Role and Impact of Coordinated EV Charging on Flexibility in Low Carbon Power Systems

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***Abstract*—The paper analyzes the impact of Electric Vehicle (EV) integration into different power systems and their flexibility potential in mitigating the uncertainty and variability of renewable energy sources (RES) generation. The problem is cast as Mixed Integer Linear Programming (MILP) unit commitment, modelling different generation mix/technologies over a number of scenarios. The results, as expected, show that different EV charging strategies have different impacts on power system operation and unit scheduling. In addition, the analyses support the premises that the greater number of EVs, with coordinated charging strategies, can have environmental benefits in terms of reducing CO_2 emissions in addition to reducing wind curtailment and system operation costs. These benefits are more obvious in low flexible power systems characterized by dominantly thermal power plants, while they are less pronounced in balanced hydro thermal systems.**

Keywords—electric vehicles; renewable energy sources integration; mixed integer linear programming (MILP); power generation scheduling; spinning reserve; power system flexibility

NOTATION

The notation used is listed below for quicker reference.

Parameters

Δ	Time period
ρ	Frequency response slope
η_h	Efficiency of hydro power plants
η_{hp}	Pumping efficiency of pump-storage
A	Fixed cost of thermal units
A_h	Fixed cost of hydro units
B	Variable cost of thermal units
B_h	Variable cost of hydro units
C_{shed}	Load shedding penalties
C_{shut}	Shut-down cost
C_{start}	Start-up cost
C_{over}	Generation shedding penalties
E_{mc}	Carbon emissions penalties
E_{mr}	Carbon emissions rate
$E_{mrstart}$	Start-up carbon emissions rate
F_{dn}	Total downward frequency response
F_{up}	Total upward frequency response
F_{Mdn}, F_{Mup}	Total required frequency response
G	Total number of thermal units
Gh	Total number of hydro units
H	Hydro power plant head
I	Hydro power plant inflow
kv	Reservoir water loss coefficient
P_{MAX} ,P_{MIN}	Generation limits of thermal PP
P_{MAXh} ,P_{MINh}	Generation limits of hydro PP
Q_{max}, Q_{min}	Turbine outflow limits
R_{up}; R_{dn},	Total upward/downward reserve
T_{dn}, T_{up}	Minimum down/up time of thermal PP
V_k	Water storage reservoir limit
V_{dn}, V_{up}	Ramp down/up rate

Variables

a_q, a_p	Pump-storage decision variable
C_{HE}	Hydro power plant total cost
C_{TE}	Thermal power plant total cost
Em	Total carbon emissions
e_{minus}	Load shedding
e_{plus}	Generation shedding
f_{dn} ; f_{up}	Frequency response of thermal PP
f_{dnh} ; f_{uph}	Frequency response of hydro PP
P	Thermal power plants generation
P_h	Hydro power plants generation
P_p	Pump-storage pumping
n ; n_h	Number of thermal/hydro units currently operating
Q	Turbine outflow of hydro power plants
Q_p	Pump flow of pump storage
r_{dn} ; r_{up}	Reserve of thermal PP units
S	Overflow of water reservoir
V	Volume of water reservoir
v_{on}	Number of start up of gen. units at time t
v_{off}	Number of shut down of gen. units at time t
w	Wind power plants generation
Ω	Wind curtailment

I. INTRODUCTION

Electric power systems are undergoing dramatic changes and challenges. Renewable energy sources penetration is on the increase and the integration of large shares of electric vehicles (EV) are one of the biggest challenges. Even though RES and EV can help reduce CO_2 emissions and increase autonomy of powers systems they can also bring disadvantages due to their intermittent characteristics. They can reduce the robustness of the power system and can increase the need for the reserve levels [1].

It is not uncommon to have a renewable energy surplus in certain generation mixes and adaptation of specific management strategies are required in order to avoid renewable generation curtailment [2]. This trend will gain on significance and different integration concepts in various generation mixes will need to be considered [3]. Different systems have different requirement for flexibility. And interdependence of reserve requirement and wind power generation is very important [4].

The goal of a unit commitment problem is to determine the outputs of all the generators with the aim to reduce the overall operational cost. All the constraints and unit parameters must be taken into account [5]. The inclusion of high wind generation and EV shares changes the unit commitment priorities of traditional power plants (hydro and thermal) [6].

The capability to control the charging of the EVs when they are plugged will lower system costs and provide additional support to power system and enable better integration of renewable energy sources. [7] estimates the cost of plug-in electric vehicle and benefits of their implementation in power system. To the opposite, this paper focuses more on reducing curtailed wind for different shares of EV in total load and investigating global impact of large EV integration on flexible and non-flexible generation mixes. EV can be used to provide temporal/energy arbitrage as a flexible load or as additional load capable of reducing the overall system price instead of increasing it. Strategies for coordinated control of all plugged EV are an important development direction [8], [9].

II. Model Formulation

Mixed-integer linear programming model was developed in commercially available solver FICO Xpress [10]. The input data is read from the external excel data sheets where the results are stored and processed. The model is used to solve unit commitment problem in different scenarios. The modeled system consists of N_i thermo and nuclear power plants, N_{ih} hydro and pumped hydro and wind with addition of electric vehicles. The total power of this global power system is 50 GW. The scenario analysis was conducted with various shares of generation technologies to simulate different systems with different inherent flexibility for the acceptance of large wind production and EV fleets. The parameters of generation units can be found in the appendix.

A. Objective function

Objective function (1) is the sum of fixed and variable costs of hydro (HE) and thermal (TE) power plants. To ensure the optimality of reached solutions two additional variables are introduced: e_{minus} and e_{plus} representing the surplus or deficiency of energy in the system. C_{shed} represents VOLL (Value Of Lost Load), the biggest price consumers are willing to pay to ensure no outages at their side occur. Penalty for the injection of energy that is not needed (surplus) is represented with C_{over}.

$$f_{obj}{}^{min} = \sum_{t=1}^{Nt} \left\{ \begin{array}{l} \sum_{i=1}^{Ni} \left[C_{TE}(t,i) \right] + \sum_{i=1}^{Nih} \left[C_{HE}(t,i) \right] + \\ + e_{minus}(t) \cdot C_{shed} + e_{plus}(t) \cdot C_{over} \end{array} \right\} \quad (1)$$

TPP cost (C_{TE}) consist of 3 parts, start-up costs (C_{start}/C_{shut}), operational costs and emissions costs (Em_c). Operational costs are dependent on the fuel consumption curve and are approximated by the linear characteristic showing the dependency of operational costs on output power. In equation (2) fixed costs (A) are not dependent on output power of plant i in time step t ($P(t,i)$) whereas variable costs (B) are.

$$\begin{array}{l} C_{TE}(t,i) = v_{on}(t,i) \cdot C_{start}(i) + v_{off}(t,i) \cdot C_{shut}(i) + A(i) \cdot n(t,i) + \\ \quad B(i) \cdot (t,i) + Em(t,i) \cdot Em_c(i), \quad t \in [1, N_t], i \in [1, N_i] \end{array} \quad (2)$$

Vector n shows how many TPP are in operation at any given moment while v_{on} i v_{off} show how many of them have been turned on or off.

$$\begin{array}{l} v_{on}(t,i) \geq n(t,i) - n(t-1,i) \\ v_{off}(t,i) \geq n(t-1,i) - n(t,i) \end{array} \quad (3)$$

Emissions consist of start-up emissions (Em_{rstart}) and follow up emission in operation (Em_r).

$$Em(t,i) \geq v_{on}(t,i) \cdot Em_{rstart}(i) + P(t,i) \cdot Em_r(i) \quad (4)$$

HPP costs are also divided on fixed (A_h) and variable cost (B_h). They are being considered because in case of surplus of renewable energy the water energy is shed.

$$C_{HE}(t,i) = A_h(i) \cdot n_h(t,i) + B_h(i) \cdot P_h(t,i) \quad (5)$$

B. System constraints

The basic equilibrium between the generation and production must be satisfied at all time steps. In equation (6) contributors on the right are: TPP generation, HPP generation, wind generation, EVs demand, surplus and deficiency of energy.

$$\begin{array}{l} \sum_{i=1}^{Ni} P(t,i) + \sum_{i=1}^{Nih} [P_h(t,i) - P_p(t,i)] + + w(t) + \ldots \\ \ldots - \sum_{i=1}^{Ni} P_{gridc}(t,i) + \sum_{i=1}^{Ni} P_{gridd}(t,i) + e_{minus}(t) - e_{plus}(t) = D(t) \end{array} \quad (6)$$

The power system must have certain amount of flexibility to compensate unplanned changes in production or in consumption. Therefore upward and downward reserves are introduced. It is assumed that only primary/secondary P-f control (P- power, f-frequency) is modeled with the synchronized generators. Sum of spinning reserve from all hydro and thermo generator units (r_{up}, r_{dn}) must meet the system requirements (R_{up}, R_{dn}) at any given time step:

$$\begin{array}{l} \sum_{i=1}^{Ni} r_{up}(t,i) \geq R_{up}(t), \quad t \in [1, N_t] \\ \sum_{i=1}^{Ni} r_{dn}(t,i) \geq R_{dn}(t), \quad t \in [1, N_t] \end{array} \quad (7)$$

The required reserve increases through time. It is the smallest in the first hour of time horizon and increases towards the end (24th hour). This is caused by the increase of standard deviation of forecast error of output power of RES generation and consumption in commonly used 24 hour planning horizon.

Primary frequency control is done by turbine regulators (f_{up}, f_{dn}) that compensate fast and sudden changes in frequency:

$$\sum_{i=1}^{Ni} f_{up}(t,i) \geq F_{up}(t), \quad t \in [1, N_t]$$
$$\sum_{i=1}^{Ni} f_{dn}(t,i) \geq F_{dn}(t), \quad t \in [1, N_t] \qquad (8)$$

C. Thermal and hydro power plants

In the following section characteristics of traditional power plants are described. The thermal power plants are described in short. Due to the limited space and a large number of modelled constraints only the hydro power plants will be described in while the same methodology with certain modifications can be applied on the pumped-hydro power plants.

The flexibility of different generator units depends on its technical minimum (equation (9)), minimum up (T_{up}) and down (T_{dn}) times (equation (10)) and ramp characteristics V_{up} and V_{dn} (equation (11)):

$$n(t,i) \cdot P_{max}(i) \geq P(t,i) \geq n(t,i) \cdot P_{min}(i) \qquad (9)$$

$$v_{on}(t,i) \leq n(\tau,i), \qquad \tau \in \left[t+1, \min\left(t+T_{up}(i)-1, N_t\right)\right]$$
$$v_{off}(t,i) \leq G(i) - n(\tau,i), \quad \tau \in \left[t+1, \min\left(t+T_{dn}(i)-1, N_t\right)\right] \qquad (10)$$
$$t \in [1, N_t - 1], i \in [1, N_i]$$

T_{up} and T_{dn} are expressed in number of time intervals.

$$P(t,i) - P(t-1,i) \leq n(t-1,i) \cdot V_{up}(i) \cdot \Delta + v_{on}(t,i) \cdot P_{min}(i)$$
$$P(t,i) - P(t-1,i) \leq \left(P_{max}(i) \cdot n(t-1,i) - P(t-1,i)\right) + v_{on}(t,i) \cdot P_{min}(i) \qquad (11)$$
$$P(t-1,i) - P(t,i) \leq n(t,i) \cdot V_{dn}(i) \cdot \Delta + v_{off}(t,i) \cdot P_{min}(i)$$
$$t \in [2, N_t], i \in [1, N_i]$$

Detailed model of spinning reserve and frequency response characteristics of TPP can be found in literature [11].

HPP have the ability to store certain amounts of water. Water equilibrium equation (12):

$$V(t,i) = V(t-1,i) \cdot kv(i) + I(t,i) \cdot 3600 \cdot \Delta - Q(t,i) \cdot 3600 \cdot \Delta - S(t,i) \cdot 3600 \cdot \Delta \qquad (12)$$

V(t,i) is the volume, *I(t,i)* is the inflow, *Q(t,i)* is the turbine flow, *S(t,i)* is spillage while *kv(i)* represent the water accumulation losses. HPP output is dependent on turbine flow and due to linearization of the model head *H(i)* and water density (ρ_h) are constant :

$$P_h(i) = \eta_h(i) \cdot H(i) \cdot Q(t,i) \cdot g \cdot \rho_h, \; t \in [1, N_t], i \in [1, N_{ih}] \qquad (13)$$

Volume must at all times be smaller than the maximum; spillage is limited with the maximum value to avoid too fast accumulation drain; turbine flow and accumulation net head have its maximum and minimum values. More details about HPP modelling is given in [12].

D. Electric Vehicles

Electric vehicles represent additional demand for power systems but with smart charging schemes the impact can not only be compensated but EV can provide additional flexibility. The basic EV behaviour is modelled with equations (14)-(17).

Energy stored in plugged EV is represented with the following equation where contributors are: total energy accumulated in EV plugged into the grid (S_{ev}), EV plugged into the grid at past time step S(t-1,i), efficiency of charge/discharge (η_c *i* η_d), charge/discharge power (P_{gridc} *i* P_{gridd}), energy of arriving (S_{arr}) and leaving (S_{leav}) EVs. $i \in [1, N_{ev}]$ where N_{ev} is the total number of EV.

$$S_{ev}(t,i) = S(t-1,i) + \eta_c(i) \cdot P_{gridc}(t,i) \cdot \Delta - \eta_d \cdot P_{gridd}(t,i) \cdot \Delta$$
$$\ldots + S_{arr}(t,i) - S_{leav}(t,i) \qquad (14)$$

The initial and final energy of EV must match according to following equation:

$$S_{ev}(N_t, i) \geq S_{ev0}(i); \quad i \in [1, N_{ev}] \qquad (15)$$

Constraints regarding the energy of arriving (equation (16)) and leaving (equation (17)):

$$S_{arr}(t,i) = n_{arr}(t,i) \cdot S_{cons}(i) \qquad (16)$$

$$S_{leav}(t,i) \geq n_{leav}(t,i) * S_{cons}(i)$$
$$S_{leav}(t,i) \leq n_{leav}(t,i) * S_{\max}(i) \qquad (17)$$
$$S_{leav}(t,i) \geq n_{leav}(t,i) * S_{minc}(i)$$

Every EV which returns to grid has lower energy accumulated in its battery, how low depending on EVs characteristics and trip length. Ones that are leaving the grid need to be charged more then they consume (S_{cons}) and more than their minimal allowed SOC is (S_{minc}). Overcharging should also be avoided.

Additionally, the model is expended to investigate the behaviour of EV fleets under different charging schemes:

- Passive charging:

Passive charging assumes that every EV that arrives and plugs into the grid will be charged at full power until charged fully. Equation (18) ensures that the total demand of all EV is higher or equal to the amount of arrived vehicles and ones that were initially plugged in. This condition is valid until time step N_c when EV that were initially connected get fully charged.

$$P_{gridc}(t,i) \geq n_{arr}(t,i) \cdot P_{evmax}(i) + P_{gridc}(t-1,i)$$
$$t \in [1, N_c], \; i \in [1, N_{ev}] \qquad (18)$$

From time step N_c to N_t (total simulation time) equation (19) ensures that the total demand of EV is higher or equal to the sum of arrived EV in certain time step and vehicles plugged in from time step *t-* N_c to *t*.

$$P_{gridc}(t,i) \geq n_{arr}(t,i) \cdot P_{evmax}(i) + \sum_{\tau=t-Nc-1}^{t-1} n_{arr}(\tau,i) \cdot P_{evmax}(i) \qquad (19)$$
$$t \in [N_c, N_t], \; i \in [1, N_{ev}]$$

P_{gridd} shows that in this charging mode EV are not able to inject power into the grid.

$$P_{gridd}(t,i)=0;\ t\in[1,N_t],\ i\in[1,N_{ev}] \tag{20}$$

- Optimal active charging G2V (*Grid-to-Vehicle)*:

G2V charging mode allows the optimal allocation of charging resources. This means the vehicles do not need to be charged at maximum power at minimum time period.

The following equations ensure that the EV demand is limited with its minimum and maximum values:

$$P_{gridc}(t,i)\geq n_g(t,i)\cdot P_{evmin}(i);\ \ t\in[1,N_c] \tag{21}$$

$$P_{gridc}(t,i)\leq n_g(t,i)\cdot P_{evmax}(i);\ \ t\in[1,N_c] \tag{22}$$

G2V charging scheme does not support injection of energy stored in EV back into the grid.

$$P_{gridd}(t,i)=0;\ t\in[1,N_t] \tag{23}$$

- Optimal active charging V2G (*Vehicle-to-Grid)* with the possibility to inject power to the grid:

V2G mode of charge allows to optimization model to use the full potential of EV and when needed consider their power injection into the grid.

The following simple equations model the behaviour of EV in V2G mode. Binary variable x_c is 1 if power is being taken from the grid (EV charging) and 0 if the power is being injected. Therefore, at the same time step EV cannot simultaneously be charged and discharged. Equations (24) and (25) model the charging of EV in V2G mode:

$$P_{gridc}(t,i)\geq n_g(t,i)\cdot P_{evmin}(i)\cdot x_c(t,i);\ t\in[1,N_c] \tag{24}$$

$$P_{gridc}(t,i)\leq n_g(t,i)\cdot P_{evmax}(i)\cdot x_c(t,i);\ t\in[1,N_c] \tag{25}$$

Discharge constraints are modelled with:

$$P_{gridd}(t,i)\geq n_g(t,i)\cdot P_{evmin}(i)\cdot(1-x_c(t,i)) \tag{26}$$

$$P_{gridd}(t,i)\leq n_g(t,i)\cdot P_{evmax}(i)\cdot(1-x_c(t,i)) \tag{27}$$

EVs are classified in two groups of transportation patterns: personal vehicles and public transportation. Personal vehicles resemble typical diurnal driving behavior patterns such as leaving in morning (to go to work) and arriving home at afternoon. This means that EVs are mostly available for charging at night (approximation of 90%) or around noon (approximation of 40%). Their behavior changes at weekends when they are used later in mornings and more uniformly throughout day. They can cover the distance of around 60 km with single charging. Second group is public transportation which implies bigger batteries and longer trips (100 km). Their driving pattern is uniformly distributed throughout day and they are available for charging only at nights. Also, both groups are divided into three trip lengths: short, medium, long (completely depletion of battery). More detailed data about EVs is given in table I.

TABLE I. ELECTRIC VEHICLES PARAMETERS

Input parameter		*Personal vehicle*	*Public transport*
P_{min} [kW]		0,2	2
P_{max} [kW]		4	40
S_{min} [kWh]		3	24
S_{max} [kWh]		15	120
Consumption [kWh/km]		0,2	0,8
S_{minc} [kWh]		15	120
η_c		0,9	0,9
η_d		0,9	0,9
Range [km]	short	20 km	60 km
	medium	40 km	80 km
	long	60 km	100 km
Percent of EVs type and range in total number of EVs	short	15%	2,5%
	medium	60%	2,5%
	long	15%	5%

III. SCENARIOS SELECTION AND RESULTS

Scenarios representing different generation mixes were selected. Table II. shows three cases, i.e. three different generation mixes:

- Dominantly nuclear-coal thermo system (non-flexible thermo - nonFTh);
- Dominantly coal-gas thermo system (flexible thermo - FTh);
- Dominantly hydro-thermo system (decently flexible system - HyTh).

TABLE II. SCENARIOS GENERATION MIXES

Gen. type *	*NPP [%]*	*Coal [%]*	*Oil [%]*	*CGT*		*HPP*		
				Open *[%]*	Comb *[%]*	Acc *[%]*	Run. *[%]*	Pump *[%]*
nonFTh	45	40	5	10	0	0	0	0
FTh	15	20	10	40	15	0	0	0
HyTh	20	20	0	10	0	15	20	15

**percent of totally needed generation capacity to cover demand, reserve and primary control requirements*

For each scenario 4 cases were considered, one without EV, and the other three with 20% EVs penetration for passive charging, G2V and V2G charging modes. Theoretically maximum EV demand is therefore 10 GW. Practically that demand level of EV is never reached since all of the EV are not connected on the grid at the same time. The simulation is run over a period of one week.

Only the case for non flexible thermo system is described since the similar process occurs in other two scenarios (flexible thermo and hydro-thermo) regarding the differences between the charging modes. Displayed graphs (Figure 1-3) point on EVs impacts on generation scheduling. EVs in passive charging mode evidently increase peak load (Figure 2) compared to the base case without EV (Figure 1). Increased peak load results in less stable power system operation and require additional generating units to be scheduled. Contrary to passive changing mode G2V and V2G modes do not increase peak load because EV are optimally charged mostly at night and therefore there is no need for new generation units startups or scheduling of extra generation capacity. Additionally, V2G mode slightly decreases required generation at peak hours.

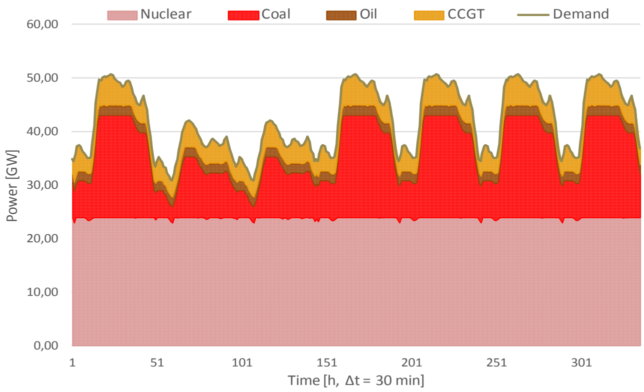


Fig. 1. Non flexible thermo system base case without EVs

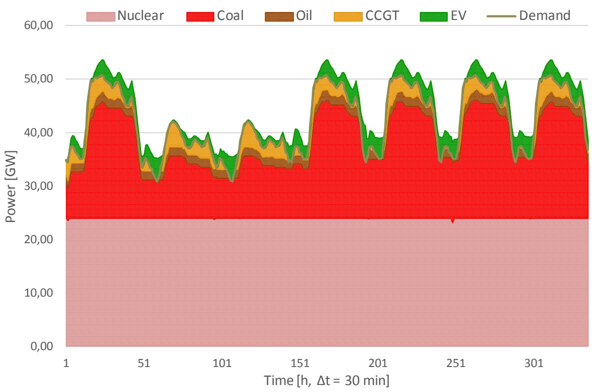


Fig. 2. Non flexible thermo system passive charging

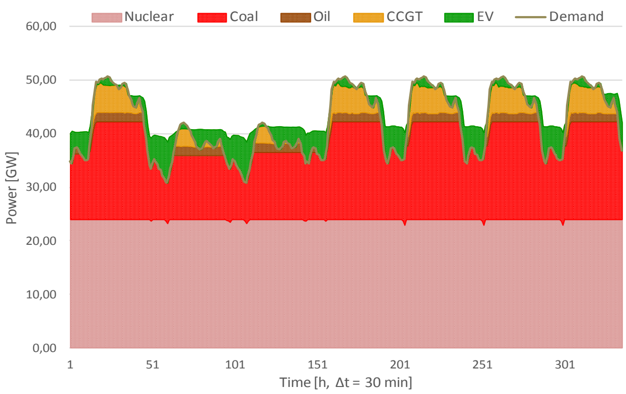
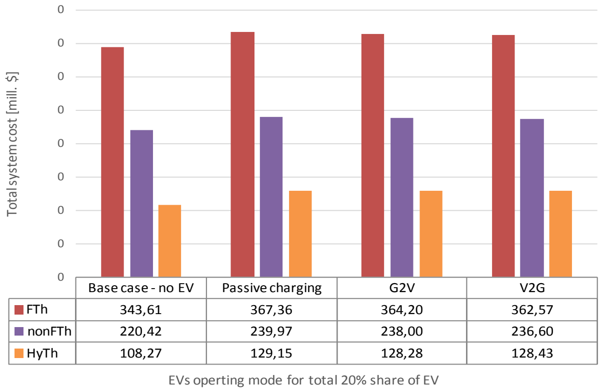


Fig. 3. Non flexible thermo system V2G charging mode

Figure 4 depicts total system cost for different scenario and charging modes. Evidently, EVs in passive charging mode increase system cost (Figure 4) in addition to the increase of peak load (Figure 1-2). When observing displayed cases, biggest increase in system costs (in percent) has hydro-thermo scenario because additional expensive thermo units needs to be started up in order to cover the newly connected load of EVs. But when comparing passive charging and G2V or V2G charging modes hydro-thermo case has the lowest cost decrease because of its high flexibility.



	Base case - no EV	Passive charging	G2V	V2G
FTh	343,61	367,36	364,20	362,57
nonFTh	220,42	239,97	238,00	236,60
HyTh	108,27	129,15	128,28	128,43

Fig. 4. Total system costs for chosen scenarios depending on charging mode

Second series of results again refer to non-flexible thermo case with different shares of wind penetration and EVs. Here are displayed 3D graphs presenting total system costs (Figure 4), total CO2 emissions (Figure 6) and curtailed wind (Figure 7) for wind and EVs penetration in range from 0% to 60 % of maximum consumption. The percentages are vast for the present state but in a longer planning horizon are not unexpected and it is worthy to study these trends.

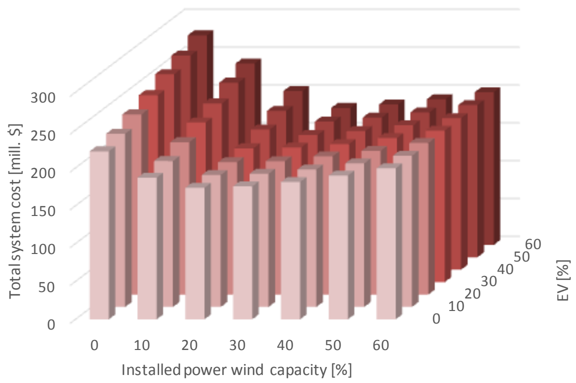


Fig. 5. Total system costs interdependance on wind and EV penetration in non flexible thermal scenario and G2V charging mode

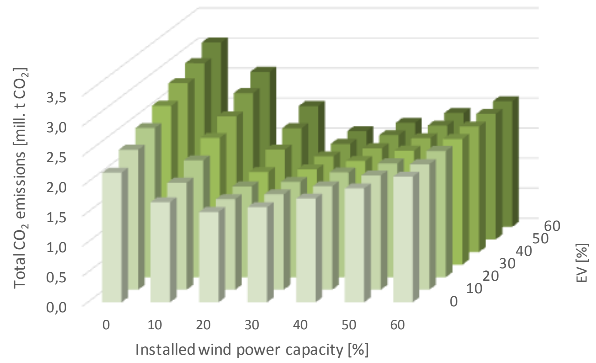


Fig. 6. Total CO_2 emission interdependance on wind and EV penetration EV penetration in non flexible thermal scenario and G2V charging mode

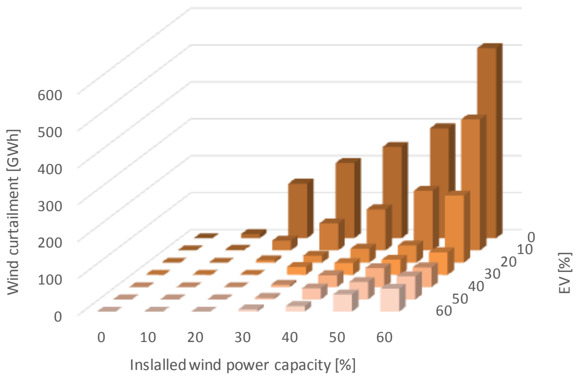


Fig. 7. Wind curtailment interdependance on wind and EV penetration EV penetration in non flexible thermal scenario and G2V charging mode

Interesting to note is result for 0% EVs penetration on all three graphs. Total system cost decrease until wind penetration reaches 30% and then it starts to increase. Reason for this lies in fact that up to 30% of wind penetration, system operator was shutting down expensive coal fired plants, and nuclear power plants were scheduled rather constantly. When wind penetration reached 30%, system operator was not able to shut down the same amount of coal fired plants because they are needed for to ensure sufficient reserve. Therefore nuclear power generation was decreased. With further increase of wind penetration reserve requirements also increase which means that total coal generation was increased and total nuclear power generation was decreased even further. This leads to increase of total system cost. When EVs penetration is increased for no wind generation case (0% wind penetration) total system costs and emissions increase as well. This happens because, from systems point of view, EV represent new load connected to system. That increase in costs is significantly lower when there is a large share of wind generation connected to the system. This means that EVs have positive impact on power systems with large shares of wind generation. Same applies vice versa for systems with large EV shares and addition of wind generation. The similar trend applies to total CO2 emissions.

Curtailed wind generation does not have such turnover at 30% of wind penetration, but rather a linear increase in curtailed wind in the range of 0% to 60% of wind penetration. Curtailed wind generation is significantly decreased up to 30% EVs, further increase in EVs have negligible impact on curtailed wind generation.

IV. Conclusion and Future Work

The presented work provides a detailed mathematical formulation of Unit Commitment model based on MILP and presents several interesting results over a set of scenarios varying energy mix, EV and RES penetration level as well as charging concept of EV.

For a Non-flexible systems total cost is increased by 7% when 10 GW EV passive load is introduced without the possibility to optimally charge it. On the other hand in highly flexible system total cost is increased 19,29% which is almost three times more than in non-flexible thermal system. On the other hand, in scenarios where coordinated charging is introduced, in V2G concept, decrease in total system cost for non-flexible thermal system is 1,3%. For the same event hydro-thermo (Hy-Th) case sees a decrease that is much smaller, only 0,55%. It should be noted that the difference are a bit more substantial if comparing coordinated and non coordinated charging where both systems gain significant benefits from intelligent EV charging. With the integration of EVs the wind curtailment in case of 30% wind penetration is reduced drastically. In case of 0% of EVs wind curtailment is 203.6 GWh. With the introduction of 10% EVs in G2V mode the wind curtailment drops 64% to the amount of 73,15 GWh. The additional increase in EV share (to total of 20%) reduces the curtailed energy to only 19,0 GWh (that is 10,2% of initial value).

Future research will be focused on changes in reserve requirements due to integration of EV and their capability to participate in mitigating reserve requirements from classical fossil based power plants. The more thorough emissions and environmental analysis will be made..

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APPENDIX

TABLE III. THERMO POWER PLANTS PARAMETERS

Input parameter	*Nuclear*	*Coal*	*CCGT*	*OCGT*	*OIL*
P_{min} [MW]	380	300	26	8	100
P_{max} [MW]	400	350	50	20	200
A [$]	190	250	626	450	500
B [$/MWh]	7,2	24	29	30	26
C_{start} [$]	35000	20000	60	46	5000
C_{shut} [$]	3500	2000	23	10	500
T_{up} [h]	36	20	6	4	10
T_{dn} [h]	24	14	4	2	8
V_{up} [MW/h]	40	60	120	90	100
V_{dn} [MW/h]	40	60	120	100	100
F_{iup} [MW]	52	42	6	2	20
ρ	0,6	0,6	0,7	0,8	0,6
Em_r [$kgCO_2$/MWh]	0	800	393	600	700
Em_{rstart} [$kgCO_2$]	0	30000	8000	3000	2000

TABLE IV. HYDRO POWER PLANTS PARAMETERS

Input parameter	*Run-of-river HPP*	*Conventional HPP*	*Pumped storage*
P_{hmin} [MW]	10	100	65
P_{hmax} [MW]	50	250	275
A_h [$]	20	200	300
B_h [$/MWh]	1	1,5	2
H [m]	100	238	519
Q_{min} [m^3/s]	15	50	15
Q_{max} [m^3/s]	60	120	60
V_k [m^3]	0	$2,60 \cdot 10^7$	$1,27 \cdot 10^7$
η_h	0,9	0,9	0,9
P_{pmin}[MW]	0	0	35
P_{pmax}[MW]	0	0	140
Q_{pmin} [m^3/s]	0	0	10
Q_{pmax} [m^3/s]	0	0	40
V_{lk} [m^3]	0	0	$1,68 \cdot 10^5$
η_{hp}	0	0	0,8