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Real-Time Tariffs for Electric Vehicles in Wind Power based Power Systems

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***Abstract*— The use of Electric Vehicles (EVs) will change significantly the planning and management of power systems in a near future. This paper proposes a real-time tariff strategy for the charge process of the EVs. The main objective is to evaluate the influence of real-time tariffs in the EVs owners' behaviour and also the impact in load diagram. The paper proposes the energy price variation according to the relation between wind generation and power consumption. The proposed strategy was tested in two different days in the Danish power system. January 31st and August 13th 2013 were selected because of the high quantities of wind generation. The main goal is to evaluate the changes in the EVs charging diagram with the energy price preventing wind curtailment.**

Keywords- Electric vehicle, Opportunity Cost, Real-time tariff, Wind generation;

I. INTRODUCTION

In future power systems, the use of renewable generation technologies based on endogenous and intermittent natural resources turns the power system management more complex. The smart grid concept applied to the power system has been proposed over the recent years [1], and it presents a structure better than the actual power systems, to accommodate all the new resources and players in the electric network. Smart grid coordinates the needs and capabilities of all generators, network operators, consumers and electricity market stakeholders to operate the power system as efficiently as possible, minimizing the costs and environmental impacts, while maximizing power system reliability, resilience and stability [2].

An important change in a near future is the use of electric and plug-in hybrid vehicles (EVs). The EVs can have the ability to charge and discharge their batteries energy into the electric network [3]. The electric network must be equipped with electronic components to enable the bi-directional power flow from the EVs. The ability of discharging power to the electric network is commonly referred as Vehicle-to-Grid (V2G). Many authors pointed out that EVs have the ability to provide ancillary services allowing the increase of the distributed generation penetration.

The EV control consists in controlling the charge and/or discharge process in terms of the amount of power and/or the period. Furthermore, it can also bring benefits to the energy resources management process of network operators. For example, EVs can be used as a support system of the intermittent renewable resources (e.g. wind or solar). EVs can be charged in off-peak periods using the excess energy from the intermittent renewable resources; consequently EVs can discharge that stored energy in the peak hours in which expensive resources are required to supply all the demand.

This is only possible if the operators have a communication system to negotiate and to control the EVs, otherwise these resources will behave as simple loads. The communication can be established in different ways: by Power Line Carrier (PLC) or by the Global System for Mobile (GSM) communication technologies [4]. The communication structure should be very efficient for scenarios with a large number of EVs to enable the accomplishment of negotiations and controls of all connected gridable vehicles. EVs can be connected to the electric network in any part of the network, such as home, parking lots of workplaces and parking lots of shopping centres. The operators need to know the status of the EV batteries to use in benefit of both players (users and network operator). The EV user must indicate its requirements to the good use of the battery, and the operator must meet them at the end of the EV connected time in the electric network.

The suggested approach could be very efficient; however this solution involves high investments in control and communications systems. Other important problem is the management of contractual aspects between players, and also the insurance in communications and in the information. Other approach could be the use of financial incentives to change the EVs owner´s behaviour. The financial incentives through special tariffs for the EVs charge and discharge processes can play an important role to control the EVs scheduling in the electric network. Figure 1 shows the EV charging behaviour with the energy price variation according the opportunity cost perspective [5]. If we have a high energy price the vehicle will charge a low amount of energy. Otherwise, the vehicle will charge closer to the fully battery state.

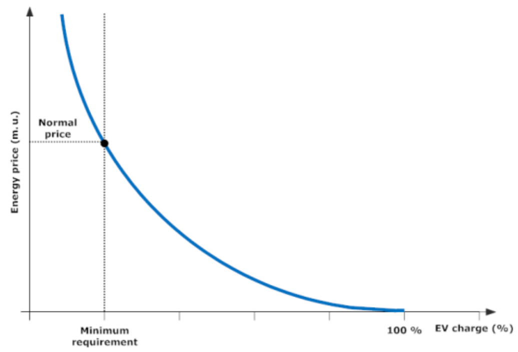

Figure 1. Opportunity cost applied to real-time EVs tariffs.

This paper proposes a price strategy based on real-time tariffs to influence the charge process of all EVs. The real-time tariff will be defined through the Wind Factor (*WF*) relation between the wind generation and the load diagram without considering EVs. This price strategy will be influenced by the wind generation profile throughout the next 24 periods. It is expected a significant change in the EVs charge scheduling comparing with a scenario without any price strategy. In periods with an excess of wind generation, the real-time price will assume a lower value in order to increase the EVs charging. Otherwise, in periods with lack of wind generation the price will be high preventing the EVs charging. It is expected that the proposed price strategy will reduce the curtailment power of wind generation due to its intermittent behaviour.

The paper is divided into 4 sections. Section I presents an introductory part of the proposed work and exposes some concepts related to the integration of EVs into the smart grid environment. Section II explains in detail the proposed price strategy to influence the EVs scheduling. Section III contains the results of the case study used to test the new price scheme. The last section presents the most relevant conclusions of the proposed work.

II. Proposed Methodology

The present methodology tries to join the perspective of macroeconomics concept about the opportunity costs with the constraints concerning the use of electric vehicle. This methodology can be used by network operators, or by aggregators, such as virtual power players. The main goal is to understand the behaviour of EVs owners when the operators change the energy prices in real-time tariffs.

A. EVs owners behaviour point of view

From the EVs owners' point of view, the main goal is to minimize the costs with the energy used to travel, charging their EVs at lower energy prices and taking advantages of energy prices variations during the day. This way, the problem can be formulated as an optimization problem considering the knowledge of the energy prices for the next 24 hours (this period depends on the operation rules). The methodology has the following assumptions:

- Each user only charge their EVs with energy required by the daily trips (E_{Trip}) (considering the regular tariff);
- The consumers respond to prices variation according to the equation $p.(z_0\text{-}z)$ proposed in [6]. The energy price (regular tariff) is represented by parameter c and the prices variation is represented by parameter Δc;
- The present formulation only considers the possibility of charging the batteries (P_{Ch}) (the discharge capability is not considered). The efficiency of charge process is also considered (η_{Ch});
- The batteries have a minimum level of stored energy ($E_{MinCharge}$) avoiding its degradation, and a maximum limit imposed by their characteristics (E_{BatCap});
- The power charge (P_{Ch}) process is limited by the charger connectors characteristics (P_{ChMax});

The problem results in a kind of minimax problem. On the one hand, consumers try to minimize the cost associated to EVs charge. On the other hand, they try to take advantage with lower energy prices increasing the quantity of stored energy in EVs batteries. These assumptions result in following problem formulation:

Objective function:

$$Minimize\ f = \sum_{t=1}^{T}\left(P_{Ch(t)} \times c_{(t)} - \Delta P_{Ch(t)} \times \Delta c_{(t)}\right) \tag{1}$$

EVs maximum stored energy:

$$E_{Stored(t)} \leq E_{BatCap}\ ; \qquad \forall t \in \{1,...,T\}; \tag{2}$$

EVs minimum stored energy:

$$E_{Stored(t)} \geq E_{MinCharge(t)}; \qquad \forall t \in \{1,...,T\}; \tag{3}$$

EVs maximum charge rate:

$$P_{Ch(t)} \leq P_{ChMax(t)}; \qquad \forall t \in \{1,...,T\}; \tag{4}$$

EVs batteries energy balance:

$$E_{Stored(t)} = E_{Stored(t-1)} + \eta_{Ch} \times P_{Ch(t)} \times \Delta t - E_{Trip(t)} \tag{5}$$

B. Energy Prices variation

The energy price for the domestic consumers is characterized, in several countries, by a single tariff during all day and by two or three different (peak and off-peak) tariffs during the day, for the large consumers. Usually, these tariffs are defined based on energy costs determined by agreements between retailers and producers, and by the participation in the electricity markets.

In some cases, to respond to the prices variation in electricity markets, resulting from the fuel prices variation, retailers change the tariffs regularly (at least every year but in many countries the prices change 1 or 4 times a year). However, in some regions, the prices in electricity markets are, currently, very influenced by the large penetration of wind power. In fact, the network operators are forced to absorb all the injected power from wind power plants, resulting in prices nearby zero in electricity markets. In some electricity markets, such as Nordpool spot or in EEX, the prices are negative in some periods.

Currently, in several countries the wind generation is very relevant to the energy mix. For example, wind generation represents 27% of the energy mix in Denmark, 17% in Portugal and 16% in Spain [7]. In the future this situation will be more complicated due to the continuous investments in wind generation. For example, in Denmark the government has the objective of achieving 100% of the electricity generation based on distributed generation (based on wind and CHP units) until 2035. In Portugal it is expected an increase around 50% of wind power installed capacity until 2020.

Considering the scenario with high penetration of wind generation and high volatility of electricity market prices (induced by the uncertainties introduced by wind generation) it is very important to develop new methodologies based on real-time prices.

In the present methodology, it is proposed the variation of energy price with the variation of wind generation. In fact, more important than the amount of power generated in wind farms (P_{Wind}), is the relation between the wind generation and the power consumption ($P_{Consumption}$). The impact of high wind power generation is different in peak and off-peak hours.

In this sense, it is proposed the use of a Wind Factor (*WF*) according to the following expression:

$$WF_{(t)} = \frac{P_{Wind}}{P_{Consumption}} \quad (6)$$

The *WF* factor can include other type of renewable resources (solar for example), if the total installed capacity was significant. On the other hand, in the power consumption, operators can include the capacity of interconnection lines trying to export the excess of generated energy. However, in many cases, like in north region of Portugal and Spain, the high wind generation occurs in the same periods.

To define the energy price evolution it is necessary to establish the reference price. In the present methodology, the regular tariff used by retailers is considered. Furthermore, it is also important to define the maximum and minimum energy price and the maximum and minimum *WF* values. Regarding the *WF* values, the minimum is zero (when the wind generation is zero) and the maximum is determined by the relation between the total installed wind capacity and the minimum power consumption in the system in a reference period (usually one year). The maximum and minimum price is determined by strategic questions and it should consider different aspects such as the quantity of hydro plants, the interconnection capacity, the load elasticity, the electricity market rules (existence of negative prices), etc.

With these values, the system operator can opt for a continuous price variation or consider levels of acceptable *WF* value. In Figure 2 are presented the types of possible curves for price variation.

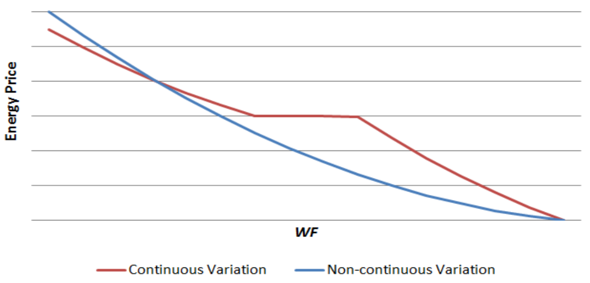

Figure 2. Real-time price variation.

III. CASE STUDY

The present case study shows the impact of EVs during two days with high impact of wind generation in Denmark, considering different real-time tariffs variation. In the end of 2012, Denmark had 4162 MW of wind power installed capacity [8] being the European country with the highest penetration of wind power in electricity consumption (27.1%) [7]. The two selected days (January 31st and August 13th 2013) present different wind profile.

Regarding the transportation, Denmark has currently around 4 million registered vehicles, 2.1 million of which are passenger cars. Approximately 50,000 of these vehicles are trucks weighing more than 3.5 tonnes [9]. In this case study 10% of EVs penetration (400 000EVs) is considered. The EVs trips profiles were obtained for groups of 2000 EVs using EVeSSI platform [10]. EVeSSI is an electric vehicles scenario generation tool in electric grids, namely in smart grids, representing EVs circulation in a given distribution network area, able to provide realistic case studies for smart grid and distribution networks operators, as well as other stakeholders or research activities working in an area related to the simulator's purpose.

In this case study it is assumed that each EV imposes a minimum stored energy of 30% of its total capacity at the end of the 24 periods. This energy allows a strategic reserve to the following day and it can be different according the power systems operation conditions [11].

The electricity price in Denmark is around 0.30 €/kWh for households, and 0.10 €/kWh for the industry [12]. The present case study considers the average price of 0.15 €/kWh. Four different functions, presented in Figure 3, are used to obtain the prices variations in real-time tariffs.

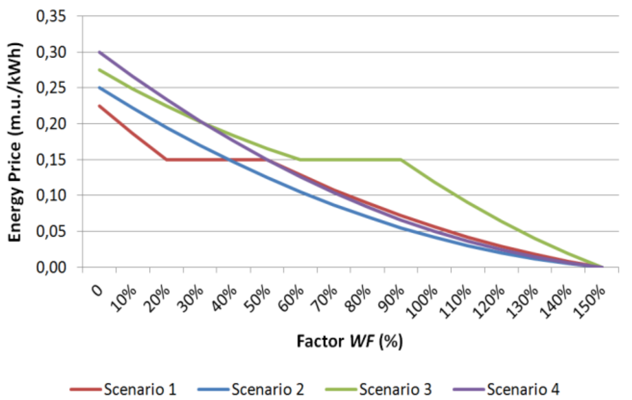

Figure 3. Electricity generation/consumption in Denmark in 01/31/2013 considering a normal electricity tariff.

The energy price functions (7 to 10) were obtained using the following conditions:

<u>Scenario 1</u>

$$\begin{aligned} &Maximum\ Price = 0.225\,€/kWh \\ &Minimum\ Price = 0\ €/kWh\ \ (WF = 150\%) \\ &WF \geq\ 50\% \Rightarrow Ep = 0.075 \times WF^2 - 0.3 \times WF + 0.281 \\ &20\% \leq WF < 50\% \Rightarrow Ep = 0.15 \\ &WF <\ 20\% \Rightarrow Ep = 0.159 \times WF^2 - 0.407 \times WF + 0.225 \end{aligned} \quad (7)$$

Scenario 2

$$\begin{aligned} &Maximum\ Price = 0.25\,€/kWh \\ &Minimum\ Price = 0\ €/kWh\ \ (WF = 150\%) \\ &Ep = 0.0833 \times WF^2 - 0.292 \times WF + 0.250 \end{aligned} \quad (8)$$

Scenario 3

$$\begin{aligned} &Maximum\ Price = 0.275\,€/kWh \\ &Minimum\ Price = 0\ €/kWh\ \ (WF = 150\%) \\ &WF \geq\ 90\% \Rightarrow Ep = 0.123 \times WF^2 - 0{,}544 \times WF + 0{,}54 \\ &60\% \leq WF < 90\% \Rightarrow Ep = 0.15 \\ &WF <\ 60\% \Rightarrow Ep = 0{,}104 \times WF^2 - 0{,}271 \times WF + 0{,}275 \end{aligned} \quad (9)$$

Scenario 4

$$\begin{aligned} &Maximum\ Price = 0.30\,€/kWh \\ &Minimum\ Price = 0\ €/kWh\ \ (WF = 150\%) \\ &Ep = 0.1 \times WF^2 - 0.35 \times WF + 0.3 \end{aligned} \quad (10)$$

The equations were obtained by fixing the minimum and the maximum energy prices and the time intervals for the regular tariff (in scenarios 1 and 3).

A. *Example 1 – Day January 31st 2013*

In the first simulation it was used the information regarding Thursday, January 31st 2013. On this day, the wind generation is higher than the demand during the first four hours of the day. In these hours, the electricity price in the NordPool Elspot Market was negative in West and East Denmark areas. Figure 4 shows the load demand consumption, the generation by resources technology and the Elspot market price in January 31st.

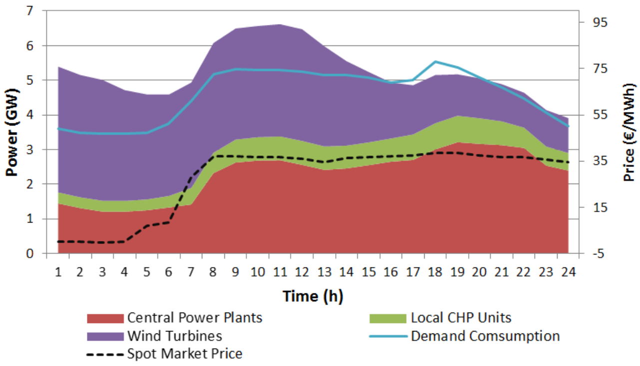

Figure 4. Electricity generation/consumption and electricity market price in Denmark in 31/01/2013 [13].

In Table I it is presented the values of *WF* for each hour of day and the energy price for each scenario, considering the expressions presented in Figure 3. In Table I, the red cells represent the hours with prices above the regular tariff (0.15 €/kWh) and the green cells represent the hours with price below the regular tariff.

Figures 5, 6, and 7 show the obtained results for 24 hours of EVs charge considering the regular tariff (Figure 5), the use of real-time tariffs in each one of the four proposed scenarios (Figure 6) and the energy stored in the EVs batteries in each hour (Figure 7).

TABLE I. JANUARY 31ST 2013 ENERGY REAL-TIME-PRICE

Hour	Wind Factor [%]	Energy Price (Scn1) [€/kWh]	Energy Price (Scn2) [€/kWh]	Energy Price (Scn3) [€/kWh]	Energy Price (Scn4) [€/kWh]
1	100.4	0.056	0.041	0.117	0.049
2	101.1	0.055	0.040	0.115	0.048
3	100.5	0.055	0.041	0.117	0.049
4	92.5	0.068	0.052	0.142	0.062
5	87.0	0.077	0.059	0.150	0.071
6	78.1	0.093	0.073	0.150	0.088
7	69.1	0.110	0.088	0.150	0.106
8	61.1	0.126	0.103	0.150	0.124
9	60.2	0.128	0.105	0.150	0.126
10	60.6	0.127	0.104	0.150	0.125
11	61.1	0.126	0.103	0.150	0.124
12	61.3	0.125	0.102	0.150	0.123
13	56.2	0.136	0.112	0.156	0.135
14	47.3	0.150	0.131	0.170	0.157
15	39.9	0.150	0.147	0.184	0.176
16	32.7	0.150	0.163	0.198	0.196
17	28.3	0.150	0.174	0.207	0.209
18	25.1	0.150	0.182	0.214	0.218
19	22.3	0.150	0.189	0.220	0.227
20	22.8	0.150	0.188	0.219	0.225
21	22.4	0.150	0.189	0.220	0.227
22	22.6	0.150	0.188	0.219	0.226
23	25.9	0.150	0.180	0.212	0.216
24	27.3	0.150	0.177	0.209	0.212

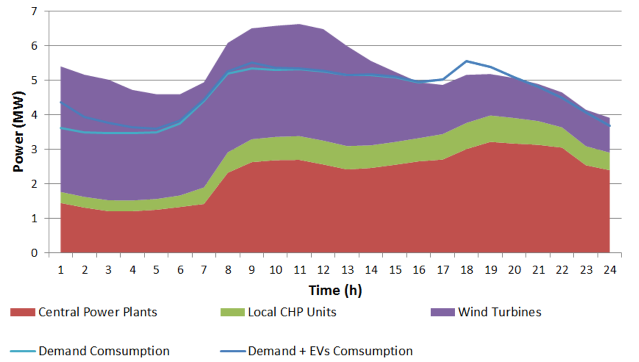

Figure 5. Impact of EVs in Denmark in 01/31/2013 considering a normal electricity tariff

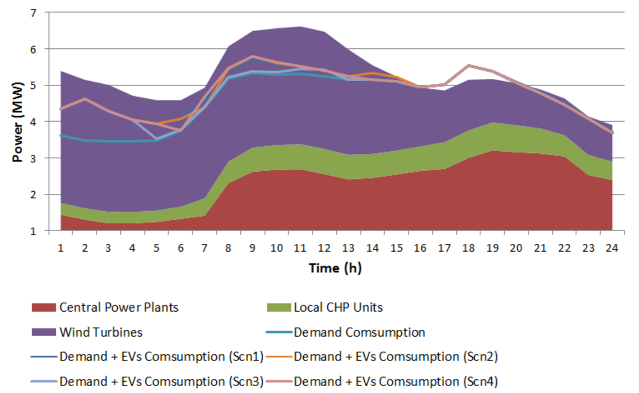

Figure 6. Impact of EVs in Denmark in 01/31/2013 considering a real-time tariff .

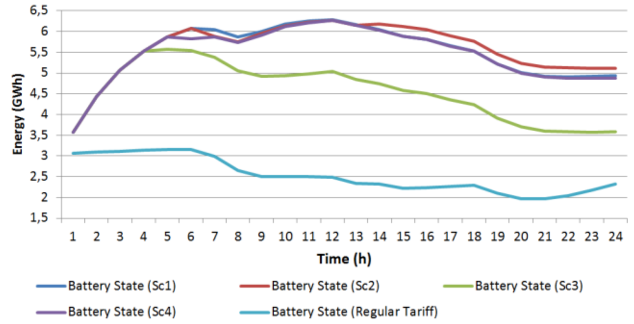

Figure 7. EVs stored energy considering a real-time tariff in Denmark in 01/31/2013.

As it is possible to see in Figure 5, in the scenario with the same tariff during the day, the consumers charge the EVs in the first hours of the day (during the night). In the simulated day, this behaviour is not bad to the system due to the high wind generation in these hours. During the day the charges are almost negligible.

In scenarios 1, 2, 3, and 4 (Figure 6 and 7) the EVs charges increase significantly between periods 1 and 6 and in scenarios 1, 2 and 4 the EVs continue charging to hour 13. This fact is due to the low prices in these hours (see the green cells of Table I). The consequence of these charges is the increase of stored energy in the EVs batteries (see Figure 7). In fact, the users leverage the low prices offered by the network operator considering the real-time tariffs to buy energy beyond their daily needs (in this simulation it was only considered the trips and not the possibility to discharge energy). In scenarios 1, 2, and 4 at the end of the day, the EVs have about 5 GWh of store in their batteries (in the scenario with regular tariff the value is less than 2.5 GWh). After hour 14 the EVs charge is practically zero, only the EVs with high number of trips have the need to charge their batteries in these periods. This behaviour results from the high prices of energy in these periods.

In scenario 3 the behaviour is very different. After hour 5, the price is equal to the regular tariff, and after hour 13 it is higher. Nevertheless, at the end of the day the EVs have 3.5 GWh energy stored in their batteries.

B. *Exemple 2 – Day August 13th 2013*

In the second simulation it was used the information for Tuesday, August 13th. On this day, the wind generation is high but not higher than consumption in peak hours (between 75% and 80% of the power consumption). The market price in Elspot does not increase significantly in peak hours, because of the high wind generation. The maximum market price was 53 €/MWh at 9 a.m. both in East and West Denmark areas. Figure 8 shows the load demand consumption, the generation by resources technology and the Elspot market price in August 13th 2013.

In Table II are presented the values of *WF* for each time of the day and the energy price for each scenario, considering the expressions presented in Figure 3.

Figures 9, 10, and 11 show the obtained results for 24 hours of EVs charge considering the regular tariff (Figure 9), the use of real-time tariffs in each one of the four proposed scenarios (Figure 10) and the energy stored in the EVs batteries in each hour (Figure 11).

TABLE II. AUGUST 13TH 2013 ENERGY REAL-TIME-PRICE

Hour	Wind Factor [%]	Energy Price (Scn1) [€/kWh]	Energy Price (Scn2) [€/kWh]	Energy Price (Scn3) [€/kWh]	Energy Price (Scn4) [€/kWh]
1	40.6	0.150	0.145	0.182	0.174
2	49.2	0,150	0,127	0,167	0,152
3	49.3	0,150	0,126	0,167	0,152
4	52.7	0,144	0,120	0,161	0,143
5	48.6	0,150	0,128	0,168	0,153
6	49.6	0,150	0,126	0,166	0,151
7	43.3	0,150	0,139	0,177	0,167
8	36.5	0,150	0,155	0,190	0,186
9	39.6	0,150	0,148	0,184	0,177
10	47.0	0,150	0,131	0,171	0,158
11	51.5	0,147	0,122	0,163	0,146
12	57.5	0,134	0,110	0,154	0,132
13	64.5	0,119	0,097	0,150	0,116
14	68.7	0,111	0,089	0,150	0,107
15	75.9	0,097	0,077	0,150	0,092
16	78.6	0,092	0,072	0,150	0,087
17	75.3	0,098	0,078	0,150	0,093
18	77.1	0,095	0,075	0,150	0,090
19	78.5	0,092	0,072	0,150	0,087
20	79.9	0,089	0,070	0,150	0,084
21	78.8	0,091	0,072	0,150	0,086
22	77.4	0,094	0,074	0,150	0,089
23	83.4	0,083	0,065	0,150	0,078
24	92.3	0.068	0.052	0.142	0.062

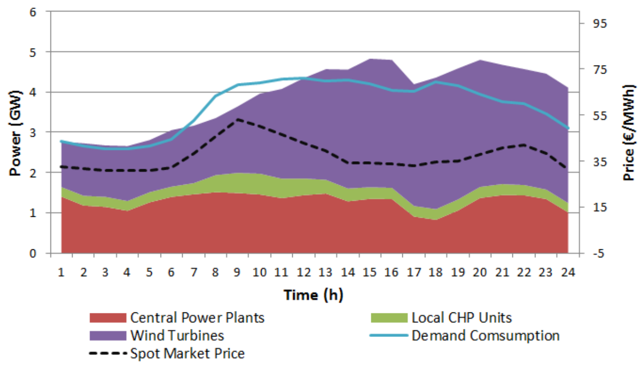

Figure 8. Electricity generation/consumption and electricity market price in Denmark in 01/31/2013 [13].

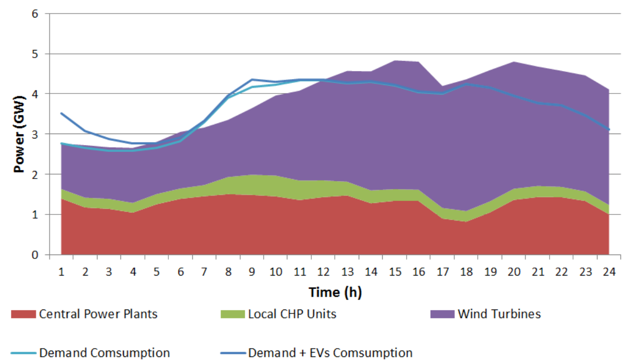

Figure 9. Impact of EVs in Denmark in 08/13/2013 considering a normal electricity tariff .

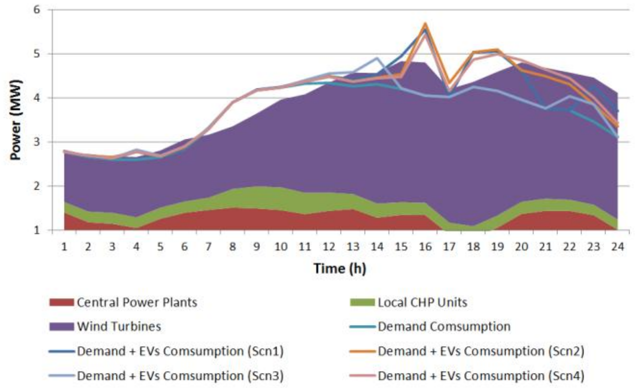

Figure 10. Impact of EVs in Denmark in 08/13/2013 considering a real-time tariff .

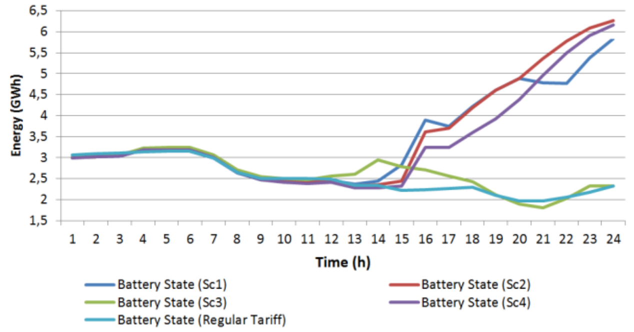

Figure 11. EVs stored energy, considering a real-time tariff in Denmark in 13/08/2013.

By analysing Figure 9 it is possible to see (like in example 1) that EVs charge in first the hours of day. However, in this example, the wind generation in these hours is low. On the other hand, in hours with high wind generation the EVs charges are nearby zero.

In Figure 10 it is possible to see the impact of real-time tariffs. In this case, the EVs only charge in hour 4 during the night. After hour 12, it is possible to see the high EVs charge levels resulting from low prices tariffs. An important point to analyse is hour 16. In this hour the EVs charge increase significantly (more than 1GW), and in hour 17 decrease abruptly (more than 1.5 GW). In fact, this change result from the wind variation (around 750 MW) but in real operation can lead to stability problems and in technical limits violations.

Figure 11 shows the batteries state during the day. In scenarios 1, 2, and 4 the EVs batteries have a lot of stored energy (around 6 GWh). This aspect could be very important in the following day.

In scenario 3 the evolution is very different from the other scenarios. In Table II it is possible to see that in this scenario the energy price is equal or higher to the regular tariff during all day (except in hour 24). Therefore, the amount of energy stored in EVs batteries at the end of the day is equal to the use of regular tariff.

IV. CONCLUSIONS

The proposed methodology will be used by the network operators to influence the electric vehicles users' behaviour using a real-time price variation based on the relation between wind generation and the total electricity consumption. In the present paper, it is also considered the opportunity cost to the EVs users, changing the amount of stored energy requirements in the EVs batteries. This methodology can be very useful, mainly in electric systems with large penetration of wind or other renewable based generation.

A case study was presented considering two days with very different wind profiles in Danish power systems. These days were used to test the impact of real-time tariffs in the power demand diagram.

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