system. FCS placement problem was solved in [12], while [13] tackles with simultaneous planning and sizing both DG and FCS as complementary technologies. Numerous papers such as [14], [15] study FCS placement in regards to driving behavior and other aspects (transmission grid, transportation grid, other social aspects etc.). Interesting economic aspect on competition of different FCS in modern EPS has been published in [16], while [17] deals with a business and operating model of EV battery swapping stations (BSS). As seen through this paragraph a great deal of recent publications provides research about FCS from planning, siting, sizing through FCS load behavior and distribution system impact assessments to economic aspects such as maximization of FCS revenues and business models. None of them deals with the impacts of FCS on the unit commitment of conventional generators, ancillary services nor with on the combined impacts of Slow charging EV (SEV) and FCS.

Rest of the paper is structured as following. Section II explains proposed model, Section III discusses gained results and last Section concludes with most important findings.

II. MODEL

Proposed model used for EV flexibility in this paper has been divided between power generation and demand. Generation is composed of conventional fossil fueled (Nuclear, Coal, Combined and Opened Cycle Gas Turbines) and hydro power plants (Run of River, Accumulation Hydro, Pump Storage) and Variable Renewable Energy Sources. Demand is composed of Electric Vehicles (EV) and Conventional Power Demand (CPD). The main balancing equation is generation-demand equation, i.e. generation and demand should be balanced at every time step as it is formulated in (1). Each of the variables contains superscript which specifies related technology (example, TP means Thermal Power).

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

Other type of balancing equations are reserve provision-requirements for primary, secondary, and tertiary reserve. Equations (2) - (3) correspond to primary reserve up and down, equations (4) - (5) to secondary reserve up and down and (6) to tertiary up reserve.

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

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

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

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

$$\sum\nolimits_{i=1}^{\mathrm{Ni\_TP}} q_{t,i}^{\mathrm{up\_TP}} \geq \mathrm{Q}_t^{\mathrm{up}} \tag{6}$$

Reserve requirements (right side of the equations (4) - (6)) are calculated through equations (7) - (11). These equations are not part of optimization algorithm, they are calculated a priori based on historical data.

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

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

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

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

$$\mathrm{Q}_t^{\mathrm{up}} = \mathrm{P}^{\mathrm{gmax}} + \\ + \sqrt{\left(3 \cdot \sigma^{\mathrm{d}} \cdot \mathrm{P}_t^{\mathrm{d}}\right)^2 + \left(3,5 \cdot \sigma_t^{(4\mathrm{h})\_\mathrm{WP}} \cdot \mathrm{P}_t^{\_\mathrm{WP}}\right)^2 + \left(\mathrm{R}_t^{4\mathrm{h\_EV}}\right)^2 + \left(\mathrm{R}_t^{4\mathrm{h\_FCS}}\right)^2} \tag{11}$$ [1]

More details about reserve modeling can be found in [18], [19] and [20].

Objective function is minimization of thermal and hydro operation and management costs (12).

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

A. Power System Model

Conventional units are constrained with technical restrictions. Both thermal (TPP) and hydro power plants (HPP) models for multi service unit commitment (MSUC) optimization are usually developed as binary problems. Details about binary TPP model, and objective function as well, can be found in [21], and about HPP UC model in [22]. In order to improve computational efficiency of the MSUC model TPP and HPP in this paper they are clustered by technology type as in [23] or [24]. Even faster MSUC be modeled using relaxed linear programming UC as in [25]. Due to succinctness of the paper, TPP, HPP and WPP mathematical representation of the constraints is omitted but briefly mentioned in the text bellow.

TPP generation is constrained with following: power generation constraints (piece-wise linear cost curve), minimum up and down times, ramping constraints, reserve provision constraints and greenhouse gas emission cost function.

HPP generation is subjected by the following: water balance equation, generation power constraints, reservoir constraints, hydro turbine constraints, spillage constraint and reserve provision constraints.

WPP generation is constrained with real historical wind generation (it can be seen as max wind generation). Curtailment of WPP production is allowed when it benefits the EPS, so their actual production can be lower than historical data. Conventional power demand (CPD) is modeled as historical data (as a parameter, not as a variable).

B. EV Model

EVs mathematical representation is one of the contributions of the paper, therefore it is discussed in this subsection in detail. EVs are modeled as variable capacity storage of aggregated electric vehicles by type (13). Energy stored in group of EV of particular type depends on energy stored in EV arriving to the electrical grid after driving (S^{arr}), energy stored in EV leaving the grid (S^{leav}), power used for EV charging (P^c) and discharging (P^d) and energy consumed by fast charging EV on fast charging stations (S^{add}).

$$s_{t,i}^{\_\mathrm{EV}} = s_{t-1,i}^{\_\mathrm{EV}} + s_{t,i}^{\mathrm{arr\_EV}} - s_{t,i}^{\mathrm{leav\_EV}} + p_{t,i}^{\mathrm{c\_EV}} \cdot \eta_i^{\mathrm{c\_EV}} * \Delta\mathrm{t} - p_{t,i}^{\mathrm{d\_EV}} / \eta_i^{\mathrm{d\_EV}} \cdot \Delta\mathrm{t} + s_{t,i}^{\mathrm{add\_FCS}} \tag{13}$$

$$p_{t,i}^{\mathrm{f\_EV}} \geq p_t^{\mathrm{perf\_EV}} \cdot \mathrm{P}_i^{\mathrm{fmax\_EV}} \cdot \left(\mathrm{G}_i^{\_\mathrm{EV}} - \mathrm{N}_{t,i}^{\mathrm{g\_EV}}\right) \tag{14}$$

$$s_{t,i}^{\mathrm{add\_FCS}} \leq \eta_i^{\mathrm{f\_EV}} \cdot p_{\left(\mathrm{Nt+t-T}_i^{\mathrm{dur\_EV}}\right),i}^{\mathrm{f\_EV}} \cdot \Delta\mathrm{t} \tag{15}$$

$$s_{t,i}^{\mathrm{add\_FCS}} \leq \eta_i^{\mathrm{f\_EV}} \cdot p_{\left(\mathrm{t-T}_i^{\mathrm{dur\_EV}}\right),i}^{\mathrm{f\_EV}} \cdot \Delta\mathrm{t} \tag{16}$$

Main input parameter for number of arriving and leaving vehicles as well as for the number of vehicles fast charging is electric vehicles weekly behavior derived from driving behavior of conventional vehicles in the US [26]. Used EV driving behavior, historical wind power production and conventional power

[1] Equations (7) and (8) apply for Rt^{4h_EV} and Rt^{4h_FCS} in (11) , the only difference is substitution of $\sigma^{0,5h\_EV}$ and $\sigma^{0,5h\_FCS}$ with σ^{4h_EV} and σ^{4h_EV}, respectively.

demand are displayed on Figure 1. Power for fast charging depends on number of on-road EV (14). Equations (15) and (16) are constraints for fast charging.

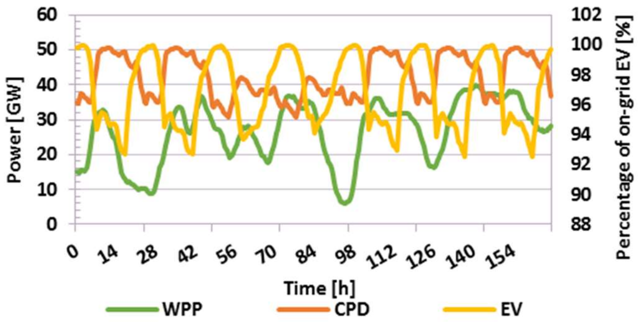

Figure 1 Input data: max wind power production, power demand and EV driving behavior

EV charging is divided as slow charging of EV (SEV; home or work charging) and fast charging at fast charging stations (FCS). Both ways of charging includes 6 modes of operation explained in Table 1 and Table 2. Most of the energy required for EV consumption is from slow home charging (≈ 70%.). Share of fast charging in total EV charging requirements in this paper is around 30%, i.e. share of on-road EV fast charging every moment is 5%.

Table 1 Slow EV charging operation modes

SEV – Slow EV charging				
Charging\ Reserve			**NR** – No Reserve	**YR** – Yes Reserve
Uncontrolled		USC – Uncon. Slow Charging	- EV slow charge at rated power from moment they plug in until fully charged - EV do not impact reserve requirements	- EV slow charge at rated power from moment they plug in until fully charged - EV causing increase in reserve requirements
Controlled	**Unidirectional**	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**	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

Mathematical representation of the EVs constraints for SEV is omitted from this paper but presented and discussed in authors' earlier papers [27], [28] and [29]. Focus of this paper is to analyze system's behavior under high penetration of wind power plants as variable renewable source and under high penetration of EV charged on FCS as a promising new flexible load on the demand side. Mathematical formulation of FCS is represented through equations (12)-(14).

Table 2 Fast charging stations operation modes

FCS – Fast Charging Stations				
Charging\ Reserve			**NR** – No Reserve	**YR** – Yes Reserve
Uncontrolled		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**	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 EES integrated in FCS - FCS/ESS optimal charging (from the grid) - no FCS/ESS discharging to the grid - FCS provide reserve
Controlled	**Bidirectional**	S2G – Station to Grid	- EV fast charge through EES integrated in FCS - FCS/ESS optimal charging & discharging - no FCS reserve provision	- EV fast charge through EES integrated in FCS - FCS/ESS optimal charging & discharging - FCS provide reserve

The availability of EV for fast charging is modelled in equation (12). Fast charging power is added to main EV equation (13) through equation (14) and (15). Equations (16) – (17) are representing UFC mode, (18) – (23) are representing G2S mode and (24) – (29) S2G mode.

$$p_{t,i}^{\text{f\_EV}} \geq p_t^{\text{perf\_EV}} \cdot \mathrm{P}_i^{\text{fmax\_EV}} \cdot \left(\mathrm{G}_i^{\text{EV}} - \mathrm{N}_{t,i}^{\text{g\_EV}}\right) \quad (12)$$

$$s_{t,i}^{\text{add\_FCS}} \leq \eta_i^{\text{f\_EV}} \cdot p_{\left(\mathrm{Nt+t-T}^{\text{dur\_EV}}{}_i\right),i}^{\text{f\_EV}} \cdot \Delta \mathrm{t} \quad (13)$$

$$s_{t,i}^{\text{add\_FCS}} \leq \eta_i^{\text{f\_EV}} \cdot p_{\left(\mathrm{t-T}^{\text{dur\_EV}}{}_i\right),i}^{\text{f\_EV}} \cdot \Delta \mathrm{t} \quad (14)$$

$$p_{t,i}^{\text{c\_FCS}} = p_{t,i}^{\text{f\_FCS}} \quad (16)$$

$$p_{t,i}^{\text{d\_FCS}} = 0 \quad (17)$$

$$\mathrm{P}_i^{\text{min\_FCS}} \cdot G_i^{FCS} \leq p_{t,i}^{\text{c\_FCS}} \leq \mathrm{P}_i^{\text{max\_FCS}} \cdot G_i^{FCS} \quad (18)$$

$$p_{t,i}^{\text{d\_FCS}} = 0 \quad (19)$$

$$r_{t,i}^{\text{up\_FCS}} \leq p_{t,i}^{\text{c\_FCS}} - \mathrm{P}_i^{\text{min\_FCS}} \cdot x_{t,i}^{\text{c\_FCS}} \quad (20)$$

$$r_{t,i}^{\text{dn\_FCS}} \leq \mathrm{P}_i^{\text{max\_FCS}} \cdot G_i^{FCS} - p_{t,i}^{\text{c\_FCS}} \quad (21)$$

$$f_{t,i}^{\text{up\_FCS}} \leq p_{t,i}^{\text{c\_FCS}} - r_{t,i}^{\text{up\_FCS}} - \mathrm{P}_i^{\text{min\_FCS}} \cdot x_{t,i}^{\text{c\_FCS}} \quad (22)$$

$$f_{t,i}^{\text{dn\_FCS}} \leq \mathrm{P}_i^{\text{max\_FCS}} \cdot G_i^{FCS} - p_{t,i}^{\text{c\_FCS}} - r_{t,i}^{\text{dn\_FCS}} \quad (23)$$

$$\mathrm{P}_i^{\text{min\_FCS}} \cdot x_{t,i}^{c\_FCS} \leq p_{t,i}^{\text{c\_FCS}} \leq \mathrm{P}_i^{\text{max\_FCS}} \cdot x_{t,i}^{c\_FCS} \quad (24)$$

$$\mathrm{P}_i^{\text{min\_FCS}} \cdot (G_i^{FCS} - x_{t,i}^{c\_FCS}) \leq p_{t,i}^{\text{d\_FCS}} \leq \mathrm{P}_i^{\text{max\_FCS}} \cdot (G_i^{FCS} - x_{t,i}^{c\_FCS}) \quad (25)$$

$$r_{t,i}^{\text{up\_FCS}} \leq \mathrm{P}_i^{\text{max\_FCS}} \cdot \left(G_i^{FCS} - x_{t,i}^{c\_FCS}\right) - p_{t,i}^{\text{d\_FCS}} + p_{t,i}^{\text{c\_FCS}} - \mathrm{P}_i^{\text{min\_FCS}} \cdot x_{t,i}^{\text{c\_FCS}} \quad (26)$$

$$r_{t,i}^{\text{dn\_FCS}} \leq p_{t,i}^{\text{d\_FCS}} - \mathrm{P}_i^{\text{min\_FCS}} \cdot \left(G_i^{FCS} - x_{t,i}^{c\_FCS}\right) + \mathrm{P}_i^{\text{max\_FCS}} \cdot x_{t,i}^{\text{c\_FCS}} - p_{t,i}^{\text{c\_FCS}} \quad (27)$$

$$f_{t,i}^{up\_FCS} \le \mathrm{P}_i^{max\_FCS} \cdot \left(G_i^{FCS} - x_{t,i}^{c\_FCS}\right)$$
$$-\mathrm{P}_{t,i}^{d\_FCS} + p_{t,i}^{c\_FCS} - \mathrm{P}_i^{min\_FCS} \cdot x_{t,i}^{c\_FCS} - r_{t,i}^{up\_FCS} \quad (28)$$

$$f_{t,i}^{dn\_FCS} \le p_{t,i}^{d\_FCS} - \mathrm{P}_i^{min\_FCS} \cdot \left(\mathrm{N}_{t,i}^{g\_FCS} - x_{t,i}^{c\_FCS}\right)$$
$$+\mathrm{P}_i^{max\_FCS} \cdot x_{t,i}^{c\_FCS} - p_{t,i}^{c\_FCS} - r_{t,i}^{dn\_FCS} \quad (29)$$

III. Case Studies

Using inflexible thermal system with high wind penetration, impact of different fast charging stations (FCS) operation modes on unit commitment and rotating reserve provision[2] is analyzed in detail. Shares of conventional units used in following simulations are: 35% nuclear, 45% coal, 15% combined cycle gas turbines (CCGT) and 5% open cycle gas turbines (OCGT). Listed shares are observed in regards to total net demand required for feasible operation (CPD – WPP + rotation reserve requirements = 50 GW). Share of WPP is 60% of total required generation capacity (CPD + rotation reserve requirements = 60 GW). When talking about EV integration, percentage corresponds to the share of EV in today's total vehicle's fleet in UK, 50% is used in this paper. One Slow EV charging operation mode is used for observation, controlled slow charging without discharging but with reserve provision G2V-YR (Figure 3). This slow charging mode seems to be most probable in slow home charging. Legend for both figures is displayed on Figure 2. Figure 3 is showing one week unit commitment (first column), provision of secondary up reserve (second column) and secondary down reserve (third column) for the observed inflexible power system. Seven cases are listed as rows of graphs, case without EV and EV fast charging through six FCS operation modes defined in Table 2. Every graph inside figures includes power in GW on x-axis and time in hours on y-axis. Unit commitment graphs are divided into two parts, first one are colored areas representing unit commitment (generated energy) and second are colored lines representing total demand (black), demand without EV (light blue), EV fast charging (blue), EV slow charging (green) and FCS charging (pink). Red area above demand line is curtailed wind energy, while purple area just under demand line is energy discharged from FCS energy storage. Reserve graphs have the same division, colored areas represent reserved energy for contingency while colored lines represent total reserve requirements (black) and reserve requirements without EV's impact (light blue).

Once again, Table 3 and Figure 3 are presenting FCS operation mode impacts on unit commitment and reserve provision in combination with slow charging mode – G2V-YR.

When observing NO-EV case (reference case) on Figure 3 (USC-YR SEV operation mode) it can be noticed that both Nuclear Power Plants (NPP) and Coal Power Plants (CPP) are working at fixed power through one week period. The only difference is that NPP generate at full power while CPP power provision is lower than rated due to reserve provision requirements (second column). Most of the reserve up and almost all reserve down is provided by CPP. Wind power plants are scheduled only in peak periods, because reserve requirements are not allowing CPP to lower their generation in order to utilize more wind energy EV's involvement in power system in observed SEV mode brings more than 40 % decrease in TSC in all FCS operation modes, more than 70% TSE decrease in all FCS operation modes and more than 94% decrease in WPC even in UFC-NR operation mode. Such great flexibility improvements are due to two main reasons: controlled (flexible) charging which allows energy arbitrage and reserve provision which eliminates reserve constraints on coal and gas power plants.

Even though we add additional flexibility requirements through UFC-NR and especially UFC-YR operation mode, all flexibility metrics are significantly reduced. It actually means that slow charging is providing more flexibility than it is required for coverage of fast charging's inflexibility. Most of the reserve up is provided by SEV as well as complete reserve down. Coal and gas units are providing up reserve in periods when they are also used for power generation (low wind periods).

In G2S-NR mode metrics are further decreased, Table 3. FCS and SEV are both operating as energy arbitrage units thus reducing WPC to almost zero value (≈ 0.16% of WPC from NO-EV case). By permitting FCS reserve capabilities, FCS are promoted to main reserve providers in both up and down reserve provision. Slow charging of EVs is less stressed, and it can be better utilized for energy arbitrage. For example, SEV charging has increased during weekends nigh periods when wind is high. Wind power curtailment is equal to zero.

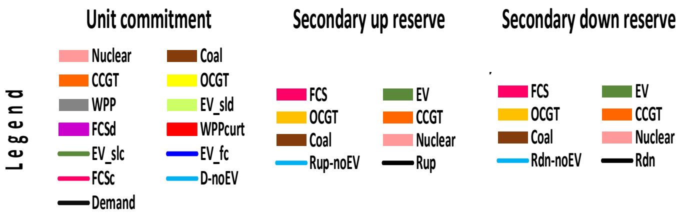

Figure 2 Legend for Figure 3

Table 3 Flexibility parameters – SEV operation mode: G2V-YR

Flexibility metricss	NO-FCS	UFC-NR	UFC-YR	G2S-NR	G2S-YR	S2G-NR	S2G-YR
TSC [10^6 €]	76,18	43,45	44,10	41,29	40,77	40,67	40,61
TSE [10^9 kg CO_2]	2,40	0,73	0,75	0,62	0,62	0,62	0,61
WPC [GWh]	2971,06	158,41	185,24	4,75	0,00	0,00	0,00

[2] Due to succinctness of the paper only secondary reserve will be discussed, but the same conclusions can be made for the primary reserve provision.

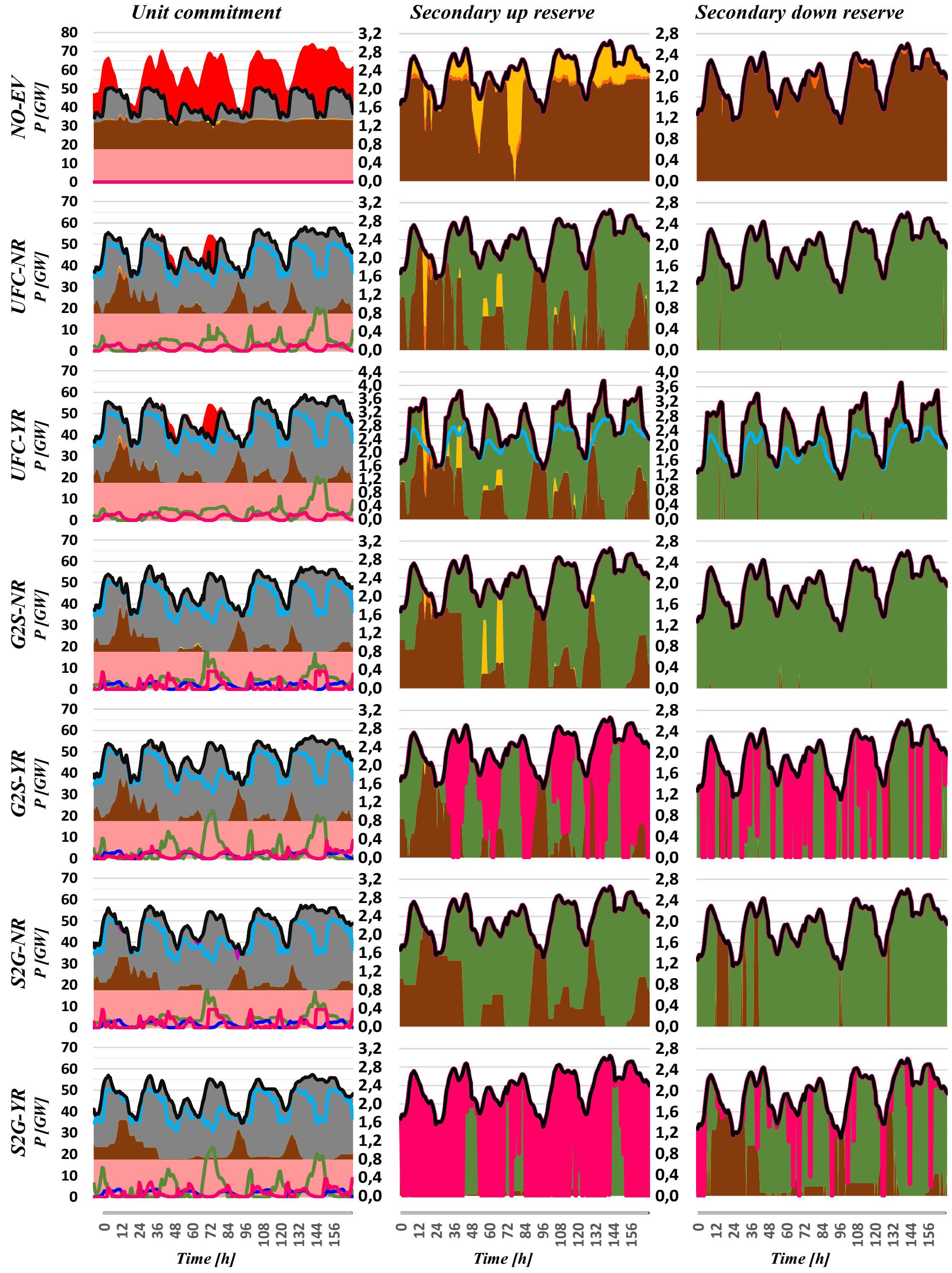

Figure 3 Fast charging impact on power system operation – SEV operation mode: G2V-YR

Usage of gas turbines is completely unnecessary when FCS discharging is included. Again, as in G2S-NR mode, SEV and FCS are providing combined energy arbitrage service. Power generated by wind turbines is completely utilized and there is no wind curtailment. S2G-YR mode provides most of up reserve, while down reserve is provided by SEV, FCS and coal power plants.

IV. CONCLUSION

Detailed model for EV's impact on power system operation has been developed using mixed integer linear programming in Fico Xpress programing environment. Electric vehicle's charging has been observed as slow charging at home or work and as fast charging at fast charging stations. Both slow and fast charging are further classified into six charging modes depending on their ability to control their charging or reserve provision. One slow charging mode with strong implementation likelihood is used in this paper representing flexible (G2V-YR) mode. In G2V-YR mode slow charging is flexible enough to coupe with uncontrollable fast charging stations and wind power plants. Also, in both SEV operation modes, flexibility gained by allowed reserve provision is higher than flexibility gained by allowed discharging.

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