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Low carbon technologies as providers of operational flexibility in future power systems

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HIGHLIGHTS

- Mixed integer linear programming model for provision of multiple services from EV.
- EV energy and reserve services provision effects on power system operation.
- Impacts of conventional unit's decommission on system's operation and flexibility.
- Assessment of power system's flexibility under different wind generation polices.

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ABSTRACT

The paper presents a unit commitment model, based on mixed integer linear programming, capable of assessing the impact of electric vehicles (EV) on provision of ancillary services in power systems with high share of renewable energy sources (RES). The analyses show how role of different conventional units changes with integration of variable and uncertain RES and how introducing a flexible sources on the demand side, in this case EV, impact the traditional provision of spinning/contingency reserve services. In addition, technical constraints of conventional units, such as nuclear, gas or coal, limit the inherit flexibility of the system which results in curtailing clean renewable sources and inefficient operation. Following on that, sensitivity analyses of operational cost and wind curtailment shows which techno-economic constraints impact the flexibility of the high RES systems the most and how integration of more flexible units or decommission of conventional nuclear, coal and gas driven power plants would impact the system's operation. Finally, two different wind generation polices (wind penalization and wind turbines as reserve providers) have been analysed in terms of operational flexibility through different stages of conventional unit's decommission and compared with the same analyses when EV were used as reserve providers.

1. Introduction

Emerging integration of so called low carbon technologies (LCT), which are considered to be the essential link in creation of sustainable energy future, redefines operation and planning concepts of traditional energy systems. As the environmental goals of reducing CO_2 emissions drive the energy regulatory frameworks toward "all electric" systems by stimulating electrification of heat and transport, power system operators face the challenge of planning and operating increasingly variable and uncertain power systems [1]. While electric vehicles (EV) and, potentially, electrified heating (EH) act as sources of the variability and uncertainty from the demand side [2] integration of renewable energy sources additionally contributes to this from the supply side [3]. To alleviate the uncertain and variable nature of renewable energy sources (RES) new sources of flexibility become of critical value. Number of studies address the integration of different energy storage technologies (ES) [4–6] or demand response programs (DR) [7,8], but they rarely address the impact on power system operation planning and scheduling and how their integration impacts the existing generation units role in the system.

The capability of EV to participate in provision of energy arbitrage, ancillary services, as well as on their impact on distribution and transmission grid has gained much attention in recent literature. The authors in [9] proposed a multi-objective optimization model assessing the impact of EV on distribution grid, clearly showing how controlled charging in regards to uncontrolled brings benefits to daily distribution gird operation in multiple technical

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Nomenclature

Decision variables

$p_{t,i}^{g\_TP}$ thermal units generation
$p_{t,i}^{g\_HP}$ hydro units generation
$p_{t,i}^{g\_PS}$ pump storage generation/pumping
$p_{t,i}^{p\_PS}$ pump storage pumping
$p_t^{g\_WP}$ $p_t^{curt\_WP}$ wind power generation, wind power curtailment
$p_{t,i}^{c\_EV}$, $p_{t,i}^{d\_EV}$ electric vehicles slow charging/discharging
$p_{t,i}^{f\_EV}$ electric vehicles fast charging
$f_{t,i}^{up\_TP}$, $f_{t,i}^{dn\_TP}$, $r_{t,i}^{up\_TP}$, $r_{t,i}^{dn\_TP}$ thermal units primary(f)/secondary(r) up/down reserve provision
$f_{t,i}^{up\_HP}$, $f_{t,i}^{dn\_HP}$, $r_{t,i}^{up\_HP}$, $r_{t,i}^{dn\_HP}$ hydro units primary(f)/secondary(r) up/down reserve provision
$f_{t,i}^{up\_PS}$, $f_{t,i}^{dn\_PS}$, $r_{t,i}^{up\_PS}$, $r_{t,i}^{dn\_PS}$ pump storage primary(f)/secondary(r) up/down reserve provision
$f_{t,i}^{up\_EV}$, $f_{t,i}^{dn\_EV}$, $r_{t,i}^{up\_EV}$, $r_{t,i}^{dn\_EV}$ electric vehicles primary(f)/secondary (r) up/down reserve provision
$f_t^{up\_WP}$, $r_t^{up\_WP}$ wind turbines primary(f)/secondary(r) up reserve provision
$q_{t,i}^{up\_TP}$ thermal units tertiary up reserve provision
$c_{t,i}^{TP}$ total thermal power plant cost
$c_{t,i}^{HP}$ total hydro power plant cost
$c_t^{curt\_WP}$ wind power curtailment cost

Input parameters

P_t^d power demand
F_t^{up} primary up reserve requirements
F_t^{dn} primary down reserve requirements
R_t^{up} secondary up reserve requirements
R_t^{dn} secondary down reserve requirements
Q_t^{up} tertiary up reserve requirements
P_t^{WP} potential wind power generation
PF^{curt_WP} penalty factor for wind power curtailment
$R_t^{EV\_0.5h}$, $R_t^{EV\_4h}$ secondary and tertiary reserve requirements increase caused by uncontrolled EVs charging
$\sigma_t^{sl(0.5h)\_EV}$, $\sigma_t^{sl(4h)\_EV}$ EVs uncontrolled charging standard deviation for secondary and tertiary reserve
$\sigma_t^{(0.5h)\_WP}$, $\sigma_t^{(4h)\_WP}$ wind power standard deviation for secondary and tertiary reserve

Input parameters

Ni_TP number of thermal technology types
Ni_HP number of hydro technology types
Ni_PS number of pump storage technology types
Ni_EV number of electric vehicles types
σ^d power demand standard deviation
P^{gmax} the largest online unit in power system
Δt time period (0.5 h) for energy calculation
$S_i^{0\_EV}$ energy conserved in (all) EVs in time step zero

Abbreviations

CCGT combined cycle gas turbine
HPP hydro power plant
EPS electric power system
ES energy storage
EV electric vehicle
G2V grid-to-vehicle
HP hydro power
LCT low carbon technologies
MILP mixed integer linear programing
NPP nuclear power plants
OCGT open cycle gas turbine
PS pump storage
RES renewable energy sources
TP thermal power
TSC total system cost
TSE total system emissions
UC unit commitment
V2G vehicle-to-grid
WPP wind power plant

and economic aspects. Similar to [9], the authors in [10] provides detail analyses of EV grid impacts and suggest DSO grid investment to support EV integration in order to better manage daily grid operations. Stochasticity of EV connection to the grid has been studied in [11] by optimization model updating if unexpected EV disconnections occur. Aggregating multiple EV units in a single market participant, so called virtual power plant, and coordinating their operation with different renewable and conventional generation units for future energy scheduling is proposed in [12]. Combined effects of high RES and EV integration is also analysed in [13] with different EV types and charging strategies emphasizing mutual benefits in scenarios with higher wind penetration. Improved utilization of wind and solar power, through flexible coordinated charging of EV has been discussed in [14] along with sensitivity analyses of different input parameters. Using EV as frequency controllers is proposed in [15] where it has been shown that EV can help utilize more variable RES by provision of frequency control. Automatic generation control (AGC) requirements are rapidly increasing with the uptake of RES, therefore, paper [16] proposes coordinated EV and battery storage frequency regulation supporting todays conventional frequency regulation providers. A novel s tochastic–probabilistic energy and reserve market clearing scheme is proposed in [17], modelling plug-in vehicles (PEV) though a new market subject, a PEV aggregators. A bi-level optimization algorithm based on multiagent systems and dynamic game theory was developed in [18], modelling the oligopoly energy and reserve market. Authors in [19] use both EV and EH to improve efficiency of system and to allow higher integration of RES. Benefits of inteligent control of EV is researched in [20], where focus is put on analysing if EV can be used to substitute cross border capacities. Interesting review of EV technology's benefits and impediments can be found in [21–23]. As it can be seen from the above the topic of EV has been in focus in recent years, analysing its pros and cons from different perspectives, jointly concluding capability of EV to act as a provider of new flexibility will be one of key factors in determining the share of variable renewable sources in future power systems. However, it needs to be mentioned that none of the papers above elaborates how behaviour of conventional units changes taking into account both energy and reserve unit commitment plans. This paper provides a comprehensive analysis of EV as provider of spinning reserve services in future low carbon systems.

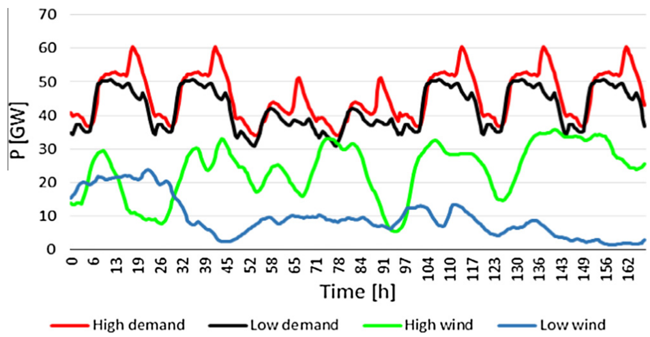

Fig. 1. Demand and wind profiles for a period of one week.

A number of models have been proposed for simulation of power system operation, in order to assess the power system operational flexibility. These mathematical models, called unit commitment schedules (UC), are most commonly based on Lagrangian relaxation [24] or more currently on mixed integer linear programing (MILP) [25], also modelling variability and uncertainty of both demand and supply by including stochasticity of wind, demand and market prices [26–28]. The model presented in this paper is based on a technique of clustering similar units, for example gas, coal and nuclear; this approach has been shown to significantly increase the computational speed of simulations [29–31] without losing on the accuracy of the results. Similar approach, simulating impact of EV integration on multiple interconnected systems can be found in [32,33]. The presented model is a continuation of work presented in [34] where the authors focus on how integration of controllable electric vehicle charging impacts the provision of secondary reserve services for various power systems with regards to the energy mix. In this paper, however, the focus is on three different analyses:

- *Flexibility contribution of LCT technologies (EV, ES and DR) through both energy and reserve services:* LCT technologies contribute to flexibility of future power systems characterized by high share of renewable sources. The results of the model clearly show how roles of traditional generation units in providing multiple services (energy and multiple reserve services) change with the integration of these technologies, specifically focusing on the role of EV.
- *Impact of traditional units decommission on future power system:* With respect to the above, the model demonstrates how decommission of traditional units impacts the flexibility of the future power system. In particular, this part focuses on redistribution between traditional and LCT sources for provision of energy and reserve services.

Table 2
Input values and constraints of EV.

Input parameter		Personal vehicle
P_{min} (kW)		0.2
P_{max} (kW)		2
S_{min} (kW h)		4
S_{max} (kW h)		20
S_{minc} (kW h)		20
η_c, η_d		0.95
P_{fmax} (kW)		50
Range (km)	Short	20
	Medium	40
	Long	80
Consumed energy per trip (kW h)	Short	4
	Medium	8
	Long	16
Percentage of EVs type and range in total number of EVs	Short	82%
	Medium	10%
	Long	8%

- *Comparison of LCT technologies and different wind policies as flexibility providers:* The last aspect of the paper focuses on single week power system operation with respect to the above decommission scenarios, analysing different wind power plant (WPP) policies. In particular it focuses on the system operation in cases of: (a) penalized wind curtailment and (b) using WPP as secondary reserve providers.

The above issues are, up to a certain point, a research topic in a number of papers, see for example [35], however with several very important differences. In [36,37] the authors define the flexibility through minimum stable generation (MSG) of the power system as metric critical for integration of large scale wind. In [36] a metric is proposed for defining the amount of wind that can integrated without curtailment, however it focuses only on the value of MSG, neglecting the ramping and other relevant technical constraints such as minimum up and down times of units being scheduled. In addition, neither of the papers elaborates on the mathematical models used to study the flexibility or elaborates on multiple services assigned/scheduled to particular units. A number of papers [38–40] propose pathways for achieving high RES integration, however they are not based on mathematical modelling nor do they focus on provision of flexibility services from specific technologies. On the other hand, [41,42] model provision of multiple services but do not focus on flexibility and integration of RES rather on reliability aspects of power system operation and reduction of CO_2 emissions. In [43,44] the authors propose a rolling UC for planning of future power systems. The focus of the work is on technical and economic constraints of the

Table 1
Input values and constraints of fossil fuel driven generation units.

Technology	P_{min} (MW)	E_{l1} (MW)	E_{l2} (MW)	P_{max} (MW)	C_{nl} ($/h)	C_{in1} ($/MW h)	C_{in2} ($/MW h)	C_{in3} ($/MW h)	C_{st} ($)	C_{sh} ($)	T_{up} (h)
Nuclear	400	400	400	400	260.86	12.093	12.663	13.233	750	75	16
Coal	140	210	280	350	199.43	17.0805	17.3955	17.7105	450	45	8
CCGT	68.9	111.6	154.3	197	359.48	35.3535	35.6865	36.0195	300	30	5
OCGT	4	9.3	14.7	20	176.92	56.937	57.1545	57.3735	46	4.6	0.5
	T_{dn} (h)	V_{up} (MW/h)	V_{dn} (MW/h)	P_0 (MW)	N_0	RHO_{up}	RHO_{dn}	F_{iup} (MW)	F_{idn} (MW)	Emiss. ($kgCO_2$/MW h)	Start emiss. rate ($kgCO_2$)
Nuclear	10	50.5	100	12.000	30	0.5	0.5	40	40	0	0
Coal	5	70	120	10.500	30	0.4	0.4	35	35	925	25.000
CCGT	4	55	99	0	0	0.6	0.6	19.7	19.7	394	8000
OCGT	0.5	30.5	70	0	0	0.7	0.7	2	2	600	3000

system for future wind scenarios. With respect to that they propose a flexibility metric for planning high RES system energy mix, taking into account MSG and ramping constraints of existing and new units. Similar idea can be found in [45] where the author analyses impact of relaxing UC constraints on the accuracy of the results in UC scheduling. Neither of these two papers considers EV nor their contribution to the flexibility services in integration of RES. Finally, in [46] the authors evaluate impact of electric vehicles on future energy portfolio. The impact of coordinated charging of electric vehicles is assessed for multiple countries where EV are controlled in order to increase the flexibility by providing energy arbitrage. None of the multiple reserve services are specifically considered.

The MILP model of UC presented in this paper is unified in terms that it allows the above mentioned analyses for different energy mix power systems, ranging from low flexible nuclear dominated power system, such as the one in UK, to highly flexible hydro dominated power system, similar to the one in Croatia. It models multiple reserve services, primary, secondary and tertiary, as in [47,48], and focuses on the impact integration of EV will have on the role of existing units in future high RES scenarios.

The paper is organized as follows: In Section 2 detailed explanation of the MILP model of multiple service UC is given. Modelling of EV is based on mobility patterns and considers different vehicles sizes and batteries on board of the vehicles. Although EV can be scheduled for provision of multiple services, in Section 3 an analysis of spinning reserves is given through different scenarios of wind and EV penetration. Section 4 further analyses the flexibility of the system in the presence of EV and wind, analysing how different decommission stages impact system's flexibility. Section 5 observes system operation through one week and changes due to decommission for different wind turbines policies (penalizing wind curtailment and using wind as reserve provider). Finally, Section 6 provides conclusions and guidelines for future work.

2. Multiple service unit commitment (MSUC) modelling

The presented model is similar to the one presented by the authors in [34], however for easier understanding it will be again elaborated in the following section.

The objective function driving the power system operation is minimization of the operational costs from all units providing energy and reserve services to the system, as shown in (1). The objective function models all operational costs of thermal (start-up, shut-down, fuel, O&M, greenhouse gas emissions) and hydro (O&M) units, linearizing fuel consumption curve of thermal power plants as in [49,50].

$$minimizeCOST = \sum_{t=1}^{Nt}\left[\sum_{i=1}^{Ni\_TP}\left(c_{t,i}^{\_TP}\right) + \sum_{i=1}^{Ni\_HP}\left(c_{t,i}^{\_HP}\right)\right] \quad (1)$$

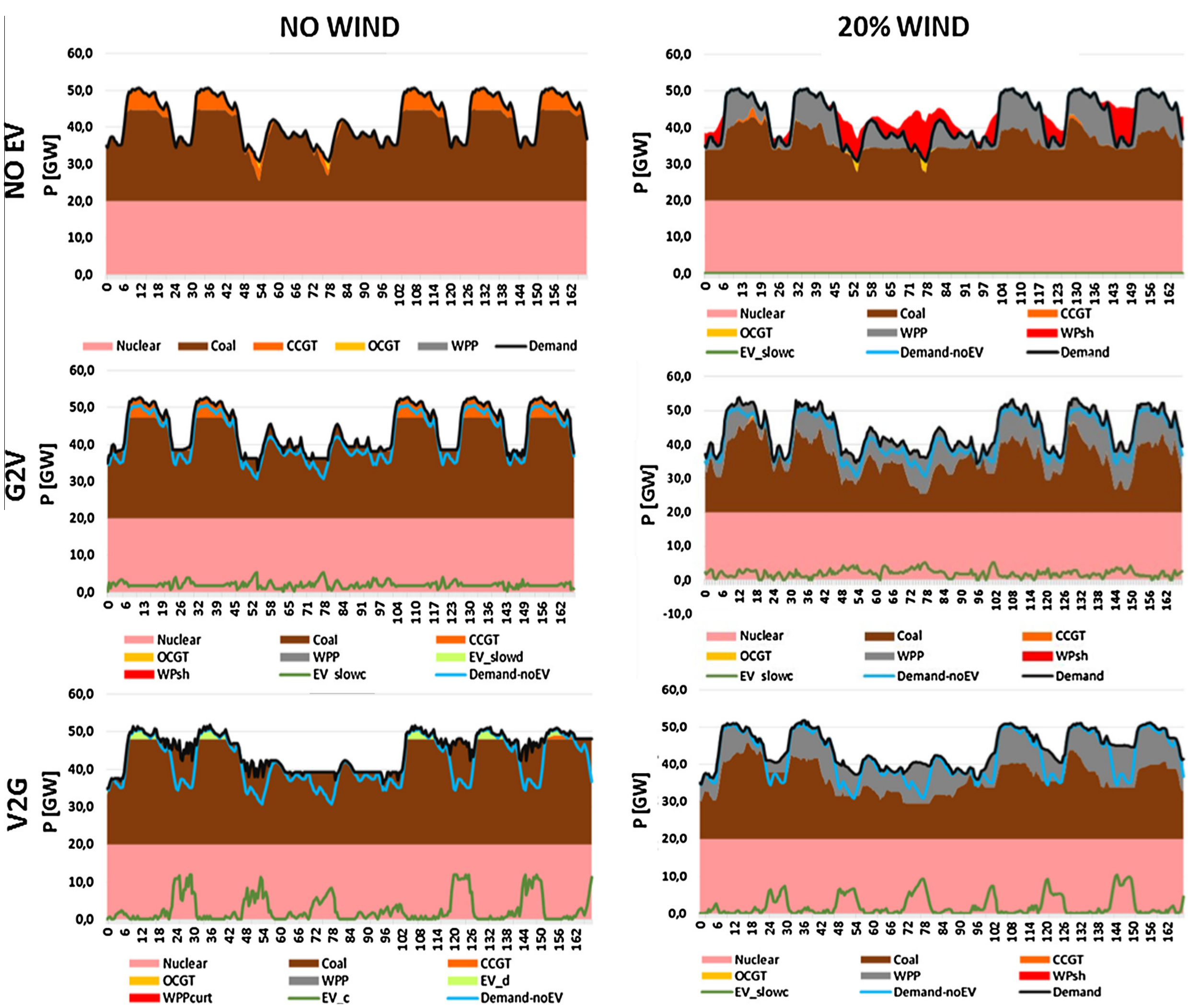

Fig. 2. Energy service scheduling in different wind and EV scenarios.

Electricity equilibrium has to be maintained in all simulation periods, meaning that the total generation from all units in the system has to be equal to the total demand as shown in Eq. (2). Left side of the equation summarizes the production of all generation units considered; conventional units (since the model is unified, these can be thermal – p^{g_TP}, hydro – p^{g_HP}, generation from hydro pump storage unit – p^{g_PS}), RESs (wind – p^{g_WP}), storage (in this paper pump storage pumping – p^{p_PS}; is considered as storage technology) with added EVs discharging (p^{d_EV}), charging (p^{c_EV}) and fast charging (p^{f_EV}). The right side of the equation models electric demand (P^{d}). For the case of UK power system, taken as an example of low flexible power system driven by thermal power plants, demand and wind profiles are shown in Fig. 1 [51]. Additional data about UK power system used can be found in [52].

$$\sum_{i=1}^{Ni\_TP}\left(p_{t,i}^{g\_TP}\right)+\sum_{i=1}^{Ni\_HP}\left(p_{t,i}^{g\_HP}\right)+\sum_{i=1}^{Ni\_PS}\left(p_{t,i}^{g\_PS}-p_{t,i}^{p\_PS}\right)+p_{t}^{g\_WP}-\sum_{i=1}^{Ni\_EV}\left(p_{t,i}^{d\_EV}-p_{t,i}^{c\_EV}-p_{t,i}^{f\_EV}\right)=P_{t}^{d} \quad (2)$$

The reserve requirements of the system are modelled by (3)–(7). Multiple reserve services are modelled; primary up reserve (f_{up}), primary down reserve (f_{dn}), secondary up reserve (r_{up}), secondary reserve down (r_{dn}), tertiary up reserve (q_{up}). The primary reserve can be provided by all units, as shown in (3) and (4), however technical limitations of the power plants usually mean that power plants participate with about 10% in the primary frequency provision. Modelling primary frequency response is based on the model in [53]. Primary reserve value that needs to be reserved for the size of the system simulated, both up and down, is set to 1.9 GW as in [51,53].

Secondary reserve can again be provided by all units in the system, conventional and EV. Although EV could also participate in tertiary reserve, due to their capability of reacting to fast system changes, they are considered only for spinning reserve service provision (primary and secondary reserve).

$$\sum_{i=1}^{Ni\_TP}f_{t,i}^{up\_TP}+\sum_{i=1}^{Ni\_HP}f_{t,i}^{up\_HP}+\sum_{i=1}^{Ni\_PS}f_{t,i}^{up\_PS}+\sum_{i=1}^{Ni\_EV}f_{t,i}^{up\_EV}\geqslant F_{t}^{up} \quad (3)$$

$$\sum_{i=1}^{Ni\_TP}f_{t,i}^{dn\_TP}+\sum_{i=1}^{Ni\_HP}f_{t,i}^{dn\_HP}+\sum_{i=1}^{Ni\_PS}f_{t,i}^{dn\_PS}+\sum_{i=1}^{Ni\_EV}f_{t,i}^{dn\_EV}\geqslant F_{t}^{dn} \quad (4)$$

$$\sum_{i=1}^{Ni\_TP}r_{t,i}^{up\_TP}+\sum_{i=1}^{Ni\_HP}r_{t,i}^{up\_HP}+\sum_{i=1}^{Ni\_PS}r_{t,i}^{up\_PS}+\sum_{i=1}^{Ni\_EV}r_{t,i}^{up\_EV}\geqslant R_{t}^{up} \quad (5)$$

$$\sum_{i=1}^{Ni\_TP}r_{t,i}^{dn\_TP}+\sum_{i=1}^{Ni\_HP}r_{t,i}^{dn\_HP}+\sum_{i=1}^{Ni\_PS}r_{t,i}^{dn\_PS}+\sum_{i=1}^{Ni\_EV}r_{t,i}^{dn\_EV}\geqslant R_{t}^{dn} \quad (6)$$

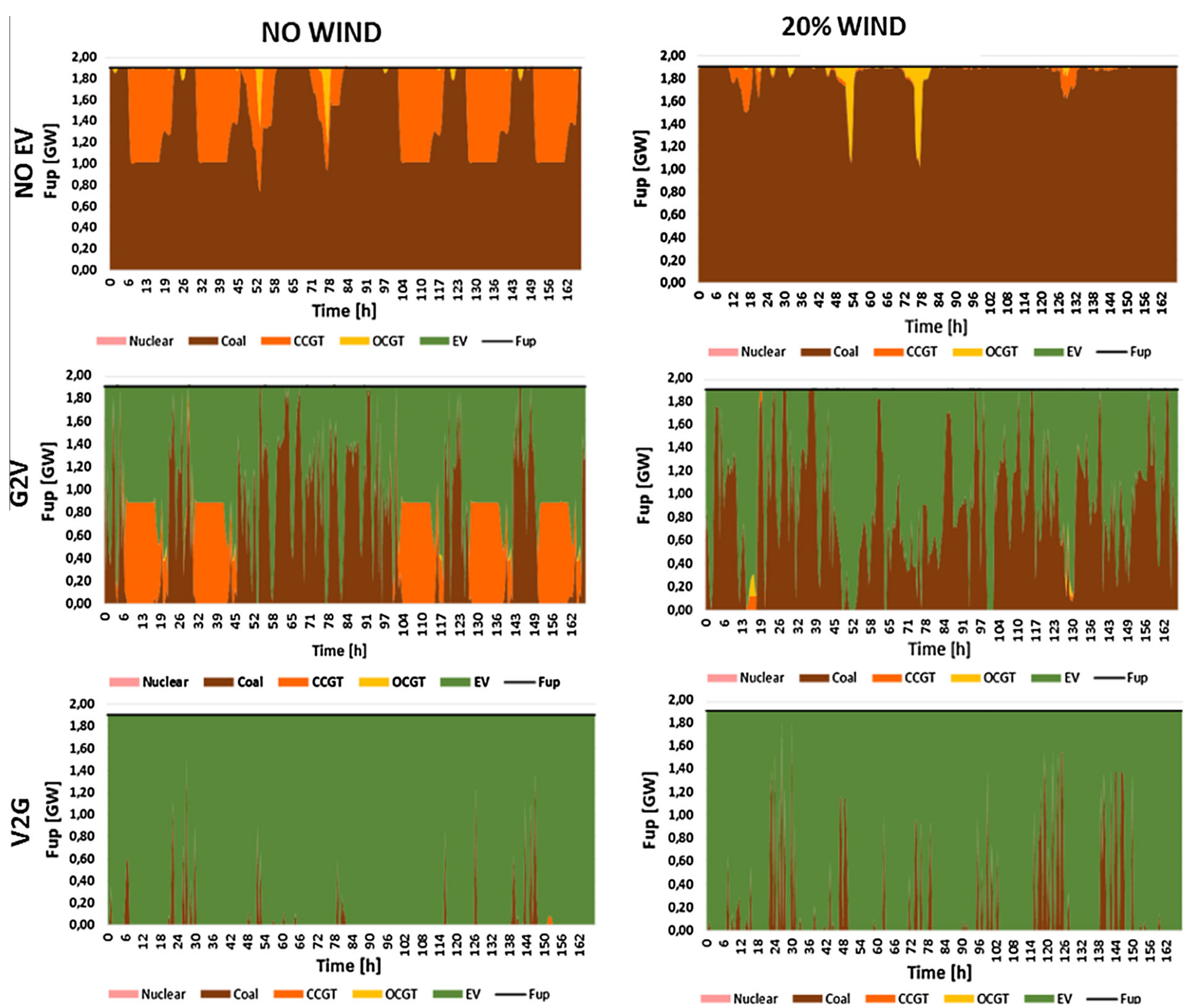

Fig. 3. Results of scheduling primary frequency reserve service in different wind and EV scenarios.

$$\sum_{i=1}^{Ni\_TP} q_{t,i}^{up\_TP} \geqslant Q_t^{up} \tag{7}$$

Secondary and tertiary reserve values are defined as time vectors depending on the electrical demand (taking into account variability of demand through standard deviations of load forecast σ^{d}), wind power production (taking into account uncertainty and variability of wind generation modelled as standard deviation of wind forecast $\sigma^{(0.5h)\_WP}$ and $\sigma^{(4h)\_WP}$) and EV's as well as the outage of the largest generating unit P^{gmax}. Uncontrollable charging of EV's results in increase of the secondary and tertiary reserve requirements. This is modelled as a fixed value, describing uncertain nature of EV arrival and battery SOC through parameters $R^{EV\_0.5h}$ and R^{EV_4h}. In this paper only controlled (G2V and V2G) charging is observed so parameters $R^{EV\_0.5h}$ and R^{EV_4h} are equal to zero. It should be noticed that both upward and downward reserve have been modelled. Modelling of secondary and tertiary reserve is similar to that in [44] and described by (8)–(12):

$$R_t^{EV\_0.5h} = \sum_{i=1}^{Ni\_EV} \left(3.5 * \sigma_t^{sl(0.5h)\_EV} * P_i^{max\_EV} * \sum_{\tau=t}^{t(-C_i^{UCH\_EV}+1)} N_{\tau,i}^{arr\_EV} \right) \tag{8}$$

$$R_t^{EV\_4h} = \sum_{i=1}^{Ni\_EV} \left(3.5 * \sigma_t^{sl(4h)\_EV} * P_i^{max\_EV} * \sum_{\tau=t}^{t(-C_i^{UCH\_EV}+1)} N_{\tau,i}^{arr\_EV} \right) \tag{9}$$

$$R_t^{up} = \sqrt{\left(3 * \sigma^{d} * P_t^{d}\right)^2 + \left(3.5 * \sigma_t^{(0.5h)\_WP} * P_t^{WP}\right)^2 + \left(R_t^{EV\_0.5h}\right)^2} + P^{gmax} \tag{10}$$

$$R_t^{dn} = \sqrt{\left(3 * \sigma^{d} * P_t^{d}\right)^2 + \left(3.5 * \sigma_t^{(0.5h)\_WP} * P_t^{WP}\right)^2 + \left(R_t^{EV\_0.5h}\right)^2} \tag{11}$$

$$Q_t^{up} = \sqrt{\left(3 * \sigma^{d} * P_t^{d}\right)^2 + \left(3.5 * \sigma_t^{(4h)\_WP} * P_t^{WP}\right)^2 + \left(R_t^{EV\_4h}\right)^2} + P^{gmax} \tag{12}$$

As mentioned in the introduction, similar approach to modelling can be applied to both energy storage systems and demand side technologies, such as electrified heating (EH). In general, both EV and EH can be modelled as variable capacity energy storage providing both energy arbitrage and reserve provision. While EV energy storage capacity depends on driving behaviour and EV charging mode, variable capacity energy storage of EH depends on heat demand of the consumers, capacity and size of heat storages (if it exists) and the comfort required by the final consumer. In this context, energy consumed by EV for driving between two adjacent periods is analogue to energy consumed by EH for heating (with the difference of efficiency factors, which are of course different). Although the main idea can appear the same, there are several important differences defining the availability and the amount of different system services. However, the logic used in the above

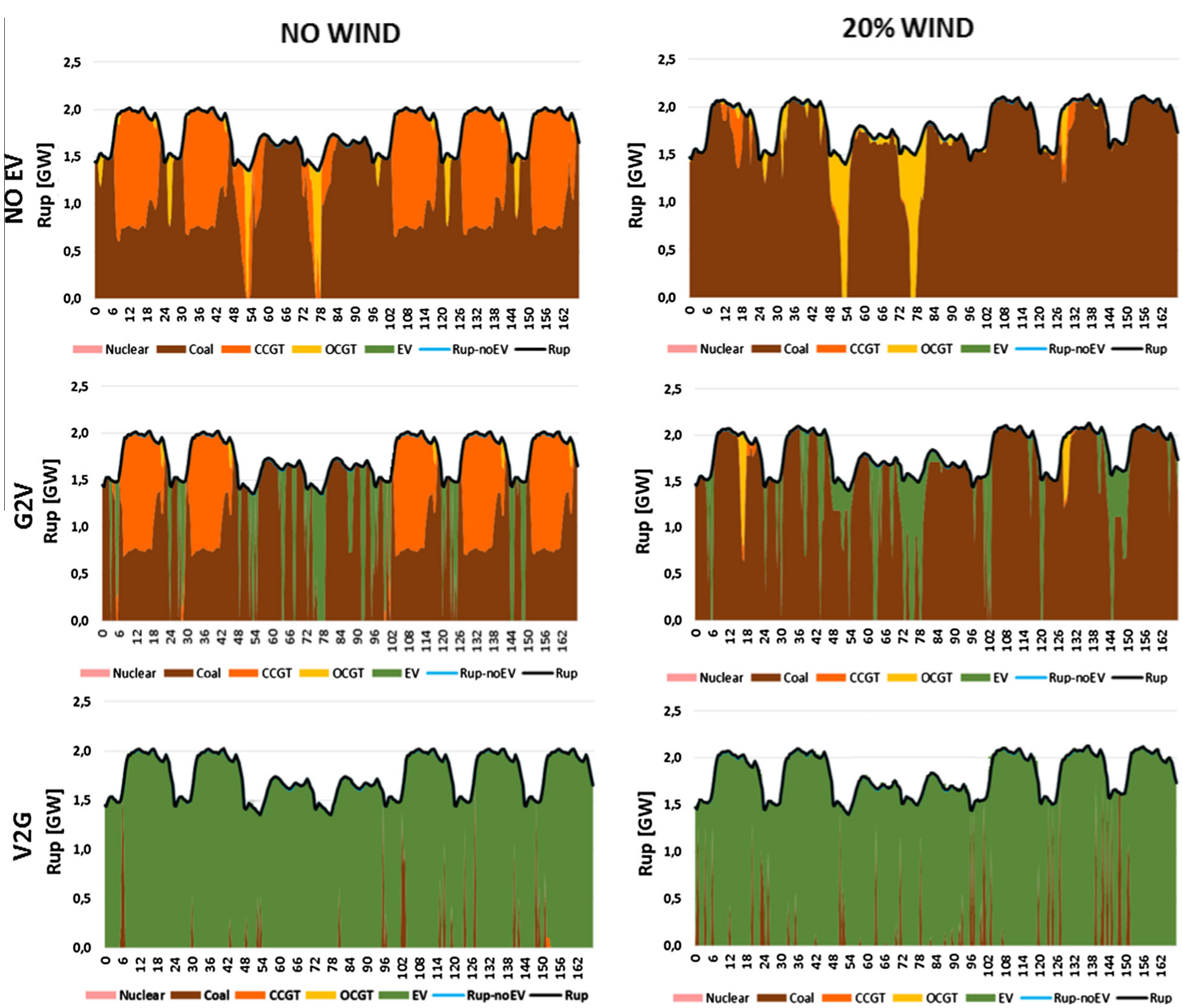

Fig. 4. Results of scheduling secondary frequency reserve service in different wind and EV scenarios.

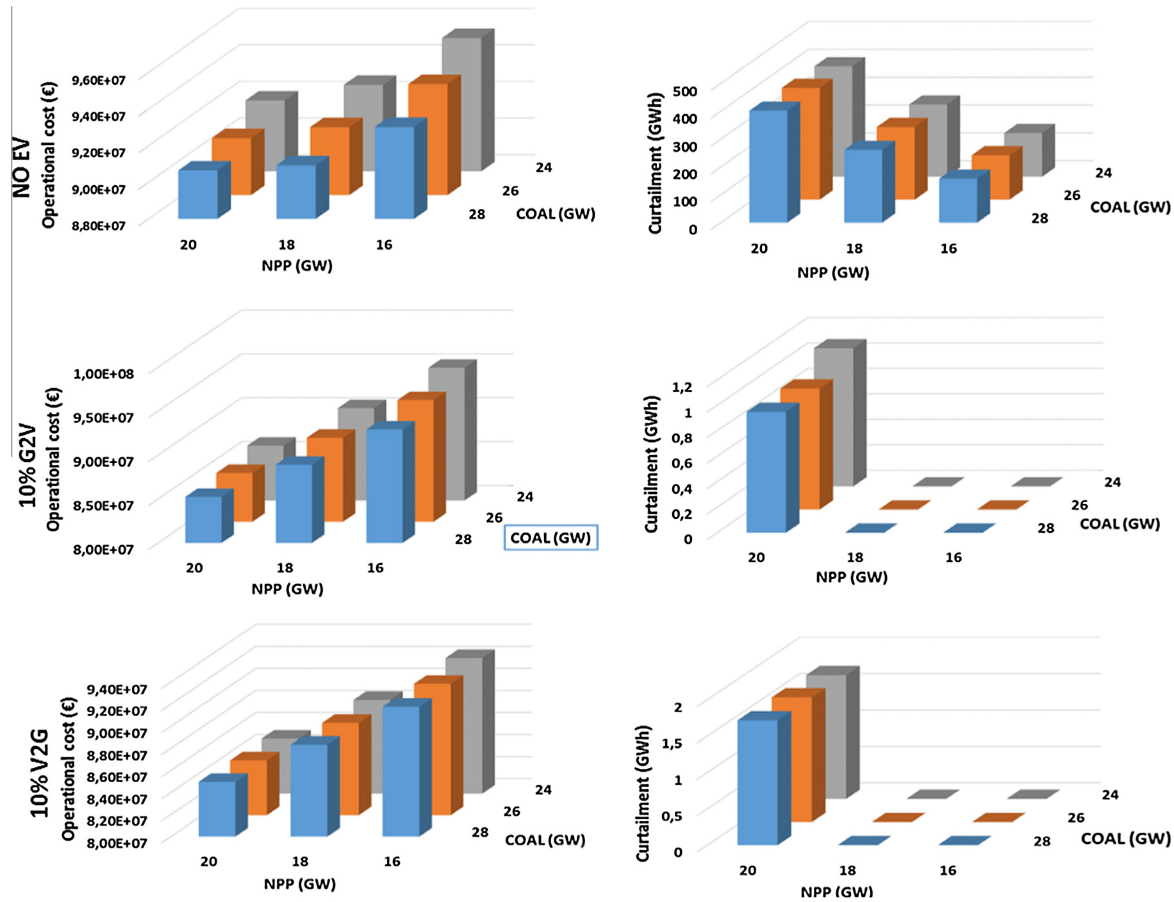

Fig. 5. Power plant decommission analysis in power system with 20% wind energy.

EV model can be applied to the electrified heating flexibility provision analyses by adjusting specific constraints and input parameters.

Modelling technical limitation of fossil fuel based power plants is taken from recent publications [54–56] where thermal units are subjected to the following constraints: power generation constraints (piece-wise linear cost curve), minimum up and down times, ramping constraints, reserve provision constraints (primary, secondary and tertiary), greenhouse gas emissions (included as additional cost in objective function). In addition, hydro power plants are modelled similar to the models in [57,58]. Details on input parameters of power plants is given in Table 1.

Mathematical models of all possible EV operational regimes are shown in [34] where 6 different concepts are presented, depending on controllability of EV and number of services these units provide. In this paper only a description of selected operating regimes used in the simulations is provided for understanding specific charging/discharging concept. In this paper only controllable charging is considered where EV provide multiple services (energy and reserve). This controllable charging can be G2V (vehicles are "only" controllably charged) or V2G (vehicles can be controllably discharged, injecting electricity back to the system and providing additional value). Once again, only 2 out of 6 EV regimes are selected for the purpose of simulations in the following Sections:

- Controlled Grid-to-Vehicle charging with possibility to provide reserve, both upward (additional electricity for charging) and downward reserve (not charging EV) – G2V.
- Controlled Vehicle-to-Grid charging with possibility to provide reserve, both upward (additional electricity for charging) and downward reserve (discharging EV) – V2G.

Input values and constraints for EV modelling are given in Table 2.

Wind power plants as variable renewable source are modelled with following equation, where right side corresponds to maximal wind power at particular moment and left side is composed of actual wind power produced and wind power curtailed.

$$p_t^{g\_WP} + p_t^{curt\_WP} = P_t^{-WP} \quad (13)$$

3. Weekly operational analyses

To define how the role of specific unit changes in systems with high wind penetration, weekly analyses of the system operation are run for several relevant scenarios. The focus is put on provision of energy as well as primary and secondary reserve, including participation of EVs in all these services. Two scenarios are further analysed for 3 different EV cases, one with no wind integrated in the system and one where installed wind power is 20% of total power demand:

– No electric vehicles integrated.
– G2V scenario: Electric vehicles can only be charged, meaning they act as controllable loads providing both energy and upward and downward reserve services.

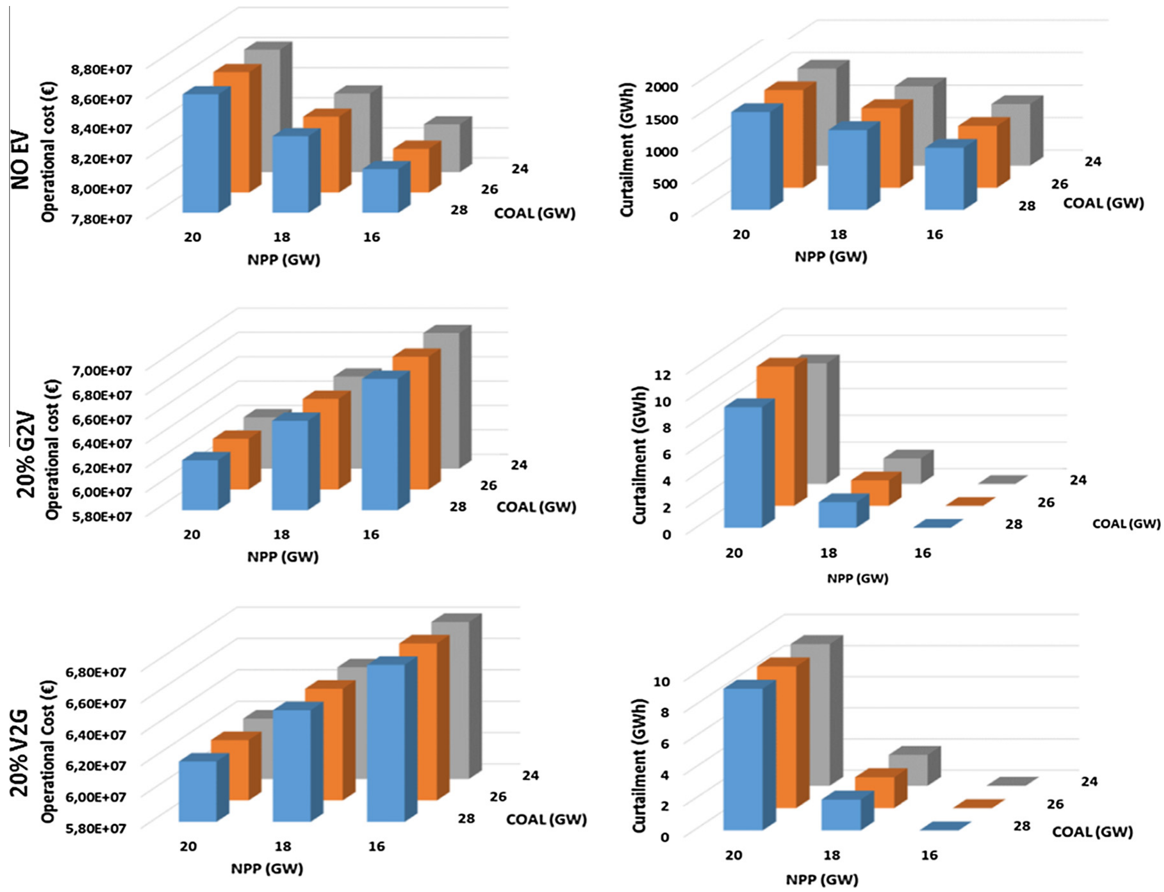

Fig. 6. Power plant decommission analysis in power system with 40% wind energy.

– V2G scenario: Electric vehicles can be both controllably charged and discharged providing both energy and upward and downward reserve services.

Fig. 2 shows the results of power system dispatch for a period of one week, in particular which units provide energy service over 6 analysed cases. The layout of the figure enables comparing both the impact of wind integration and the impact of EV flexibility on provision of multiple services.

Looking at the first two scenarios, where EVs are not included in provision of flexibility services (first "row" of Fig. 2), it can be seen that the current system is not flexible enough and, to maintain the security of supply, wind is curtailed. Alongside wind curtailment, changes in coal and gas thermal plants behaviour can be noticed when wind takes part in providing energy. The most expensive gas turbines are shut down and their former production is now substituted by wind. Wind integration reduces operating periods of gas power plants to only two cases: when demand is high and wind is low (insufficient generation requires starting up of CCGT units) and when demand is low and wind production is high. Already in G2V mode wind curtailment is eliminated (as can be seen in second row of Fig. 2). In G2V mode EV charging is uniformly distributed (both in case with wind and without wind) since EVs are used for reserve provision. On the other hand, in V2G mode and no wind, EVs takes on the role of fast responding units covering daily peak demand.

Fig. 3 shows the provision of primary frequency response (PFR) for all of the above 6 scenarios. It should be noted that integration of wind does not directly affect the amount of primary reserve required, however due to different dispatching of the conventional units which provide secondary and tertiary reserve service, provision of PFR is assigned to the different units. Since EV have, due to their technical characteristics, the capability to respond to fast changes, the role of providing PFR switches from classical thermal units (coal and CCGT) to electric vehicles with the integration of EV and wind, in particular in cases where they can be controllably charged and discharged (V2G case). This mitigation of PFR service means more efficient thermal units operation and reduction of expensive units' start-ups (e.g. CCGT, see Table 2), resulting in lower system operational cost.

Provision of secondary frequency reserve service (SFR) from specific units, is shown in Fig. 4, for all the above described scenarios of wind and flexible EV integration. Similar to PFR, EV take over the role in providing SFR from expensive CCGT units and, in case where they can provide additional flexibility by discharging, coal units.

To summarize; by integrating wind, gas driven units are initially substituted by that of coal. Gas units are taking the role of standing reserve, since they are the most expensive ones, and, since primary and secondary reserve needs to be provided by spinning units, coal units take on the role of providing PFR and SFR. Furthermore, in case when EVs have the capability to both charge and discharge (V2G regime) they cover over 95% of PFR and SFR needs in the system while conventional units solely provide energy and tertiary reserve service.

4. Impact of different units in future flexible power systems

Integration of renewable energy sources are often put in the context of replacing conventional units such as high carbon intensity coal and low flexible nuclear power plants. Several strategies

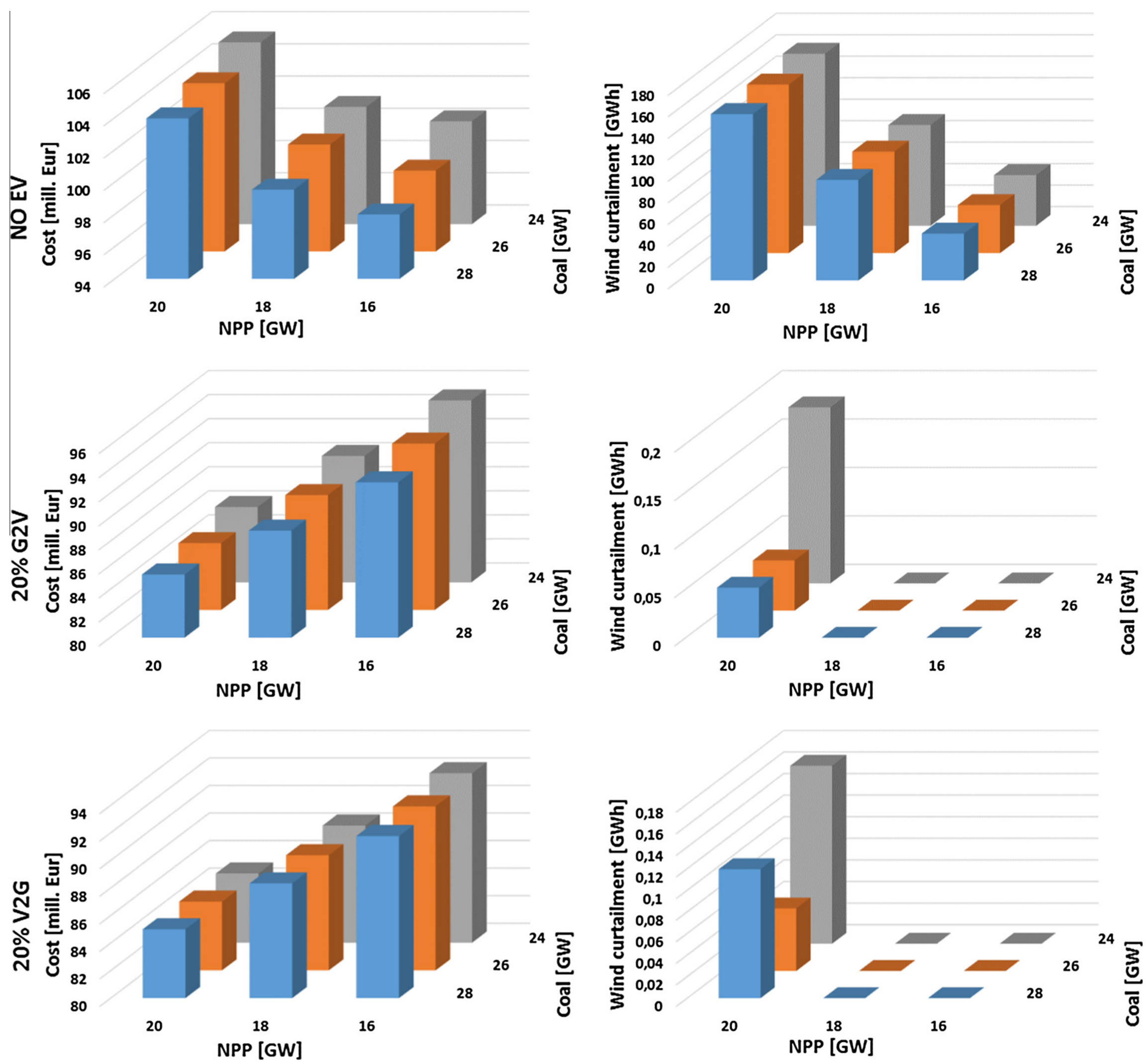

Fig. 7. Power plant decommission analysis in power system with 20% wind energy and curtailment penalty.

even suggest that these units should be decommissioned and that RES and LCT will take on their role in the power system. However, very little research has been done on how such actions reflect on total system operational cost and system's flexibility. In this paper insufficient flexibility is expressed as the curtailed wind energy. In the following Section a detailed analysis is provided answering these questions.

Governments worldwide made a decision to decommission or to rely less on nuclear energy, particularly after the Fukushima incident in 2011. In addition, national greenhouse gas goals suggest shutting down coal power plants. The main idea of this Section is to analyse how decommissioning of conventional low flexible power plants, in case coal and nuclear, reflects on system operational cost and wind curtailment. It has been shown in Fig. 2 that nuclear power plants serve as base load units and are not scheduled for provision of reserve services nor for load following. Although NPP have the flexibility to ramp and respond to variability of the system, they are, for security reasons, operated either on their maximum power, at their minimum stable generation point (MSG) or they are offline. It should be noted that once NPP is shut down it takes between 24 and 48 hours to start it back again; each NPP start-up is expensive and these actions are thus avoided if possible. Although a bit more flexible, coal power plants, once shut down, cannot be put online for the next 4–6 h (depending on the level of shut down; hot, warm or cold).

Fig. 5 shows the results and the effects of decommissioning coal and NPP for the same scenarios as in the previous Section. A general conclusion can be made that, by decommissioning either coal or NPP, curtailment of wind is reduced and total systems operational cost increases. Although the last statement might seem a bit contradictory, decommissioning of low flexible units in fact reflects in changing the role of conventional units. In fact, with the decommission of inflexible units (coal and NPP) highly flexible, but expensive, gas units (CCGT and OCGT) take on the role of energy provision and due to their higher flexibility they are capable to follow fast wind power generation alternations. Since wind curtailment is decreased (due to the increase in systems flexibility) and more "free" wind power is supplied to the customers, the total systems operational cost should decrease. However, the higher cost result should not be observed only through the shift of energy being provided from wind and gas instead of coal and NPP, but also through different scheduling of spinning reserve. As the number of NPP and coal units decreases this consequently results in less available coal base power plants for providing reserve services. This "void" is in particularly noticeable in reserve up provision, where gas units take the role of reserve provider.

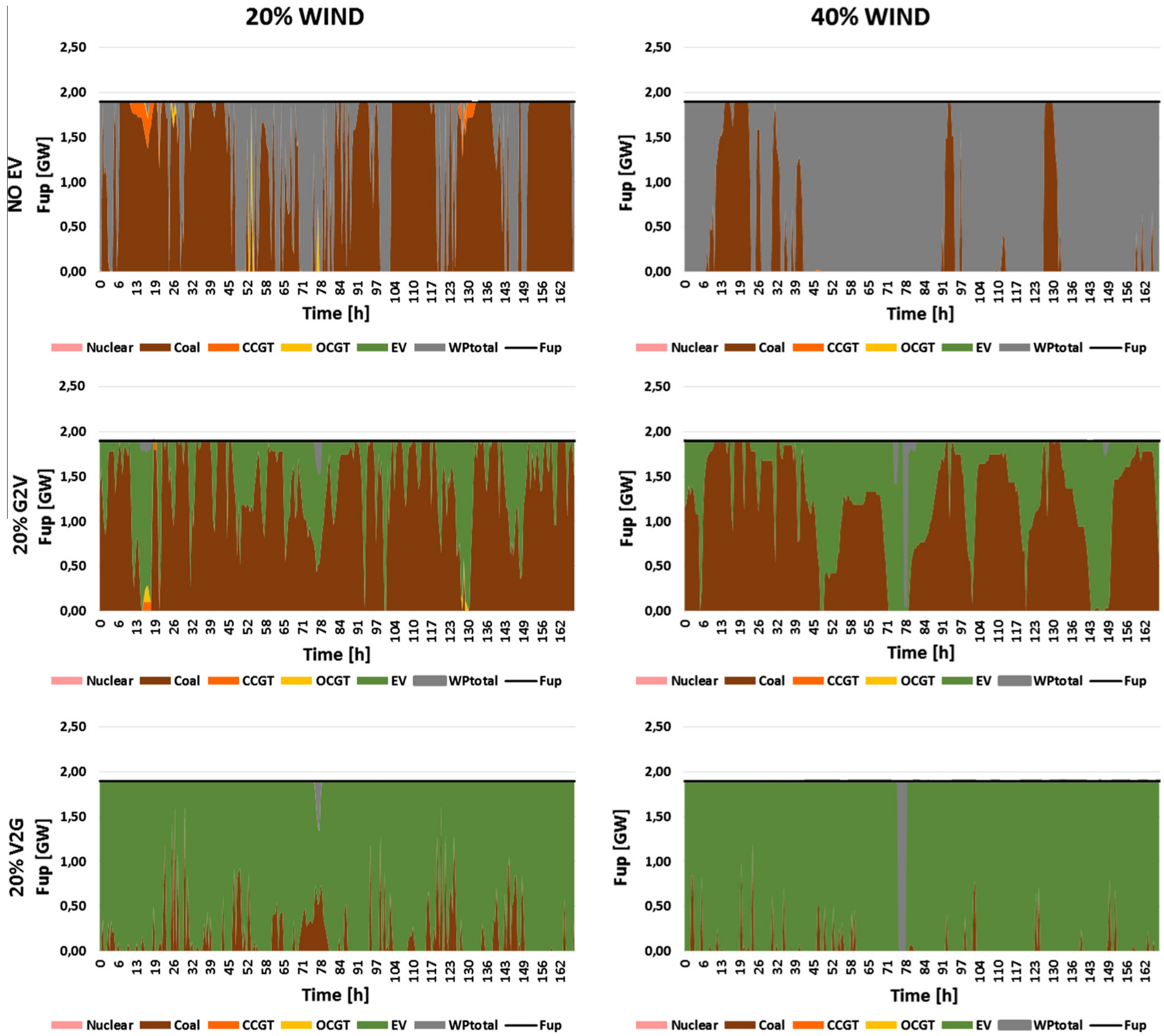

Fig. 8. Results of scheduling primary frequency reserve service in different wind and EV scenarios (with wind turbines reserve provision).

As in previous scenarios, integration of controllable EV charging results in significant wind curtailment reduction (300 times lower than without EV). The most significant change in scenarios with flexibility provided from G2V is in reserve down provision, which is now completely provided by controllable EV for all analysed decommission scenarios. Additional provision of flexibility by deploying V2G capability is manifested through lower total operational cost than in previous scenarios; the role of other units remain the same.

The same analyses are conducted for an even larger penetration of wind, doubling the share of wind power to 40%, and the results are shown in Fig. 6.

By decommissioning low flexible NPP and coal the curtailed wind energy is significantly reduced, which directly impacts the operational cost. Gas turbines are, similarly as in previous Section, used for load following and peak covering (mainly CCGT units) as well as during periods when reserve cannot be entirely provided by operating coal power plants (in those cases fast responding OCGT units start up).

Integration of controllable EV additionally reduces wind curtailment by a margin of 1000. In addition, similar as in 20% wind scenario, operational cost increases when non flexible units are decommissioned. High wind penetration changes operational regime of coal power plants by increasing their number of start-up times and forcing them to more frequently ramp in both directions, which leads to lower efficiency of these units.

A general conclusion can be made that by decommissioning NPP and coal units the system flexibility increases, completely eliminating wind curtailment. However, and this in particular is valid for NPP, decommissioning the low cost base load units means that more expensive gas driven units take on the role of providing both energy and reserve services, cycling and increasing the number of their start-ups. This in turn results in total operational cost increase.

5. Wind power plants as flexibility providers

In previous Sections wind curtailment is regarded as an indicator of insufficiently flexible system and it has not been not penalized, similar to the model in [35]. The literature proposes two approaches: penalizing wind curtailment and not penalizing, each with its pros and cons. On one hand high cost assigned to wind energy not utilized creates large operational cost spikes and indicates inflexibility, however it sets the operating points of power plants to unlikely states (in reality, wind generation would be curtailed if this favoured the security and economy of the system operation). On the other hand, avoiding to penalize wind not used

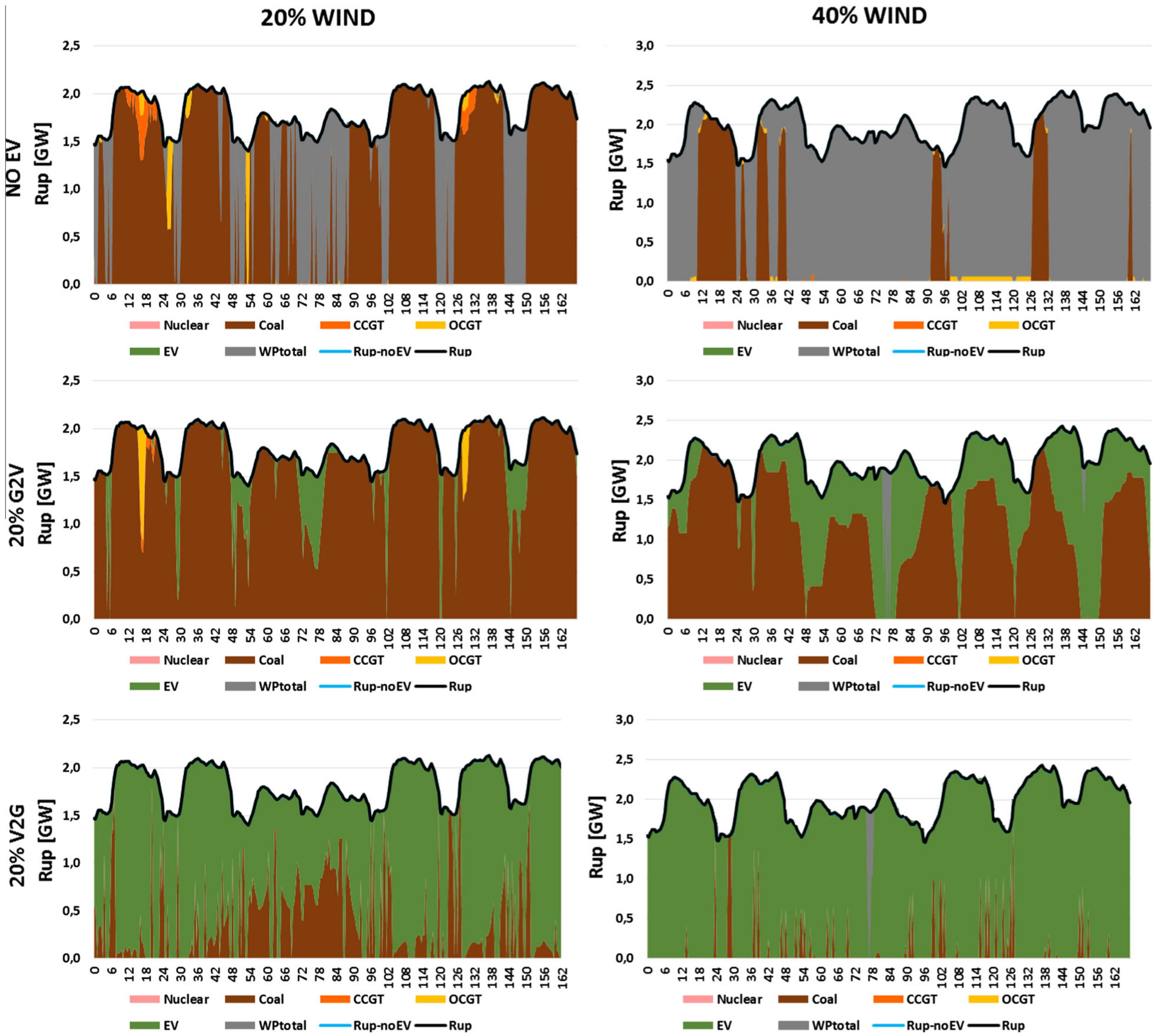

Fig. 9. Results of scheduling secondary frequency reserve service in different wind and EV scenarios (with wind turbines reserve provision).

might result in overestimating the share of wind being curtailed in low flexible systems as the one analysed in this paper.

A lot of research has been done over past few years in order to reduce or even eradicate wind curtailment [59–63]. Following this research the focus of the Section will be on two most likely roles wind power plants will have in the future: (i) wind curtailment as an indicator of inflexibility and penalized as in [64] and (ii) wind used for upward reserve provision as in [65]. For the first approach a new variable is added to the objective function, $c_t^{curt\_WP}$, which denotes curtailed wind energy at every moment; this energy is multiplied with penalty factor (PF^{curt_WP} = 46.7 €/MW h). New objective function, including new curtailment cost function, is represented with Eqs. (14) and (15), respectively.

$$minimizeCOST = \sum_{t=1}^{Nt}\left[\sum_{i=1}^{Ni\_TP}\left(c_{t,i}^{TP}\right) + \sum_{i=1}^{Ni\_HP}\left(c_{t,i}^{HP}\right) + c_t^{curt\_WP}\right] \quad (14)$$

$$c_t^{curt\_WP} = p_t^{curt\_WP} * \Delta t * PF^{curt\_WP} \quad (15)$$

As mentioned above, the second approach considers the case when wind power plants are providers of flexibility, participating in primary and secondary up reserve. In this sense, Eqs. (3), (4) and (13) are replaced with (16), (17) and (18) respectively, introducing new variables f^{up_WP} (upward primary frequency response provided by wind power plants) and r^{up_WP} (upward secondary reserve provided by wind power plants).

$$\sum_{i=1}^{Ni\_TP} f_{t,i}^{up\_TP} + \sum_{i=1}^{Ni\_HP} f_{t,i}^{up\_HP} + \sum_{i=1}^{Ni\_PS} f_{t,i}^{up\_PS} \sum_{i=1}^{Ni\_EV} f_{t,i}^{up\_EV} + f_t^{up\_WP} \geqslant F_t^{up} \quad (16)$$

$$\sum_{i=1}^{Ni\_TP} r_{t,i}^{up\_TP} + \sum_{i=1}^{Ni\_HP} r_{t,i}^{up\_HP} + \sum_{i=1}^{Ni\_PS} r_{t,i}^{up\_PS} \sum_{i=1}^{Ni\_EV} r_{t,i}^{up\_EV} + r_t^{up\_WP} \geqslant R_t^{up} \quad (17)$$

$$p_t^{g\_WP} + p_t^{curt\_WP} + f_t^{up\_WP} + r_t^{up\_WP} = P_t^{WP} \quad (18)$$

The goal of this study is to understand the decommissioning effect with different wind policies for both cases with and without EV. Fig. 7 shows how introducing wind curtailment penalty factor reflects on previously analysed scenarios of decommissioning of NPP and coal power plants. In the initial scenario with no EV, shown in first row of Fig. 7, by reducing the installed power of low flexible units - total system operational cost reduces, unlike the previous analyses shown in Fig. 5. With the introduction of wind power curtailment penalty factor (PF) the amount of wind

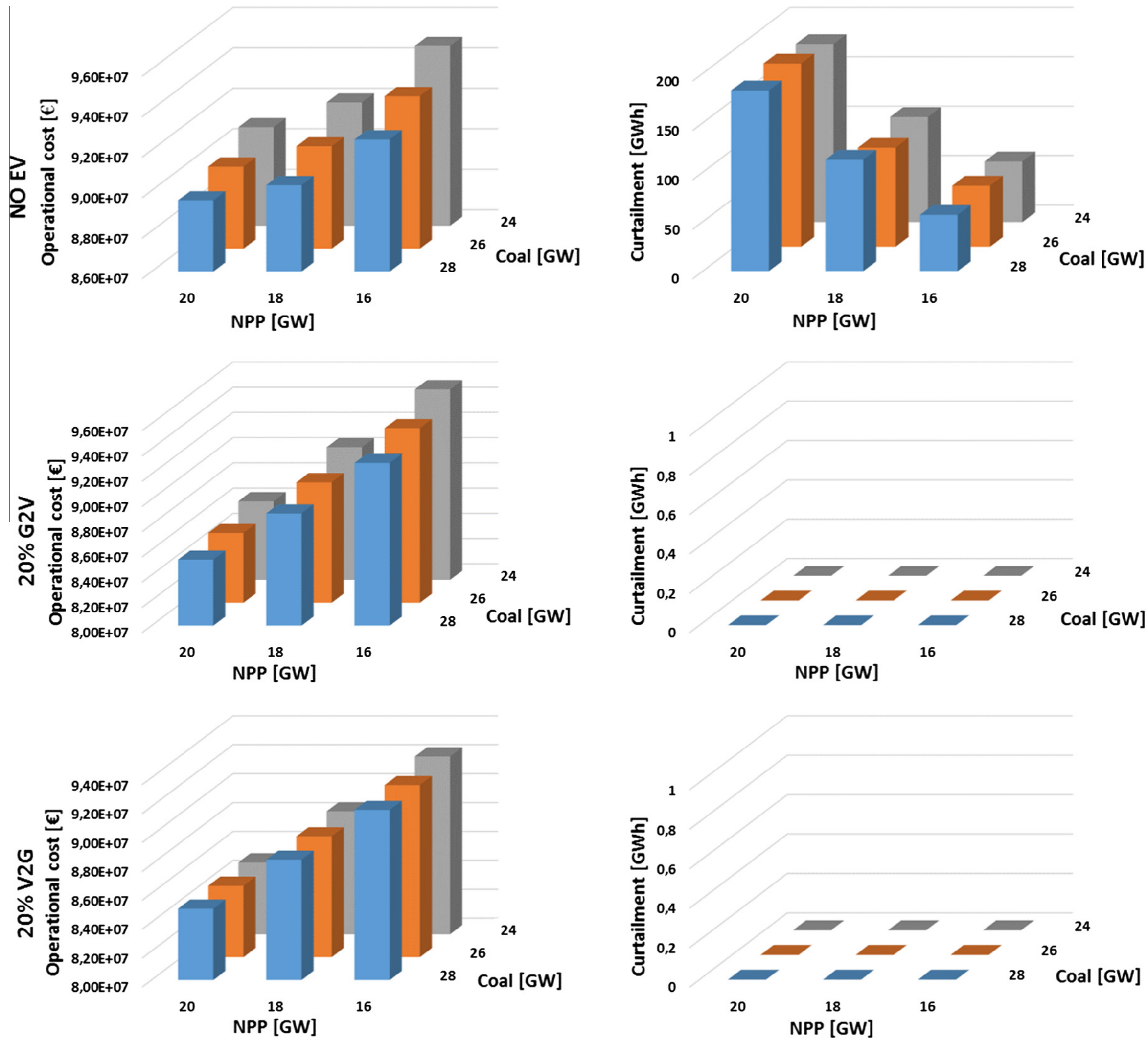

Fig. 10. Power plant decommission analysis in power system with 20% wind energy and possibility of wind upward reserve provision – graphical results.

energy curtailed is reduced by more than 50%. However, at the same time total system operational cost increases by more than 12% compared to the case shown in Fig. 5. This suggests that monetary gains due to lower curtailed wind are higher than cost increase due to the usage of more expensive conventional units (in this case of gas units). In the remaining cases, with EV integrated, no noticeable changes in power system operation are visible – introduction of PF does not impact cost and curtailment trends in power systems with high wind and EV penetration. The results for the systems with 40% wind share are similar to the scenarios of 20% wind share or no PF introduced.

Although wind curtailment can, to a certain extent, be considered as an "emergency flexibility" service provision, an interesting concept is presented by authors in [65], where they explain in details how upward reserve provision from wind turbines can decrease both wind curtailment and total system cost. As wind is used for up reserve provision in high wind periods it decreases both required reserve and reserve provided by conventional power plants thus allowing more efficient operation of those conventional units. Conventional units run closer to their optimal points and their intra-day cycling is reduced.

In order to better elaborate on the changes in system scheduling with wind turbines as reserve providers, weekly analyses, similar to those shown in Figs. 2–4 are again shown here in Fig. 8 (for scheduling provision of primary reserve) and Fig. 9 (for scheduling of secondary reserve). Again, three different EV charging regimes are considered, NO EV, G2V and V2G, for wind penetration levels 20% (left column of Figs. 8 and 9) and 40% (right column of Figs. 8 and 9). New variable *WPtotal* is referring to wind reserve provision. The energy service diagram is omitted because of the succinctness of the paper.

In the initial case, with no EV, both primary and secondary reserve are scheduled differently when reserve can be provided by wind turbines. In the reference case whenever power system (due to its technical constraints) could not use wind for power generation there was significant amount of wind curtailed. Here, surplus of the available wind power is used for primary and secondary reserve provision. In general, it means that expensive gas turbines have significantly fewer start up times in order to provide energy of reserve services. Still, during some critical periods (for example from 13 to 16 h) when there is not enough wind, gas turbines are started up from cold state to provide needed energy and reserve services. In case where wind energy can meet 40% of total demand, these "critical periods" are eliminated; the need for gas turbines, in particularly expensive start-up of gas units, is eliminated since more wind entails more curtailment which leaves more space for wind energy provision and, more importantly, reserve provision. More wind reserve provision also means relaxed and more efficient operation of coal units.

Introduction of EV by G2V mode brings new changes to the reserve scheduling problem. With 20% of wind penetration almost all wind reserve provision is shifted to EV; EV take over reserve provision enabling higher wind utilization for provision of energy. In general, periods when reserve is not provided by conventional units can be regarded as systems inflexible points, when any kind of new flexibility provider is welcome just to hold of starting up or shutting down inflexible units from the cold state. In V2G mode EV provide both primary and secondary reserve in 20% and 40% wind penetration scenarios.

Similar to previous analyses, Fig. 10 offers a detailed perspective on how different stages of decommissioning NPP and coal impacts total system cost and wind curtailment, this time considering wind power plants as additional flexibility provider (providing primary and secondary upward reserve). Initial scenario, not considering EV, shows decrease in both total system operational cost and wind curtailed (when compared to the reference case in Fig. 5).

Introduction of EV brings new flexibility to power system mitigating provision of flexibility services from wind turbines to EV. Total system cost increases similar as in the reference case, while flexible EVs entirely eliminate wind curtailment.

To conclude the Section the following conclusions can be made:

(i) Case 1: Wind curtailment penalized:
- Wind curtailment penalty factor increases total system cost and sets operating points of other power plants to non-realistic states.
- Decommission of low flexible units in such system, without EV, decreases total system cost. While scheduling more expensive gas units to take on the role of nuclear and coal results in operating cost increase, this is still less than decrease due to lower wind energy curtailed. However, a similar conclusion is valid as for the above point – due to "forcing" of wind usage the remaining units operating points are not reflecting the realistic state resulting higher ramping and more cycling of the units.
- When EV are included (both G2V and V2G mode) PF does not affect power system operation since EV provide enough flexibility and there is no wind curtailment.

(ii) Case 2: Wind turbines provide upward primary and secondary reserve:
- In scenarios not considering EV, wind is used for primary and secondary reserve provision instead of gas turbines. The higher wind penetration is, the lower system requirement for gas turbine services is.
- Usage of wind for reserve provision decreases total system cost and wind curtailment.
- Low flexible unit decommissioning in such system (without EV) increases total system cost and decreases wind curtailment in the same manner as in reference case (Section 4).
- When EV are included (both G2V and V2G mode) wind turbines are not preferred as reserve providers any more since EV introduce enough flexibility.
- When EV are included (both G2V and V2G mode) while decommissioning total system cost increases similar to the reference case.

6. Conclusion

The paper presents a mathematical model of power system operation capable of analysing systems flexibility and the impact of integrating renewable energy and flexible low carbon technologies, in this case EV. The model captures all technical characteristics and constraints of power system components, modelling different types of EV and different aspects of controllable charging/discharging where EV can provide multiple system services. In low flexible power systems, and usually highly carbon intensive, integration of controllable EVs has a positive effect on all aspects of power system operation, ranging from reduced operational cost, lower curtailed wind energy to lower carbon emissions due to more efficient operation of conventional units. Their capability to respond to fast changes following systems variability and uncertainty means they take over the role that is traditionally assigned to coal and gas power plants in providing of PFR and SFR, resulting in lower operational cost and CO_2 emissions. Another aspect, reflecting more planning than operation aspect of future low carbon systems, is addressed in the paper by showing the effect of decommissioning coal and nuclear power plants in systems with high share of wind power plants and flexible EV. The results clearly show that, although the system in general becomes more flexible by lowering systems MSG and increasing its ramping capability, the positive effects of reduced wind curtailment is followed by increase in systems operational cost. This occurs due to increased utilization of gas units, their cycling behaviour and high start-up costs. Third aspect involves different wind policies: penalization of wind curtailment and wind upward reserve provision. If no EV are present in the system as a source of flexibility, penalizing wind curtailment has a negative effect on power system operational cost, increasing it by 12%, even though curtailment is decreased by 50%. However, under this policy, decommission of low flexible units affects the system positively reducing both flexibility indicator values: total system cost and wind curtailment. On the other hand, in cases when EV are included, wasted wind penalization does not affect systems operation; neither in the reference case nor in other stages of decommission. Wind upward reserve provision causes decrease in cost and curtailment when no EVs are included, however, in scenarios with EV, provision of flexibility services from wind does not provide any additional benefits to power system operation.

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