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Value of flexible electric vehicles in providing spinning reserve services

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HIGHLIGHTS

- Mixed integer linear programming model for provision of multiple services from electric vehicles.
- Flexibility benefits of electric vehicles in provision of spinning reserve and energy.
- Impact of different electric vehicles charging strategies on electric power system operation.
- Assessment of environmental and economic benefits under different energy mix scenarios.
- Assessment of wind curtailment reduction under different energy mix scenarios.

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ABSTRACT

As the share of integrated renewable energy sources (RES) increases, traditional operation principles of the power systems need to change in order to maintain reliable and secure service provision, on one hand, and minimal cost and environmentally friendly electricity generation on the other. The challenge of alleviating additional uncertainty and variability brought by new sources to the system operation is seen as defining both flexibility capacities and flexibility requirements through provision of multiple services. In this context the role of emerging technologies, such as electric vehicles (EV) and energy storage (ES), is recognized through their active participation in providing both energy and reserve service.

This paper elaborates on the benefits of active EV participation in multiple system services through various charging strategies. The presented mixed integer linear programming (MILP) unit commitment problem (UC) considers the capability of EV to provide primary, secondary and tertiary reserve as well as energy, however the focus is put on the benefits of EV providing spinning reserve services. The results clearly show benefits of multiple EV role to that of providing energy only. In addition the paper analyses multiple power systems, with regards to their energy mix, and recognizes how integration of EVs reflects on power system flexibility through metrics expressed as operational cost, environmental benefits and reduced wind curtailment.

1. Introduction

Electric power systems are experiencing tremendous transformation over the past few decades as the introduction of new low carbon technologies (LCT) brings changes in economic, environmental and regulatory aspects. One of key challenges in power systems today is the integration of renewable energy sources (RES) which are at the same time creating benefits to national energy policies (energy security, independence on import oil and gas), national economy (new jobs in rural communities) and to human health (decrease of greenhouse gas emissions and waste), but are also creating additional uncertainty and variability and challenging traditional principles of maintaining generation and consumption equilibrium. To compensate these imbalances the system operator is compelled to have enough reserve in every moment, meaning that the system must have enough flexibility. These services are provided by controllable, generating units through ancillary services forcing traditional fossil fuel based generators to operate in non-optimal working states, sometimes resulting in the overall operation cost and emissions increase despite the integration of clean energy sources [1,2].

With the uptake of LCT, new concepts for providing systems flexibility are emerging where both interconnections to other, more flexible power systems, or integration of new market participants, such as energy storage (ES), electric vehicles (EV) and multi-energy concepts [3], will change the paradigm of how low carbon power systems operate. Advancements in the field of energy storage technologies, improving their performance and reducing their investment cost, are making them a relevant future

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Nomenclature

Decision variables

$p^{g\_TP}_{t,i}$	thermal units generation
$p^{g\_HP}_{t,i}$	hydro units generation
$p^{g\_PS}_{t,i}, p^{p\_PS}_{t,i}$	pump storage generation/pumping
$p^{g\_WP}_{t}$	wind power generation
$p^{c\_EV}_{t,i}, p^{d\_EV}_{t,i}$	electric vehicles slow charging/discharging
$p^{f\_EV}_{t,i}$	electric vehicles fast charging
$f^{up\_TP}_{t,i}, f^{dn\_TP}_{t,i}, r^{up\_TP}_{t,i} r^{dn\_TP}_{t,i}$	thermal units primary(f)/secondary(r) up/down reserve provision
$f^{up\_HP}_{t,i}, f^{dn\_HP}_{t,i}, r^{up\_HP}_{t,i} r^{dn\_HP}_{t,i}$	hydro units primary(f)/secondary(r) up/down reserve provision
$f^{up\_PS}_{t,i}, f^{dn\_PS}_{t,i}, r^{up\_PS}_{t,i} r^{dn\_PS}_{t,i}$	pump storage primary(f)/secondary(r) up/down reserve provision
$f^{up\_EV}_{t,i}, f^{dn\_EV}_{t,i}, r^{up\_EV}_{t,i} r^{dn\_EV}_{t,i}$	electric vehicles primary(f)/secondary(r) up/down reserve provision
$q^{up\_TP}_{t,i}$	thermal units tertiary up reserve provision
$s^{\_EV}_{t,i}$	total energy in a cluster of EVs
$s^{arr\_EV}_{t,i}$	total energy in cluster of EVs arriving to the charging stations
$s^{leav\_EV}_{t,i}$	total energy in a cluster of EVs leaving the grid
$p^{f\_EV}_{t}$	percentage of fast charging EVs
$x^{c\_EV}_{t,i}$	number of EVs charging
$p^{sh\_WP}_{t}$	curtailed wind power
$c^{\_TP}_{t,i}$	total thermal power plant cost
$c^{\_HP}_{t,i}$	total hydro power plant cost

Input parameters

P^{d}_{t}	power demand
F^{up}_{t}	primary up reserve requirements
F^{dn}_{t}	primary down reserve requirements
R^{up}_{t}	secondary up reserve requirements
R^{dn}_{t}	secondary down reserve requirements
Q^{up}_{t}	tertiary up reserve requirements
$P^{\_WP}_{t}$	potential wind power generation
$R^{EV\_0.5h}_{t}, R^{EV\_4h}_{t}$	secondary and tertiary reserve requirements increase caused by uncontrolled EVs charging
$\sigma^{sl(0.5h)\_EV}_{t}, \sigma^{sl(4h)\_EV}_{t}$	EVs uncontrolled charging standard deviation for secondary and tertiary reserve
$\sigma^{(0.5h)\_WP}_{t}, \sigma^{(4h)\_WP}_{t}$	wind power standard deviation for secondary and tertiary reserve
$N^{arr\_EV}_{\tau,i}$	number of EVs arriving (plugging in) to the grid
$N^{g\_EV}_{t,i}$	number of EVs connected to the grid
$N^{leav\_EV}_{t,i}$	number of EVs leaving the grid
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 biggest online unit in power system
$C^{UCH\_EV}_{i}$	time needed to fully charge EVs at full power
$\eta^{c\_EV}_{i}$	EV charging efficiency
$\eta^{d\_EV}_{i}$	EVs discharging efficiency
Δt	time period (0.5 h) for energy calculation
$S^{0\_EV}_{i}$	energy conserved in (all) EVs in time step zero
$S^{min\_EV}_{i}$	the lowest SOC value for one EV
$S^{max\_EV}_{i}$	the highest SOC value for one EV
$S^{cons\_EV}_{i}$	energy conserved in one EV which arrives to the grid
$S^{minc\_EV}_{i}$	the lowest allowed SOC in EVs leaving the grid
$P^{fmax\_EV}_{i}$	fast charging power maximum
$G^{\_EV}_{i}$	total number of EVs
$P^{max\_EV}_{i}$	slow charging power maximum

Abbreviations

BS	battery systems
CCGT	Combined Cycle Gas Turbine
CHPP	Conventional Hydro Power Plant
CoInTh	conventional inflexible thermal system
EPS	electric power system
ES	energy storage
EV	electric vehicle
FlTh	flexible thermal system
G2V-NR	grid-to-vehicle without reserve provision capabilities
G2V-YR	grid-to-vehicle with reserve provision capabilities
HP	hydro power
HyTh	Hydro Thermal system
InTh	inflexible thermal system
LCT	low carbon technologies
LoInFl	low carbon inflexible thermal system
MILP	Mixed Integer Linear Programing
NO-EV	Mode without Evs
NPP	nuclear power plants
OCGT	Open Cycle Gas Turbine
PS	pump storage
RES	renewable energy sources
RoR	run-of-river
SO	system operator
SOC	state-of-charge
TP	thermal power
TSC	Total System Cost
TSE	Total System Emissions
UC	unit commitment
UCH-NR	uncontrolled charging without additional reserve requirements
UCH-YR	uncontrolled charging with additional reserve requirements
V2G-NR	vehicle-to-grid without reserve provision capabilities
V2G-YR	vehicle-to-grid with reserve provision capabilities
WPP	Wind Power Production

flexibility provider as can be found in [4–7]. Microgrids are another promising concept where, by aggregating groups of geographically close loads and generators, the focus is shifting from centralized service provision to local, more system independent as described in [8,9]. However, currently the only integrated concept is that of demand response programs which includes changes in electric consumption by end-users in response to changes in electricity prices throughout day [10,11]. This concept has the potential to increase the systems flexibility by providing reserve to power systems in exchange for lower cost electricity for the end-users.

The focus of this paper is highlight the benefits of controlled electric vehicles charging which can be considered as a combination of all those aforementioned concepts; the battery on board acts as a storage unit, while a parallel can be drown between behaviour of drivers and household consumers and their geographical disparity which resembles that of multi microgrid components. Electric vehicles (EVs) are in fact additional demand to electric power system, however depending on their charging behaviour they can be seen as uncontrolled (inflexible) or controlled (flexible) load. Controlled charging of EVs means that EVs are demand responsive loads whose interaction with electric power system (charging) is driven by market or system operator signals throughout day. Since EVs can store energy they can also be observed as mobile energy storage units that can charge or discharge energy. Although EVs could be charged at home or work (slow charging) or at charging stations (fast charging), this paper observes only slow-charging EVs. Integration of new electricity consumers is often followed by additional investments into transmission and distribution network infrastructure, since investments follow human activity. This in terms means most of potential network upgrades would be at residential level. However, if EV charging is managed wisely investing in electric networks could be deferred. When all mentioned is recapitulated, EVs seem to have significant potential for providing flexibility both in energy and ancillary services.[1]

This paper will provide a critical estimation of EVs benefits to the high share RES power systems through a detailed analyses of participation in both energy and reserve services analysing different energy mixes and EV charging strategies.

2. Main contributions and literature overview

One of the most energy-consuming sectors, with more than 25% contribution in total energy consumed worldwide, is transportation sector [12], similar to the share of greenhouse gases coming from it. Regulatory trends drive the transformation of transportation sector from oil-consuming to electricity-consuming sector. Large number of EVs is already on the roads and more of them is predicted to be released into the market in the next few years [13–15].

A number of papers focuses on the capability of EVs to participate in the ancillary service markets. However, there is still a lack of research defining what are the benefits of coordinated EVs charging with respect to different energy mix and overall system cost or elaboration how does the participation of EVs alter the role of traditional plants in providing different services. Paper [16] proposes aggregated EVs command architecture where EVs communicate with their aggregator who then acts as a single market entity and posts bids on energy and ancillary services market. The availability, reliability and value of EVs provided ancillary services is calculated both for single EV direct participation and aggregated architecture and compared with that of gas turbines. Aggregative architecture has higher or same availability and reliability as that of gas turbines but, as one would expect, lower revenues for ancillary services compared with direct EV participation. There is significant potential for financial return for the EV's owners when V2G is used for regulation provision and even higher when combined with peak reduction (EVs power injections during peak hours) as found in [17]. Authors in [18] have revealed that profitable peak reduction could be achievable through real-time scheduling techniques. Brief description of control reserves, similar to those used in this paper, and V2G revenues for ancillary services provision with different levels of charging infrastructure is provided in [19]. Costs and revenues for ancillary services provision for different EV's fleets and different regulation markets are presented in [20]. Authors used four regulation markets (NYISO, CAISO, ERCOT and PJM) for annual profit calculation which is on some level similar to different energy mixes analyses in this paper. Different markets entails different internal generation structure, e.g. energy mixes. The difference is that this paper observes savings for system operator whereas authors of aforementioned research analyse profits for EV owners. Papers [21–23] present primary frequency control of EVs on smaller timescale, few hours, with higher power fluctuations resolution (minutes). Primary reserve in this paper is analysed as pre-occupied space which could be otherwise used for power generation. EVs as responsive demand (in this case it means to unplug EVs if frequency drops) for frequency support through different charging strategies with different charging profiles are observed in [24]. Detailed unit commitment (UC) model is presented in [25] where EVs are analysed through five modes: EVs charging, EVs discharging, EVs for reserve provision only, EVs used for transport and idle plugged-in EVs. The studies in the paper focus on peak increase in case where EVs are uncontrollably charged, charging and discharging behaviour over day for different mark-ups for power injections, state-of-charge (SOC) of EVs over day, reserve provision by EVs over day for different price of reserve, etc. However, all the analyses are again conducted only for a single day and from the aspect of the EV owner as market participant. Stochastic EVs model is formulated in [26] where objective function incorporates multiple markets (day-ahead energy, stochastic intraday energy, regulating reserve) and costs (reserve compensation and driver satisfaction cost). The last mentioned cost represents penalties for non-supplied energy to EVs which results in a conclusion that committing EVs for reserve introduces profit reduction for EV. However, it does not provide insight into scheduling of energy and reserve services and does not answer a question of how these services shift to new units with the introduction of EV. In addition, it does not provide annual analyses to properly evaluate the benefits of EV integration. In [27], a UC model of thermal generation based power system with incorporated EVs is presented. Authors modelled EVs as additional cost and included revenues for ancillary service provision. Traditional units act differently when EVs are used for ancillary services. EVs reserve provision increases efficiency of online units and turn-off the most expensive one. Although similarities with this paper's analyse exist, mentioned paper provides shallower analyse of thermal units reserve provision, unit commitment, system decreased cost etc. Another detail model of V2G assets is defined in [28]. Different EV's battery replacement costs and different types of EVs are used in these simulations. Higher battery replacement cost entails smaller amount of energy injected back to grid and smaller amount of regulation up capacity sold to the system operator (SO). Positive interaction between high wind power production and EV's contingency reserve provision are explained the case of Irish power system (52% of wind penetration) in [29]. Interesting work is presented in [30] where EVs charging is explored as an alternative for additional cross-border transmission investments. Besides transmission investment deferral, the paper found that RES curtailment, electricity price and energy storage usage are reduced when EVs charging is controlled. Covering EVs charging by means of variable renewable generation is done in [31]. Authors compare coordinated and uncoordinated charging in a week and annual simulations with sensitivity analyses on charging power, generation portfolio and charging availability. The last two papers observe only EVs charging, while EVs discharging and reserve provision has not been discussed. Worth mentioning study, focusing on energy provision by EV, is [32]. Authors are observing EVs as distributed energy storage system on a single day time scale but they do not consider EVs as potential reserve providers. Detail research on EVs emissions performance on different driving patterns, charging profiles and electricity mix is done in [33]. Along with the presented literature a short review of the EVs participation in frequency regulation is given in [34].

[1] Term of ancillary services in this paper is used for multiple reserve services, with focus on provision of spinning reserve services (in particular secondary reserve).

Most of the above mentioned papers observe revenues for potential EV owners analysing participation in ancillary service markets as potentially interesting business model for the end EVs users or aggregators. The goal of the paper is to define the impact of EV integration from the standpoint of the power system operator. Benefits from EV aggregation is not the topic of this paper; in other words the system does not care whether EVs cooperate under the aggregator principle or they work alone, as long as they provide the required service. Results of this paper are primarily recognizing benefits and improvements for power system operation in terms of operational cost, environmental benefits and reduced wind curtailment. The important questions that will be answered throughout paper are: how do EVs affect traditional unit commitment for energy and reserve services? How does provision of reserve from EV's affect traditional unit commitment for power and reserve? When will the system gain most from the EV's? How does the increase in EV's percentage affect the profitability of EV's reserve provision? How do EVs affect wind curtailment in future high share wind systems? Is there a positive correlation between increase in WPP and increase in EV's percentage? Which energy mixes acquire most benefits from EV's reserve provision?

Compared to the existing literature, the paper brings novelty through detailed analysis of provision of spinning reserve services and elaboration how service provision shifts from traditional units to more flexible and environmentally friendlier units. It also recognizes that flexibility benefits are different for different energy mixes through annual analyses of all three relevant flexibility metrics: operational cost, CO_2 emissions and wind curtailment.

The following Section, Section 3, elaborates the unit commitment model based on mixed integer linear programming (MILP) and input parameters used, focusing on thorough explanation of EVs behaviour equations. First part of Section 4 provides an answers on the above stated questions by analysing one-week simulation results. In second part of Section 4 annual analyses defines benefits of EV coordinated participation in multiple markets for various energy mix power systems. Section 5 provides concluding remarks, emphasizing the most important contributions of the paper.

3. Power system components and modelling

All simulations are run in Fico Xpress programming environment [35] on a Lenovo ThinkCentre computer (4 GB RAM). The electric power system is composed of conventional power plants such as hydro, fossil based thermal power plants and nuclear power plants with the capability of changing the energy mix and, by doing that, representing specific country system. This system is upgraded with models of emerging new technologies such as EVs, wind power plants (WP), and stationary battery systems (BS). Simulation model's architecture is designed to correspond to different national power systems; depending on the input data it can provide results for whatever power system's architecture. To speed up the simulations the system components are clustered by type of particular technology, since number of relevant papers have demonstrated accuracy of such approach, see [36,37]. The following subsections explain in detail vital components of proposed model and their input parameters. Graphical representation of proposed EPS and used scenarios are shown later in the paper, Section 3.3 in Fig. 3. For better understanding of the mathematical expressions it is important to keep in mind:

- Decision variables are written in italic lower case.
- Input parameters are written in roman upper case (or roman Greek letters).
- Extended variable/parameter name is written as roman superscript before underline.
- Technology to which variable/parameter is referring to is written as roman superscript after the underline.
- Indexes are written as italic subscript.
- Index i corresponds to type of particular technology.
- Index t corresponds to particular time step.
- All equations are written for one particular time-step/technology but they all apply to all time-steps/technologies in observed range (with the exception of initial conditions).
- Time step in this paper is 0.5 h which entails 336 time steps for one week period.
- Unless otherwise noted decision variables are nonnegative values.

3.1. Power system and electrical demand

Electric generation and consumption equilibrium must be satisfied in all time-steps. Mathematical notation of the last sentence is contained in (1). Left side of the equation present conventional (thermal – p^{g_TP}, hydro – p^{g_HP}, pump storage – p^{g_PS}) and RESs (wind – p^{g_WP}) generation and pump storage pumping (p^{p_PS}) with added EVs discharging (p^{d_EV}), charging (p^{c_EV}) and fast charging (p^{f_EV}), while left side present electric demand (P^{d}). Electric demand for UK power system, which is a typical low flexible power system relaying on thermal power plants, is displayed in Fig. 1 for typical high (60 GW – winter peak) and low-demand week (50 GW) [38]. Additional data about UK power system used can be found in [39].

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

Other system related Eqs. (2)–(6) are reserve provision requirements. As it can be seen from the following equations, five reserve services are modelled:

- Primary reserve up (f^{up}).
- Primary reserve down (f^{dn}).
- Secondary reserve up (r^{up}).
- Secondary reserve down (r^{dn}).
- Tertiary up (q^{up}).

$$\sum_{i=1}^{Ni\_TP}f_{t,i}^{up\_TP}+\sum_{i=1}^{Ni\_HP}f_{t,i}^{up\_HP}+\sum_{i=1}^{Ni\_PS}f_{t,i}^{up\_PS}+\sum_{i=1}^{Ni\_EV}f_{t,i}^{up\_EV}\geqslant F_{t}^{up} \quad (2)$$

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

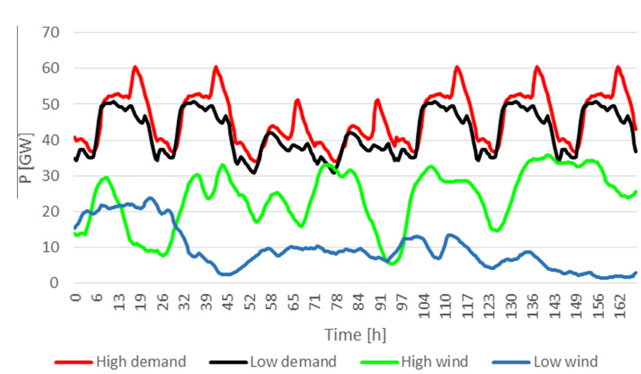

Fig. 1. Weekly demand and wind profiles.

$$\sum_{i=1}^{Ni\_TP} r_{t,i}^{up\_TP} + \sum_{i=1}^{Ni\_HP} r_{t,i}^{up\_HP} + \sum_{i=1}^{Ni\_PS} r_{t,i}^{up\_PS} + \sum_{i=1}^{Ni\_EV} r_{t,i}^{up\_EV} \geqslant R_t^{up} \tag{4}$$

$$\sum_{i=1}^{Ni\_TP} r_{t,i}^{dn\_TP} + \sum_{i=1}^{Ni\_HP} r_{t,i}^{dn\_HP} + \sum_{i=1}^{Ni\_PS} r_{t,i}^{dn\_PS} + \sum_{i=1}^{Ni\_EV} r_{t,i}^{dn\_EV} \geqslant R_t^{dn} \tag{5}$$

$$\sum_{i=1}^{Ni\_TP} q_{t,i}^{up\_TP} \geqslant Q_t^{up} \tag{6}$$

Detailed description of mentioned control reserves could be found in [40]. Primary and secondary reserve in this work are provided by online units (thermal, hydro, EVs), whereas tertiary control can be provided from both online and offline quick-start (CCGT, OCGT) units. Primary control reserve, both up and down, are at constant values of 1.9 GW as they corresponds to the reserve for frequency response in UK power system [38]. Secondary and tertiary control are time vectors of constant values. They depend 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 by standard deviation of wind forecast on different time scales through variables $\sigma^{(0.5h)\_WP}$ and $\sigma^{(4h)\_WP}$) and EV's charging mode (by taking into account a fixed value describing uncertain nature of EV arrival and battery SOC through variables $R^{EV\_0.5h}$ and R^{EV_4h}), as well as the outage of the largest generating unit P^{gmax} [41]. Uncontrolled charging (UCH) mode, due to its uncontrollability, cannot participate in energy markets (in terms of shifting its charging to a more favourable periods) nor provide ancillary services to the system operator. In addition, due to its unpredictability and variability UCH can increase system's reserve requirements. An estimation of UCH mode reserve increase (7) is added to standard reserve requirements formulas (8)–(10). Up reserve requirements include the largest online unit (this is taken into account as the largest generator outage). Reserves are modelled as in [37,42].[2]

$$R_t^{EV\_0.5h} = \sum_{i=1}^{Ni\_EV} \left(3.5 * \sigma_t^{sl(0.5h)\_EV} * P_i^{max\_EV} * \sum_{\tau=t}^{(t-C_i^{UCH\_EV}+1)} N_{\tau,i}^{arr\_EV} \right) \tag{7}$$

$$R_t^{up} = \sqrt{\left(3 * \sigma^{d} * P_t^{d}\right)^2 + \left(3.5 * \sigma_t^{(0.5h)\_WP} * P_t^{\_WP}\right)^2 + \left(R_t^{EV\_0.5h}\right)^2} + P^{gmax} \tag{8}$$

$$R_t^{dn} = \sqrt{\left(3 * \sigma^{d} * P_t^{d}\right)^2 + \left(3.5 * \sigma_t^{(0.5h)\_WP} * P_t^{\_WP}\right)^2 + \left(R_t^{EV\_0.5h}\right)^2} \tag{9}$$

$$Q_t^{up} = \sqrt{\left(3 * \sigma^{d} * P_t^{d}\right)^2 + \left(3.5 * \sigma_t^{(4h)\_WP} * P_t^{\_WP}\right)^2 + \left(R_t^{EV\_4h}\right)^2} + P^{gmax} \tag{10}$$

3.2. Conventional power plants

As already mentioned, the core of the analysed EPS's are hydro-thermal generating units. All units are modelled as clustered and participate in daily schedule together. Additional explanation of the conventional and clustered UC thermal model with or without RES could be found in [37,42,43]. Also, interesting recent publications related to the UC issues can be found in [44–46]. 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).

Four different types of thermal power plants (TP) are considered:

- Nuclear power plants.
- Coal-fired thermal power plants.
- Combined-Cycle Gas Turbines (CCGT).
- Open-Cycle Gas Turbines (OCGT).

Hydro Power Plants (HP) are modelled with small adjustments relative to the models in the available literature [1,47]. Hydro units are subjected to the following constraints[3]:

- Water balance equation.
- Power generation constraints.
- Reservoir constraints.
- Hydro turbine constraints.
- Spillage constraint.
- Reserve provision constraints (primary, secondary and tertiary);

Three different types of hydro power plants (HP) are considered:

- Run-of-river hydro power plants (RoR).
- Conventional Hydro Power Plants with daily accumulation (CHPP).
- Pump storage (PS).

Thermal and hydro power plants parameters can be found in Appendix (Tables 3 and 4).

3.3. Electric vehicles

As stated above, RES introduced new challenges to traditional EPS's operation principles. The incapability to accurately forecast their next day schedule resulted in new operating costs to the EPSs. Flexible and responsive units have to be scheduled in order to provide stable operation and unavailability of such units leads to wind curtailment, lower generation efficiency of conventional units, and transmission congestions. Smart planning of EV's charging infrastructure and EV's batteries has the potential to alleviate some of the challenges and to provide the needed flexibility enabling further integration of variable and uncertain RES. Depending on their operation mode EVs could behave as new source of flexibility or they could further damage system's flexibility. For the purpose of this work EV's are modelled through six operation models as follows:

- Uncontrolled CHarging with No additional Reserve requirements (UCH-NR) – EVs plug-in when they stop driving and charge until fully charged and their charging does not affect reserve requirements.

[2] The same formula applies for Rt^{EV_4h} in (10), the only difference is substitution of $\sigma^{sl(0.5h)\_EV}$ with $\sigma^{sl(0.5h)\_EV}$.

[3] Pump storage units are subjected to "double" constraints (upper and lower reservoir, generation and pumping, etc.).

- Uncontrolled CHarging with (Yes) impact on Reserve (UCH-YR) – EVs plug-in when they stop driving and charge until fully charged. The uncertainty of their arrival time and SoC of batteries increases reserve requirements. These first two types focus on an issue still not properly addressed in the literature – EV as additional source of uncertainty and variability.
- Controlled grid-to-vehicle charging with No possibility for providing Reserve (G2V-NR) – optimal allocation of EVs charging resources without possibility to inject power back to grid or to provide reserve services.
- Controlled grid-to-vehicle charging with (Yes) possibility to provide Reserve (G2V-YR) – optimal allocation of EVs charging resources without possibility to inject power back to grid but with possibility to provide primary and secondary reserve.
- Controlled vehicle-to-grid charging with No possibility for providing Reserve (V2G-NR) – optimal allocation of EVs charging resources with possibility to inject power back to grid but without participating in different reserve services provision.
- Controlled vehicle-to-grid charging with (Yes) possibility to provide Reserve (V2G-YR) – optimal allocation of EVs charging resources with possibility to inject power back to grid and with the possibility to provide reserve services.

All of these operating modes are subjected to the following constraints:

$$s_{t,i}^{\_EV} = s_{t-1,i}^{\_EV} + s_{t,i}^{arr\_EV} - s_{t,i}^{leav\_EV} + p_{t,i}^{c\_EV} * \eta_i^{c\_EV} * \Delta t + p_{t-1,i}^{f\_EV} * \eta_i^{c\_EV} * \Delta t - p_{t,i}^{d\_EV}/\eta_i^{d\_EV} * \Delta t \quad (11)$$

$$s_{1,i}^{\_EV} = S_i^{0\_EV} + s_{1,i}^{arr\_EV} - s_{1,i}^{leav\_EV} + p_{1,i}^{c\_EV} * \eta_i^{c\_EV} * \Delta t + p_{Nt,i}^{f\_EV} * \eta_i^{f\_EV} * \Delta t - p_{1,i}^{d\_EV}/\eta_i^{d\_EV} \Delta t \quad (12)$$

$$s_{Nt,i}^{\_EV} \geqslant S_i^{0\_EV} \quad (13)$$

$$N_{t,i}^{g\_EV} * S_i^{min\_EV} + s_{t,i}^{arr\_EV} - s_{t,i}^{leav\_EV} \leqslant s_{t,i}^{\_EV} \leqslant N_{t,i}^{g\_EV} * S_i^{max\_EV} + s_{t,i}^{arr\_EV} - s_{t,i}^{leav\_EV} \quad (14)$$

$$0 \leqslant s_{t,i}^{arr\_EV} \leqslant N_{t,i}^{arr\_EV} * S_i^{cons\_EV} \quad (15)$$

$$N_{t,i}^{leav\_EV} * S_i^{minc\_EV} \leqslant s_{t,i}^{leav\_EV} \leqslant N_{t,i}^{leav\_EV} * S_i^{max\_EV} \quad (16)$$

$$p_{t,i}^{f\_EV} \geqslant p_t^{f\_EV}/100 * P_i^{fmax\_EV} * \left(G_i^{\_EV} - N_{t,i}^{g\_EV}\right)\Big/3 \quad (17)$$

EVs are aggregated and observed as one unit with time-dependant parameters. Energy conservation equation of aggregated EVs is represented in (11). Energy stored in all EVs of type *i* (the model observes three types of EV, as explained later) at time step *t* is on the left side of equality sign ($s^{\_EV}$), whereas right side is composed of energy stored at past time step ± energy stored in arriving/leaving (s^{arr_EV}/s^{leav_EV}) EVs, ± charged (slow p^{c_EV} and fast p^{f_EV}) and discharged (p^{d_EV}) EVs energy at actual time step. Initial and final conditions are shown as (12) and (13). Eq. (14) represent boundaries for EVs storage size. EVs usually do not discharge their entire stored energy for driving, meaning that most of the energy is still stored when they plug-into the charging point. Three types of EVs are developed based on their trip lengths (based on their consumed energy for driving) as shown in Table 1. Percentage of EV's types in EV's fleet is chosen to match real proportions (Table 1) based on the [48]. One week driving patterns are extracted from the same study [48]. Every day is modelled with representative driving patterns as shown on Fig. 2. Input vectors $N_{t,i}^{g\_EV}$, $N_{t,i}^{arr\_EV}$ and $N_{t,i}^{leav\_EV}$ are derived from those curves. Variable $s_{t,i}^{arr\_EV}$ denotes unconsumed energy of returning EVs (15). Variable $s_{t,i}^{leav\_EV}$ denotes energy stored in EVs leaving the grid (16). It is assumed that all EV's owners require 100% SOC when leaving the grid ($S_i^{minc\_EV} = S_i^{max\_EV}$). Although the number of vehicles can be modelled as variable (17), fast charging in this paper is taken as constant value; 5% of on-road EVs are allowed to use fast-charging stations ($p_t^{f\_EV}$ = 5%). The assumed duration of fast charging is ten minutes and to assure this, right side of (17) is divided by 3 ((30 min time period/3) = 10 min charging). Fast charging is assumed to be uncontrolled so it increases reserve requirements in a similar manner as uncontrolled slow charging as shown in Eqs. (8)–(10). This paper analyses only slow charging effect on the EPS so no additional description of fast charging model will be provided.

Table 1
Electric vehicle's parameters.

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%

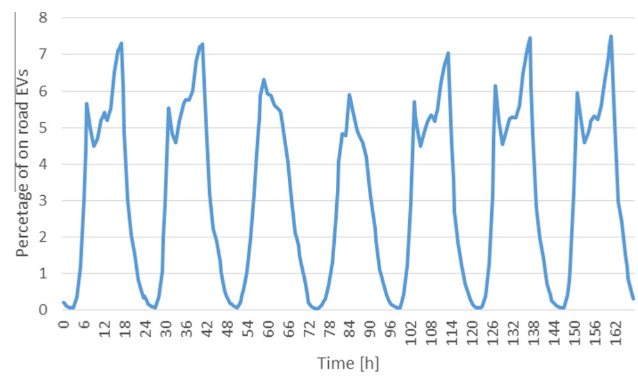

Fig. 2. EVs driving pattern.

Specific constraints for different charging modes are listed below (18)–(26).

UCH:

$$p_{t,i}^{d\_EV} = 0 \quad (18)$$

$$C_i^{UCH\_EV} = round\left\{\frac{S_i^{max\_EV} - S_i^{cons\_EV}}{P_i^{max\_EV} * \Delta t}\right\} \quad (19)$$

$$\sum_{(\tau=Nt+t-C^{UCH\_EV}+1)}^{Nt}\left(N_{\tau,i}^{arr\_EV} * P_i^{max\_EV} * 0.9\right) + \sum_{\tau=1}^{t}\left(N_{\tau,i}^{arr\_EV} * P_i^{max\_EV} * 0.9\right) \leqslant p_{t,i}^{c\_EV} \leqslant \sum_{(\tau=Nt+t-C^{UCH\_EV}+1)}^{Nt}\left(N_{\tau,i}^{arr\_EV} * P_i^{max\_EV} * 1.1\right) + \sum_{\tau=1}^{t}\left(N_{\tau,i}^{arr\_EV} * P_i^{max\_EV} * 1.1\right) \quad (20)$$

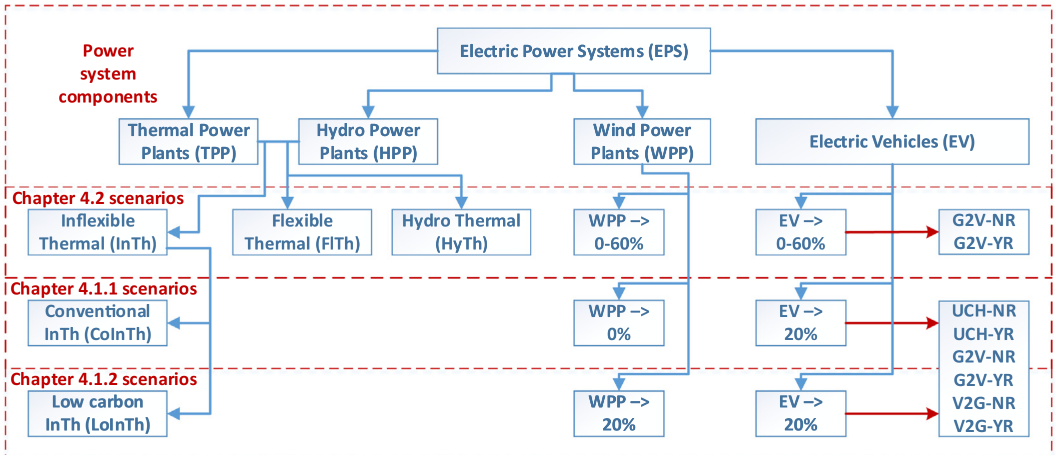

Fig. 3. Modelled power system and scenarios used in simulations.

$$\sum_{(\tau=t-C^{UCH\_EV}+1)}^{t}\left(N_{\tau,i}^{arr\_EV} * P_i^{max\_EV} * 0.9\right) \leqslant p_{t,i}^{c\_EV} \leqslant \sum_{(\tau=t-C^{UCH\_EV}+1)}^{t}\left(N_{\tau,i}^{arr\_EV} * P_i^{max\_EV} * 1.1\right) \tag{21}$$

G2V:

$$p_{t,i}^{d\_EV} = 0 \tag{22}$$

$$0 \leqslant p_{t,i}^{c\_EV} \leqslant P_i^{max\_EV} * N_{t,i}^{g\_EV} \tag{23}$$

V2G:

$$0 \leqslant x_{t,i}^{c\_EV} \leqslant N_{t,i}^{g\_EV} \tag{24}$$

$$0 \leqslant p_{t,i}^{c\_EV} \leqslant P_i^{max\_EV} * x_{t,i}^{c\_EV} \tag{25}$$

$$0 \leqslant p_{t,i}^{d\_EV} \leqslant P_i^{max\_EV} * \left(N_{t,i}^{g\_EV} - x_{t,i}^{c\_EV}\right) \tag{26}$$

Uncontrolled charging mode does not allow EVs to inject power back into the distribution grid (18). Auxiliary constant $C_i^{UCH\_EV}$ represents time necessary to fully charge EV's battery while charging is at rated power. Initial conditions are modelled in (20). EV's driving patterns are constructed continuously from available weekly data, meaning that $N_{t,i}^{arr\_EV}$ data from time steps before time step 1 are the same as that of the last time steps. In other words required $N_{t,i}^{arr\_EV}$ for periods before first time step are not exclusively modelled but taken from last periods. Charging in remaining periods is modelled with (21).

The concept of UCH is inflexible, meaning once EVs are plugged-in they are being charged at power ranging from 90% to 110% of battery's rated power till they fully charged. Controlled G2V charging mode allows only charging during periods beneficial for the system as shown in (22) and (23). On the other hand in the controlled V2G regime, discharging energy into the grid is additionally allowed as modelled in (25) and (26). Integer variable $x_{t,i}^{c\_EV}$ denotes the number of EVs being charged at time t (24), whereas $(1 - x_{t,i}^{c\_EV})$ denotes the number of EVs being discharged at time t.

All of the charging modes (UCH, G2V and V2G) may have an impact on reserve requirements. Due to its uncontrollability, variability and uncertainty, UCH will most likely negatively affect the reserve requirements, resulting in increase in system reserve requirements, as shown in (8)–(10). G2V and V2G due to their controllability can be observed in the context of additional reserve provision to the EPS. In all three modes, EV's influence on reserve is included or excluded from consideration based on author's decision, resulting in multiple scenarios for different service provision. The secondary reserve provision in the G2V charging mode is modelled with (27) and (28), and in the V2G mode in (31) and (32). Same applies for primary reserve plus additional decrease for already allocated secondary reserve ($r_{ti}^{up\_EV}/r_{ti}^{dn\_EV}$) as can be seen in (29), (30), (33) and (34).

G2V:

$$r_{t,i}^{up\_EV} \leqslant p_{t,i}^{c\_EV} \tag{27}$$

$$r_{t,i}^{dn\_EV} \leqslant P_i^{max\_EV} * N_{t,i}^{g\_EV} - p_{t,i}^{c\_EV} \tag{28}$$

$$f_{t,i}^{up\_EV} \leqslant p_{t,i}^{c\_EV} - r_{t,i}^{up\_EV} \tag{29}$$

$$f_{t,i}^{dn\_EV} \leqslant P_i^{max\_EV} * N_{t,i}^{g\_EV} - p_{t,i}^{c\_EV} - r_{t,i}^{dn\_EV} \tag{30}$$

V2G:

$$r_{t,i}^{up\_EV} \leqslant P_i^{max\_EV} * \left(N_{t,i}^{g\_EV} - x_{t,i}^{c\_EV}\right) - p_{t,i}^{d\_EV} + p_{t,i}^{c\_EV} - P_i^{min\_EV} * x_{t,i}^{c\_EV} \tag{31}$$

$$r_{t,i}^{dn\_EV} \leqslant p_{t,i}^{d\_EV} - P_i^{min\_EV} * \left(N_{t,i}^{g\_EV} - x_{t,i}^{c\_EV}\right) + P_i^{max\_EV} * x_{t,i}^{c\_EV} - p_{t,i}^{c\_EV} \tag{32}$$

$$f_{t,i}^{up\_EV} \leqslant P_i^{max\_EV} * \left(N_{t,i}^{g\_EV} - x_{t,i}^{c\_EV}\right) - P_{t,i}^{d\_EV} + p_{t,i}^{c\_EV} - P_i^{min\_EV} * x_{t,i}^{c\_EV} - r_{t,i}^{up\_EV} \tag{33}$$

$$f_{t,i}^{dn\_EV} \leqslant p_{t,i}^{d\_EV} - P_i^{min\_EV} * \left(N_{t,i}^{g\_EV} - x_{t,i}^{c\_EV}\right) + P_i^{max\_EV} * x_{t,i}^{c\_EV} - p_{t,i}^{c\_EV} - r_{t,i}^{dn\_EV} \tag{34}$$

3.4. Renewable energy sources

Real historical data (P_t^{WP}) from Fig. 1 are used to model actual wind power production ($p_t^{g\_WP}$) and it is displayed in Fig. 1. Decision variable $p_t^{sh\_WP}$ allows wind curtailment (shedding). Wind curtailment is undesirable and it is a metric to evaluate the EPS's flexibility; the larger the curtailment the less flexible the EPS is. Wind Power Production (WPP) is represented with (35).

$$p_t^{g\_WP} + p_t^{sh\_WP} = P_t^{WP} \tag{35}$$

3.5. Objective function

The objective function is minimization operational costs from the units providing energy and reserve services to the system (36). Thermal (start-up, shut-down, fuel, O&M, greenhouse gas emissions) and hydro (O&M) costs are included. Thermal fuel consumption curve is piece-wise linearized (3 segments) [37,42].

$$\min \ COST = \sum_{t=1}^{Nt}\left[\sum_{i=1}^{Ni\_TP}\left(c_{t,i}^{TP}\right) + \sum_{i=1}^{Ni\_HP}\left(c_{t,i}^{HP}\right)\right] \quad (36)$$

4. Simulation and results

Weekly and annual simulations are performed in this section to gain insight into EV impact on UC performance and traditional principles of providing market services. First part of simulations aim to show EV's physical and economic impact on power and reserve one-week unit commitment. This is shown in Figs. 4 and 7 through three different graphs presenting: (i) EVs charging/discharging and their impact on conventional energy scheduling; (ii) secondary up and (iii) secondary down reserve. Although the designed model enables multi reserve service analyses, as already mentioned, due to space constraints only secondary reserve scheduling will be shown. The results are shown for the base case (without EVs or NO-EV case) and compared with other above listed EV's operating modes. In addition, two different scenarios are taken into account: Conventional Inflexible Thermal (CoInTh) system, with no wind penetration, and low carbon inflexible thermal system with 20% of RESs (LoInFl).

Second part of simulations focuses on EVs and WPPs interaction for G2V charging mode with and without EV's reserve provision capabilities. EPS's savings and wind curtailment decrease caused by EV's reserve provision are the main indicators of EV's capability to enhance flexibility of high RES systems. Seven different percentages of EVs and WPPs, ranging from 0% to 60% with 10% step increase, and three different energy mix scenarios are used: Inflexible Thermal (InTh), Flexible Thermal (FlTh) and Hydro-Thermal (HyTh) system. Details on these scenarios are provided in later subsections. Integration of particular technologies used in different scenarios is presented in Table 2. EV's input parameters are shown in Table 1.

4.1. One-week simulations

4.1.1. Conventional inflexible thermal system (CoInFl)

Fig. 4 displays EV's charging and discharging behaviour as well as secondary up and down reserve provision (these are represented by three graphs in each row shown on *x*-axis) for simulations of the CoInTh system. The analyses are done for base case without EVs (NO-EV) and are compared with 6 other scenarios changing charging/discharging modes of EV as well as type of services they can provide (this are in order shown on *y*-axis in Fig. 4). For easier understanding of the results in Fig. 4 the following should be kept in mind:

- First vertical column graphs present scheduling of energy in UC for total of 7 scenarios; the first one without EV and six for different charging strategies of EV.
- Second and third vertical column present secondary up and down reserve for total of 7 scenarios; the first one without EV and six for different charging strategies of EV.

Although the presented UC model considers scheduling of multiple services, due to limited space, Fig. 4 shows the results only for secondary reserve service. It should be mentioned that the same comparison and analyses could be done for primary and tertiary reserve as well.

The analysed EPS resembles that of the UK and for relevant analysis and comparison all the other data is taken for the UK system as well. There are approximately 30 million cars in UK at the moment [49]. For the purposes of this simulation the assumption is made that 10% of those vehicles is going to be replaced with EVs. If all those EVs would charge at the same moment it would increase the electricity demand by 20%, i.e. by 12 GW. Further in the paper number of EVs will be expressed as percentage of total electric demand not as percentage of total number of vehicles on road.

Base case (NO-EV) represents conventional unit commitment model with no RESs and EVs. Nuclear units cover base load, they do not alter their production and do not provide any kind of reserve. Although NPP are not inflexible units, traditional approaches suggest NPP are not used for provision of ancillary services, with the exception of contingency reserves, nor for following net demand changes. Coal power plants are units of limited flexibility and they provide both the up and down reserve. CCGT units cover workday's daily peak period demand, and are almost completely shut down on weekends due to lower electricity demand. The only period when CCGT units provide up reserve are those days of the week when they also cover part of the energy demand. This is happening only during peak periods since lower cost coal power plants are running at their maximum and additional required reserve is provided by more expensive online units such as CCGT. Although some CCGT units are scheduled to provide down reserve during peak periods, almost all down reserve is provided by coal. Aforementioned occurs since coal units are used to provide most of the energy (taking into account only units that can provide reserve, so excluding NPP) and thus, a logical way to provide down reserve is to ramp coal units down. OCGT units are the most expensive units and also the most flexible units, however they are offline most of the time. With the exception of some specific periods, they are primarily used to provide the required tertiary reserve.

The second analysis shows how EPS operation changes with the integration of non-flexible EVs. Charging of uncontrollable EV is presented by green line in first graph (energy graph, second row and first column of Fig. 4) of the unit commitment. The demand curve of EVs charging requirements follows their driving patterns (Fig. 2). Required power for EV charging is high throughout day, with peak charging power in the afternoon when most of the EVs return home. Blue line in the energy graph displays demand without EV, so comparing it with the black line (total demand) it can be seen that demand has increased. Increased demand, i.e. increased energy consumption, entails increased power generation and thus increased Total System Cost (TSC) and Total System Emissions (TSE). In addition, increase in TSC is the result of running more expensive units to cover the higher demand. The third reason is larger requirements for up reserve, in particular scheduling of more OCGT units. Cheaper coal and CCGT units during peak periods are providing energy so OCGT units are required to provide reserve. Increased production from gas turbines does not necessarily mean the increase in TSE since the emissions rate of OCGT is lower than that of coal. Down reserve is provided purely from coal units same as in the base case.

In the third case scenario uncontrolled charging results in additional reserve requirements (UCH-YR case); this can be easily explained by the difficult to predict arrival time and difficult to predict state of charge of EV's batteries. To cover this new reserve demand, new units need to be online to provide it. Although no additional energy is required, OCGT units need to be scheduled to cover energy demand during weekly minimum to be able to correspondingly provide more reserve. Higher reserve requirements, provided by OCGT, in addition to running expensive OCGT to

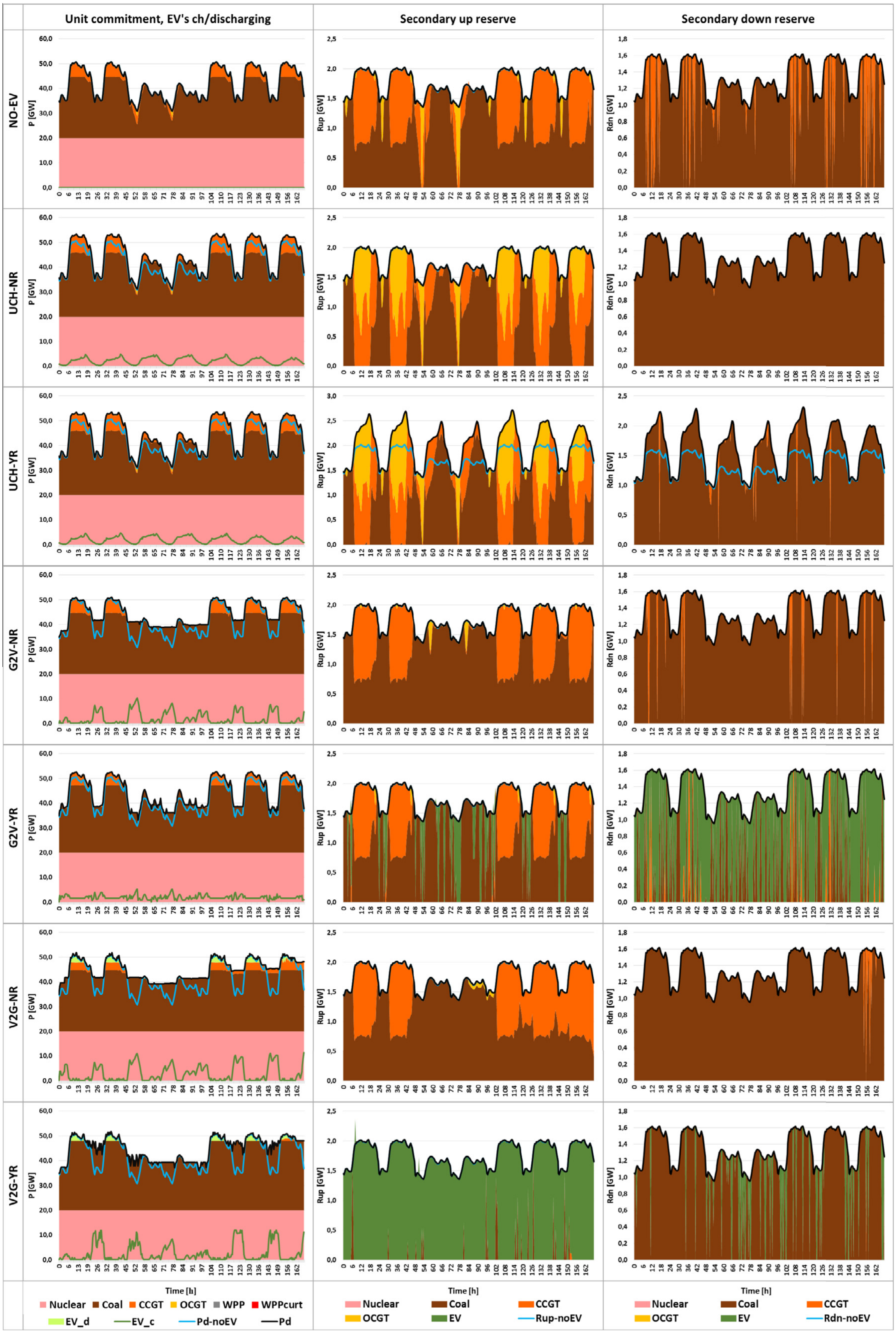

Fig. 4. CoInFl system results.

Table 2
Scenarios generation mixes.

Generation type[a]	Thermal power plants (TPP)				Hydro power plant (HPP)		
	Nuclear (%)	Coal (%)	CCGT (%)	OCGT (%)	CHPP (%)	RoR (%)	PS (%)
InTh	35	45	15	5	0	0	0
FlTh	15	25	45	15	0	0	0
HyTh	20	20	15	0	15	15	15

[a] Percentage of totally needed generation capacity to cover demand, reserve and primary control requirements.

provide energy, means increase in TSC and slight decrease in TSE (less power is produced from more emission intensive coal).

The fourth scenario analyses the controllable EV scenario, where EV can only be charged from the power system. G2V-NR mode follows different charging pattern compared to that in UCH as shown in Fig. 4. EVs are charged at low-demand periods (at night and weekends) and this results in the lower TSC and highest system benefits. Coordinated charging results in more evenly distributed generation and consumption and, due to lower number of unit's start-up and shut-downs, lower TSC. In addition, the flexible EV charging had an impact on both up and down reserves requirements resulting in lower demand when compared to previous two cases.

In the fifth analysed scenario controllable EVs can provide both energy and reserve, this is G2V-YR scenario mode. Unlike the previous case the charging does not occur only during the night, it is rather uniformly distributed through the day during the entire week. TSC is lower than in all previous scenarios since EV's will be assigned to provide secondary reserve instead of more expensive coal, CCGT or OCGT units. Another interesting phenomenon, associated with G2V-YR mode, is a slight increase in TSE. Since coal power plants do not provide down reserve they are scheduled to operate at technical minimum during low demand periods. Although this is less costly than to work at full power, the emissions rate (expressed as tCO_2/MW h) is higher. Also, assigning less up reserve to coal units means they will participate more in energy provision during peak periods, resulting in higher total system emissions.

The sixth scenario allows both controlled charging and discharging in V2G-NR mode. It can be easily noticed that TSC additional decreases, compared to G2V-NR mode, due to back-to-grid power injections during peak periods. Although total energy demand is higher in this scenario since part of the energy is lost due to charging/discharging efficiencies, but more energy is generated by lower cost units. Energy discharged by EVs is shown with light green area in Fig. 4 and can be noticed particularly during peak demand periods. EVs are being charged during low demand periods resulting in even more flattened net demand curve. An interesting observation is that G2V-YR mode has lower TSC than V2G-NR mode, which is mostly caused by more energy that needs to be generated by thermal units in the latter case. The same can be noticed for TSE.

The seventh scenario allows controlled EV charging and discharging and participation in both energy and reserve services. This scenario is characterized with the lowest TSC. Coal units are being replaced completely from providing up reserve which enables them to operate at optimum operation point for provision of energy. In addition, CCGT and OCGT units are completely shut down since EVs replace their flexibility services. EV's charging and discharging patterns are very similar to those from V2G-NR mode. Up reserve is completely covered by EVs, while a small portion of down reserve is still covered by coal. This can be explained by practical reasons: if coal power plants are run for provision of energy as this is the less cost option, it makes sense to use their capability to provide down reserve. EV's are charged/discharged during optimal periods during the day so the algorithm does not assign them provision of down reserve. Although TSC is the lowest, TSE reaches highest value of all observed scenarios since most of the energy generated comes from highly pollutant coal units.

4.1.2. Low carbon inflexible thermal system (LoInFl)

Studies in this subsection are similar to those in the previous one, with addition of wind power plants (WPP) and additional reserve requirements caused by this variable and uncertain source. The system scheduling is analysed in details for WPP integration of 20% (12 GW for the observed system). Weekly wind power production (for a high wind generation week) pattern is displayed in Fig. 1. Wind power production increases the required reserve as shown in Eqs. (8)–(10). Fig. 7 displays EV's charging and discharging behaviour, energy provision from thermal power plants as well as contributions of secondary up and down reserve assigned to different units of LoInTh system. Conceptually all graphs in the Fig. 7 follow the same logic as those in the previous subsection. The only new variables in Fig. 7 are that of wind power production. Grey area represents actual power generated by wind power plants and it is displayed beneath load demand curve (black line). Red area represents curtailed wind power and it is displayed above power demand curve since it is not being used and should be seen as insufficient flexibility of the observed system. Since all scenarios are same as those in the previous section, most of the explanations are very similar so only the differences between the two cases will be highlighted. Whereas in the last chapter flexibility metrics were TSC and TSE, in this chapter wind curtailment is added to those two.

In the base case (NO-EV) Wind Power Production (WPP) is fully exploited during weekday's peak periods, while it is curtailed (WPcurt) during low demand periods, at night and weekends. Comparing it to the previous section simulations, it can be seen that expensive units, OCGT and CCGT, have been replaced by WPP in energy provision. Reserve requirements in both directions are almost completely covered with coal (gas turbines are not online so they are not able to provide spinning reserve service). Gas turbines are scheduled to provide up reserve during few specific periods, when there is either not enough coal or coal is shut down due to low demand and therefore fast response units are scheduled to substitute the coal.

If the first scenario is upgraded with the addition of inflexible EVs (UCH-NR scenario), electricity demand is higher and less wind is curtailed. Although there is an increase in TSC and TSE, the values are lower than in the previous section when the same EVs charging mode was analysed but without wind. This can be simply explained; less curtailed wind means lower generation from expensive and environmentally less friendly thermal power generation. CCGT's up reserve provision during peak periods has increased (higher demand – less coal available to provide reserve), however OCGT scheduled to provide reserve have decreased their provision during low demand periods (higher demand means more coal is scheduled to provide energy and therefore is also available for reserve provision).

Scenario two, UCH-YR mode, results in higher TSC, TSE and wind curtailment. Larger reserve requirements caused by variability and uncertainty of both wind and EV, suggest higher number of scheduled units.

Flexibility of EVs in G2V-NR mode, allows higher WPP to be accommodated; lower wind curtailment also means lower thermal power generation and, correspondingly, lower TSC and TSE. EV's are being charged during periods when otherwise wind power would be curtailed. The flexibility of EV to be charged when it benefits the system also reduces the need for gas turbines energy and reserve provision.

Allowing EVs to provide reserve (G2V-YR) further increases system's flexibility since zero wind is curtailed and provision of energy and reserves from gas turbines is minimized. This in turn also means TSE and TSC is additionally reduced. Similar to the analyses in the previous section, it can be seen that EVs charging is evenly distributed throughout week. Since EV's are completely providing down reserve and most of the up reserve, coal units are able to ramp up or down from technical minimum to full power, enabling them to work at their optimal operating points (which is not the case when they have to provide reserve services).

As it can be seen from analyses of scenario six, V2G-NR mode is not able to utilize all available wind power thus very small wind curtailment exist during low demand weekend periods. Periods of EV charging are very similar to those of G2V-NR mode and to V2G-NR mode of previous section while discharging rarely happens due to production from WPP (which was not the case in previous section analyses). Two direction roles of EV results in reserve being provided only by coal units.

Last operating mode is the most flexible one where no wind is curtailed, similar to G2V-YR mode. Although the system behaviour in G2V-YR and V2G-YR modes is similar, the V2G mode has lower TSC as it could be seen at Fig. 6. Major difference is that V2G mode have the possibility to discharge. Discharging is, similar to previous case, almost zero and even though that possibility is not being used for provision of energy, this capability contributes to rescheduling of up reserve which is completely provided by EVs as displayed at Fig. 7. Consequently, coal power plants have less start-ups, shut-downs and ramping and thus TSC is lower. Still the same amount of energy is generated by coal so the TSE is the same as in G2V-YR scenario (Fig. 6).

4.1.3. Discussion and conclusion

The analyses in Section 4.1.1 show that the most expensive case for the power system operations is the one when integrating uncontrollable charging EVs, in particular when difficulties of predicting their time and power/energy demand as this results in increased reserve requirements. Uncontrolled charging requires new peak units to be started and new reserve providing units compared with NO EV scenario. Controlled charging could alleviate provision of these services from low efficient and environmentally unfriendly units to low carbon system. It is clear that controlled charging is improving power systems stability as power demand diagram becomes more flattened, i.e. less ramping and start-ups occur in normal daily operations (Fig. 4). It could be seen from Fig. 5 that TSC line decreases when EV's introduce new flexibility services to system operation. The most promising operational mode appears to be V2G-YR mode where valleys in power demand diagram almost correspond to high peaks and TSC is the lowest of all observed operational modes. However, two main issues need to be kept in mind when considering V2G charging mode. Power injections, or constant cycling caused by changing and discharging, could harm and reduce the lifetime of EV's battery. In addition, using EVs as both source and sink of energy results in the increase in TSE. From Fig. 5 it can be noticed that, opposite to TSC, TSE curve has constant increase. It appears that EV's flexibility enhancement negatively affect system TSE. For a power system whose energy mix is based on fossil fuel driven power plants it can be concluded that TSC and TSE are mutually opposed variables and that integrating controllable loads will challenge the environmental policies. Situation improves with the simultaneous integration of RES. This is demonstrated through a set of studies in Section 4.1.2 where 20% of wind power plants is included.

Analyses in Section 4.1.2 define three parameters for defining the systems flexibility; on top of the TSC and TSE (Fig. 6), wind

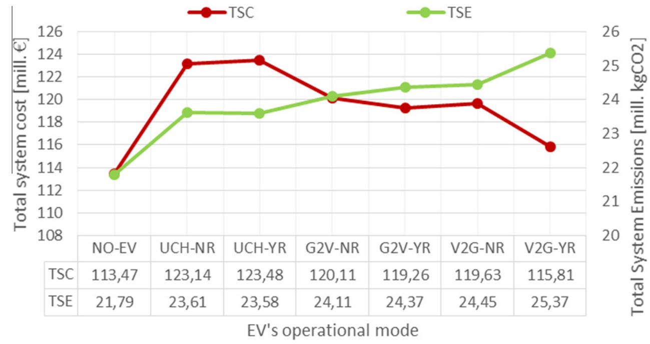

Fig. 5. Total system cost and emissions for CoInTh system.

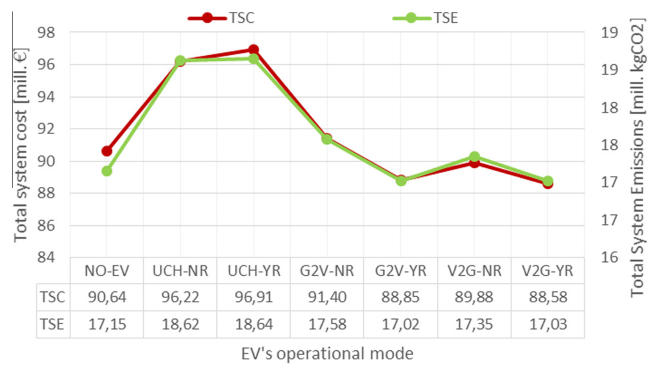

Fig. 6. Total system cost and emissions for LoInTh system.

curtailment serves as a metric of insufficient system flexibility (Fig. 8). The worst case for power system operations, in terms of flexibility metrics TSC, TSE and wind curtailment, is UCH-YR mode. It is clear that this kind of EV's charging should be avoided. Similar to the previous scenario, with no wind in the system, TSC decreases when EV's introduce new flexibility services to power system operation providing energy and reserve, but, unlike in the previous scenarios, TSE also decreases. More precisely TSE and TSC have the same pattern of behaviour. This is a positive change and aforementioned problem of TSE increase is solved. Wind curtailment decreases even in UCH modes, but major decrease is when controllable modes are observed. G2V-YR and V2G-YR fully exploit WPP, meaning that wind curtailment is zero in both modes. The latter control mode, V2G-YR, is an excellent example of flexibility enhancement gained by EV's reserve provision. Another problem mentioned in the previous analyses is discharging effect on battery's life cycle. This problem is indirectly solved by WPP integration, since V2G-YR mode uses option of EVs discharge just for up reserve provision and not for energy service provision, resulting in a lower number of EV battery cycles.

4.2. Benefits of EV participation in spinning reserve provision with respect to power system energy mix

Although the results in the previous chapter provide an insight into benefits of integrating EV for provision of various services, their behaviour is highly dictated by flexibility of the existing power plants in the power systems energy mix. For this reason, additional analyses will be provided focusing on EVs and RESs (WPP) interaction for different energy mix systems.

Following on the results from the previous section, the focus will by only on G2V-NR and G2V-YR charging modes. Figs. 9, 11 and 13 display power system's savings caused by EV's reserve provision capabilities. The *Y* axis shows "savings" calculated as the difference of TSC for a system where EVs can provide

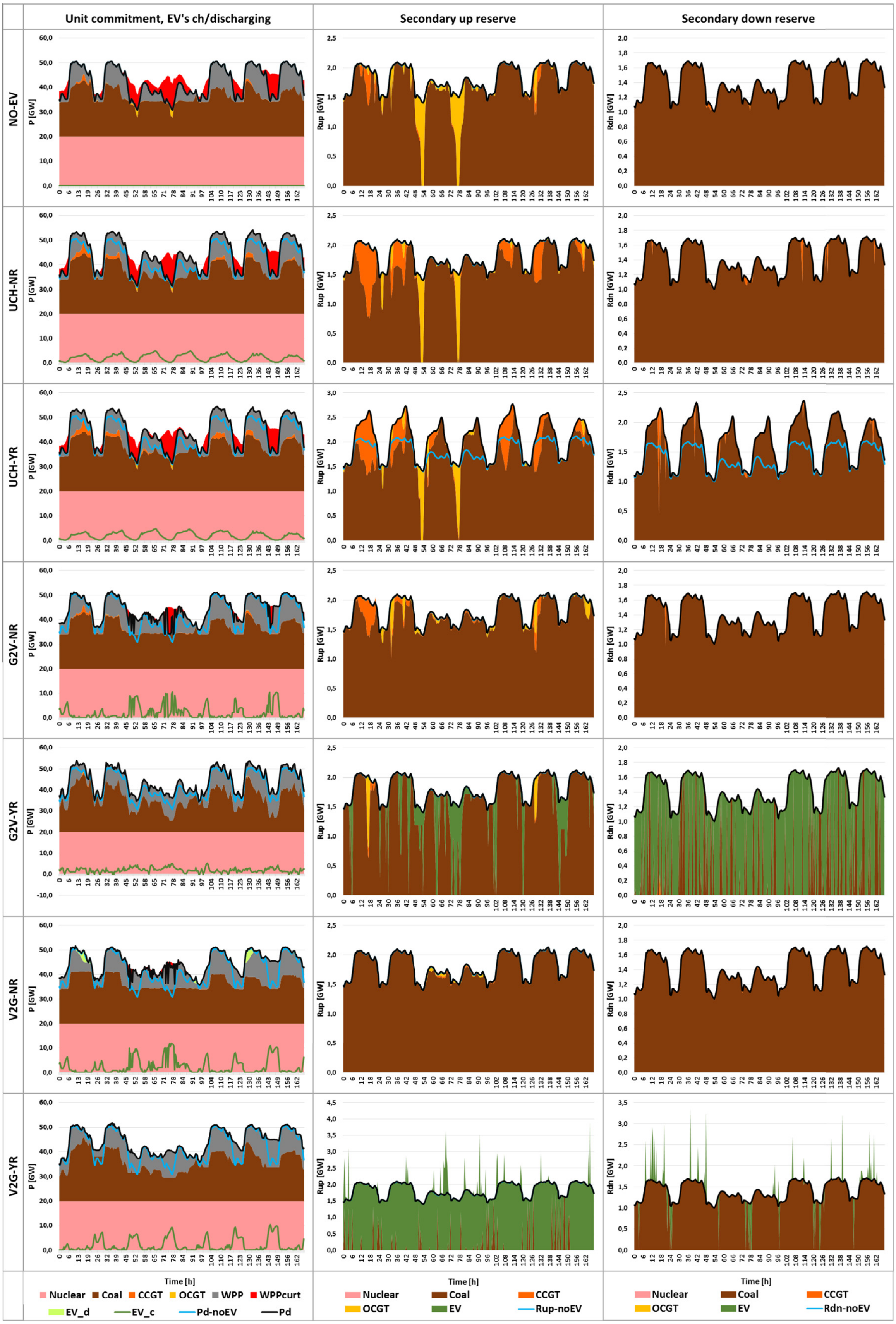

Fig. 7. LoInFl system results.

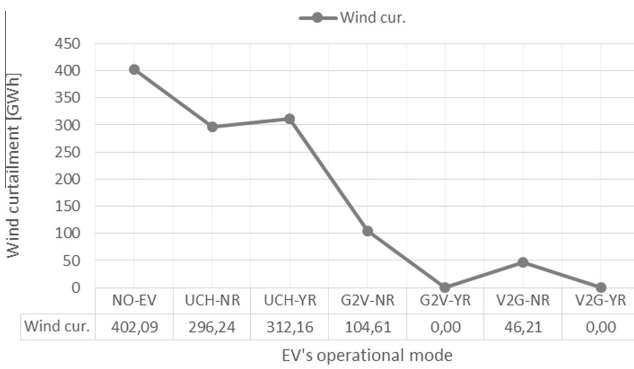

Fig. 8. Wind curtailment for LoInTh system.

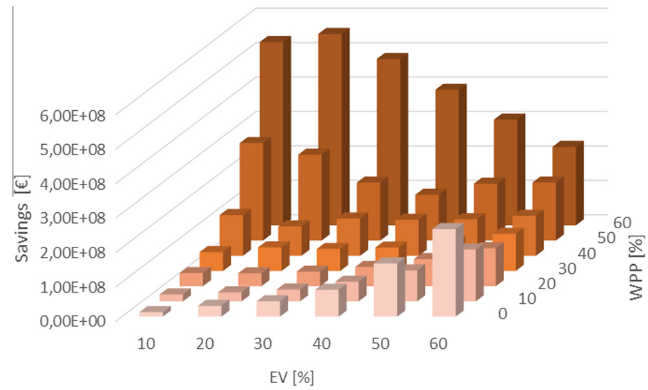

Fig. 11. System savings for FlTh system.

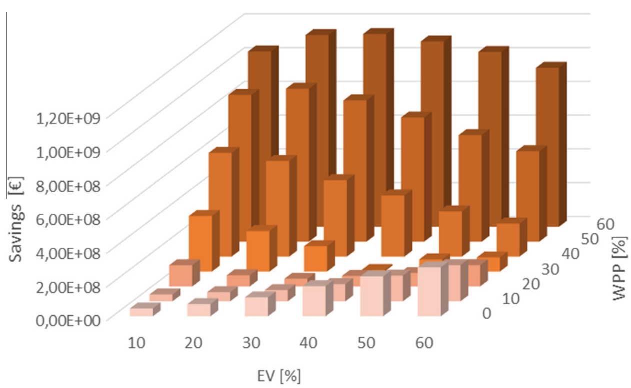

Fig. 9. System savings for InTh system.

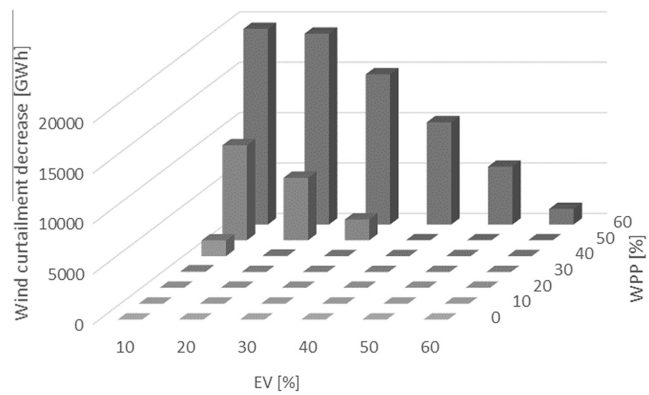

Fig. 12. Wind curtailment for FlTh system.

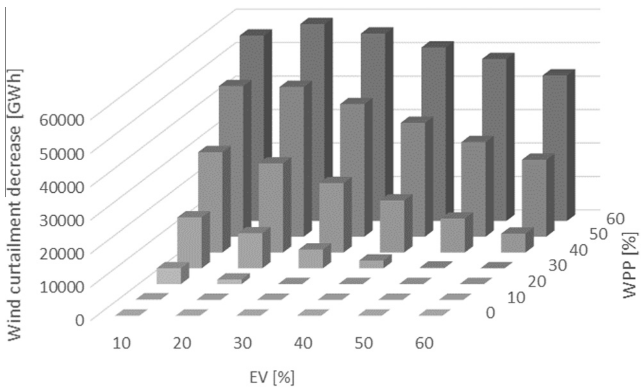

Fig. 10. Wind curtailment for InTh system.

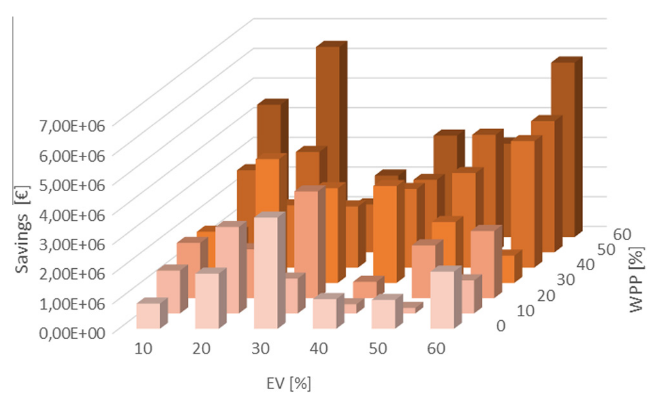

Fig. 13. System savings for HyTh system.

reserve to the one where they cannot. In addition, Figs. 10 and 12 display wind curtailment decrease as the results of EV's additional capability to provide reserve services. The analyses are shown for seven different cases of EVs and WPPs penetration ranging from 0% to 60% in 10% step increase. It provides the analyses for three different scenarios: Inflexible Thermal (InTh), Flexible Thermal (FlTh) and Hydro-Thermal (HyTh) system. Each systems energy mix and belonging characteristics are elaborated next to the results.

First two figures correspond to the InTh system which was analysed in the previous section. When there is no wind or in scenarios when wind penetration is low (<20%), higher EVs penetration results in larger savings. New flexibility introduced by EVs reserve provision capabilities is "relaxing" coal reserve constraints and they can ramp up and down more freely; in other words EVs flexibility has been mitigated to coal units. Still, the mentioned savings are relatively small compared to TSC. Higher wind penetration (>30%) shows different TSC savings behaviour. It can be easily noticed that for different wind penetration percentage there is an "optimal" EVs percentage when savings are the highest. It can be seen that those optimal points are placed in areas of low EVs penetration, e.g. for 40% WPP optimal EVs penetration level is 10%. When more WPP is included optimal points move to higher EVs penetration levels, e.g. for 60% WPP optimal EVs penetration level is 30%. More WPP means more wind curtailment and EV's capability to provide reserve is no longer used just for substituting coal power plants role in reserve scheduling, rather for decreasing wind curtailment. This can be easily seen in Fig. 10 where wind curtailment is reduced as EV share increases. It should be noted that the algorithm does not penalize wind curtailment, as in some publications [9], in order to give more realistic results.

The second analyses focus on a more flexible system still dominated by thermal power plants, the FlTh system. The size of the system, in terms of demand, is the same to make the results comparable. In addition, compared to InTh system, FlTh system has less nuclear and coal units and relies more gas turbine power plants, as shown in Table 2. The first thing that can be noticed comparing Figs. 11 and 13, is that TSC savings are much lower in FlTh system. Highest saving for InTh is 1.14 billion € (this accounts for 23.1% to TSC in InTh), while for FlTh this value is 0.56 billion € (for comparison, this is 9.5% of the TSC for FlTh). Similar case is with wind curtailment in Figs. 10 and 12. Highest wind curtailment reduction for InTh system is 58.83 TW h (85%), while in FlTh it is 19.4 TW h (80%), which clearly shows how InTh gains more by new flexibility providers, EV. For the more flexible system, FlTh, wind curtailment occurs only for 50% or more WPP. FlTh, due to its higher flexibility, can utilize most of integrated WPP even without EV and their reserve capabilities. When there is no wind or wind penetration is low (<20%), higher EVs penetration causes higher TSC savings (savings are again expressed as scenarios when EV can provide reserve services to that where they cannot) for the same reason as in InFl system. For 40–50% of WPP share, higher values of TSC savings happen for very low and very high EVs penetration. TSC savings for highest WPP share analysed, 60%, are very similar to 50% WPP share in InTh system.

The third analyses discuss flexibility enhancement by EVs reserve provision in highly flexible hydro-thermal power system (HyTh). The share of thermal and hydro units in this system is about the same and covers 50% of total installed power capacities. Due to flexible hydro power plants (RoR hydro power plants are modelled to have accumulation of few hours while CHPP can have accumulation of 2 days) and pump-storage power plants (modelled with upper reservoir accumulation of 2.5 days and lower reservoir accumulation of 1 day) WPP is fully exploited even for high WPP penetration levels (60%), meaning wind curtailment for all analysed cases is zero. Highest saving for this system is 6.41 mill. € (0.5% of the TSC for HyTh system) and is significantly lower when compared to savings in first two cases. In Fig. 13 it can be seen that no uniform conclusion in terms of savings exist as it was the case in previous two analyses. High inherited flexibility of hydro units and new flexibility enhancement of EVs ensure sufficient low-price reserve provision even without EVs reserve provision. Irregularity in gained savings (Fig. 13) occurs since reserve provision from both hydro and EVs have similar benefits to system; none or very small additional cost occurs when reserve is provided either from hydro or EVs.

5. Concluding remarks

The results and analyses presented in the paper clearly show EV uncontrolled charging should be rigorously avoided as it creates additional costs and increases emissions compared to the systems where there is no EV. On the other hand it can be clearly seen how controlled charging strategies, even without discharging and/or reserve provision capabilities, decrease overall system cost and wind curtailment and, at the same time, increase the EPS's capability to integrate variable and uncertain sources. Additional discharging and reserve capabilities further improve EPS operations and further reduces overall system cost and wind curtailment. A key finding of the paper is that EV capability to provide spinning reserve introduces additional flexibility to EPS displacing high cost and emission units. An interesting results can be noticed for G2V mode (charging only) with the capability to provide reserve, when compared to V2G mode (both charging and discharging capability) without option to participate in reserve services. The first option outperforms the second one, and its performance is comparable to that of V2G with capability to provide both reserve and energy services.

The savings gained, both in terms of cost and CO_2 emissions, are a result of shifting the scheduling of energy and spinning reserve services from coal and gas power plants to EV. By doing this, the fossil fuel based power plants are either turned off or are operating closer to their optimal operating points, unlike in the scenarios when they have the task to alleviate issues caused by variable and uncertain wind generation.

The paper additionally contributes by clearly recognizing EVs contribution to flexibility for different power systems energy mix. While these benefits are rather high for inflexible systems, such as the one of UK, both in terms of operational cost, environmental benefits and reduced wind curtailment, they are significantly lower for already flexible systems. From the results it can be clearly seen that low flexible systems would benefit greatly from EV participation in both energy and reserve services, with the TSC reduction of 23.1% and wind curtailment reduction of 80%, while for already highly flexible systems these savings are almost negligible and are below 1% of total system cost.

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Appendix A

See Tables 3 and 4.

Table 3
Thermal units parameters.

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	260.865	12.093	12.663	13.233	750	75	16
Coal	140	210	280	350	199.435	17.0805	17.3955	17.7105	450	45	8
CCGT	68.9	111.6	154.3	197	359.485	35.3535	35.6865	36.0195	300	30	5
OCGT	4	9.3	14.7	20	176.925	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

Table 4
Hydro units parameters.

Techn.	P_{min} (MW)	P_{max} (MW)	H_{min} (m)	H_{max} (m)	Q_{min} (m^3/s)	Q_{max} (m^3/s)	V_0 (m^3)	V_k (m^3)	etah	kv	T_{ak} (d)	C_nl	C_{in}
Run-of-river	10	60	0	100	15	60	2.16E+05	8.64E+05	0.9	1	0.167	20	1
CHPP	100	250	0	238	50	120	5.25E+06	2.10E+07	0.9	1	2.025	200	1.5
	P_{gmin} (MW)	P_{gmax} (MW)	H_{gmi} (m)	H_{gma} (m)	Q_{gmin} (m^3/s)	Q_{gmax} (m^3/s)	V_{0up} (m^3)	V_{kup} (m^3)	etag	kv	T_{akup} (d)		
PS	33	275	0	519	0	60	0	12,650,000	0.9	0.99	2.44020062		
	C_{nl}	C_{in}	P_{pmi} (MW)	P_{pma} (MW)	H_{pmin}	H_{pmax}	Q_{pmin}	Q_{pmax}	V_{0dn} (m^3)		V_{kdn} (m^3)		
PS	200	1.5	35	140	0	519	0	40	84,000		3,500,000		

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