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# OPPORTUNITY OF FREQUENCY REGULATION USING ELECTRIC VEHICLES IN DENMARK

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## Abstract

Utilization of electric vehicles (EVs) for grid ancillary services, especially for frequency regulation, in Denmark is analysed. Denmark has two different electricity grids: DK1 (Western Denmark) and DK2 (Eastern Denmark). However, although both of the grids are coordinated by the same transmission service operator (TSO, which is Energinet.dk), they have different characteristics related to the capacity, supply composition, and grid connections. The capacity of DK2 network is significantly smaller than DK1, although the share of renewable energy in DK1 is higher. However, as DK1 is connected to very large European grid, DK1 seems to be more stable than DK2. Related to frequency regulation, especially the primary regulation, DK2 provides symmetrical regulation for both up and down regulations, while DK1 adopted an independent price for each of up and down regulations. From revenue comparison of services conducted by passenger EVs, frequency regulation in DK2 brings higher revenue than one conducted in DK1. However, as the frequency and fluctuation of both up and down services are higher in DK2, faster battery degradation of EVs in DK2 feared to occur.

Keywords: Denmark, Electric vehicle, Frequency regulation, Revenue analysis Renewable energy.

## 1. Introduction

Electric vehicles (EVs) has gained an intensive attention in the last decade due to their advantageous characteristics of high energy efficiency [1], driving convenience, and lower environmental impact [2, 3]. To accelerate and facilitate the adoption of massive EVs, replacing the current internal combustion engine vehicle, several countries and local governments have issued several policies, including tax reduction, incentives, and increase of supporting infrastructures [4]. However, massive adoption of EVs also causes several problems including huge energy consumption for charging [5] and increase of secondary battery due to capacity degradation [6]. Related to the former, a coordinated charging is urgently required together with the vehicle to grid (V2G) technology to avoid any kind of improper huge demand increase of electricity, as well as improve the utilization and economic value of EVs [7-9]. Moreover, recently, several technologies to mitigate the sudden increase of electricity demand due to EVs charging also have been developed [10, 11], in addition to the policy settlement, such as charger distribution and demand response [12].

Nowadays, the liberalization of energy market, including the electricity, has motivated all of the related entities, including power supplier, consumer, and transmission operator, to actively monitor the grid condition and take part in its market [13]. In addition, transmission service operator (TSO), who is responsible for balancing both supply and demand and maintaining the grid quality, is strongly forced to develop new function in managing the grid system [14], including the management of V2G. EVs can potentially play a key role to meet such challenges and contributing to balancing the future power system. By using the characteristics of the EV as a power resource, EVs can actively support the grid. Therefore, several ancillary services in V2G have been developed, including frequency regulation [15], voltage regulation, load levelling [16], congestion mitigation, and power storage [17,18]. However, among these ancillary services, frequency regulation is considered able to achieve high economic benefit for EV owners due to the high participation price [19].

The basic concept of V2G is shown in Fig. 1. EVs are connected to the bidirectional chargers to facilitate both charging (down regulation) and discharging (up regulation). The EV owners have a contract with a certain aggregator which is responsible for controlling the behaviour of EVs' charging and discharging for ancillary service. In addition, aggregator also has a communication with the TSO, as well as the electricity market, to bid and participate in the available ancillary service programs. Once the aggregator won the bid, it will communicate with EVs and chargers to absorb or discharge the electricity from and to the grid, respectively.

Several studies have analysed the feasibility of frequency regulation by EVs in certain countries and regions, including US and Europe in general [20, 21]. However, to the best of authors' knowledge, there is almost no study deals with the effort to analyse the economic feasibility of frequency regulation in Denmark. Therefore, this study focuses on this issue in Denmark, as Denmark is considered unique having two different grid networks with different characteristics. In addition, as there are several frequency regulations services available, this study focuses mainly on the primary frequency regulation service in both different grid networks in Denmark.

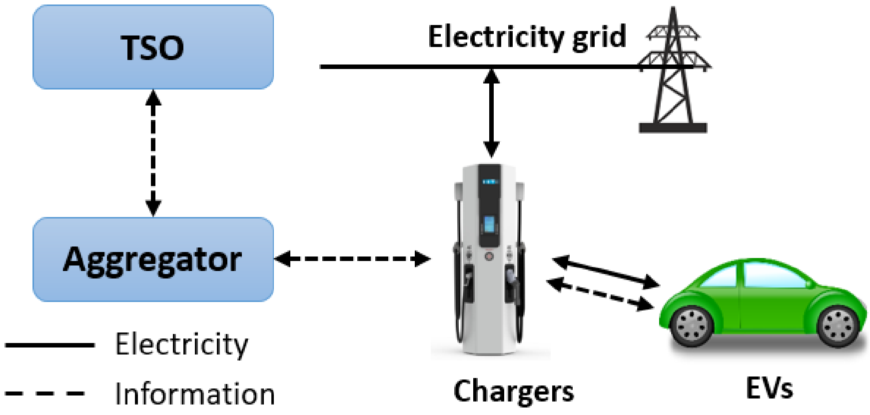



**Fig. 1. Basic concept of V2G.**

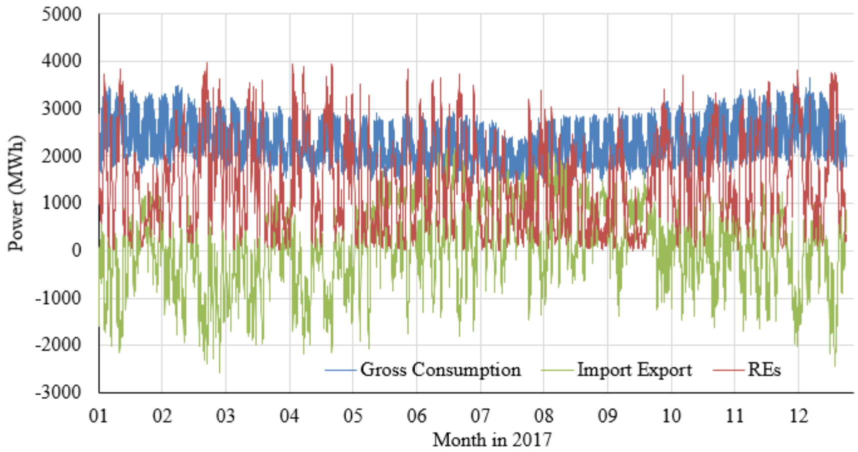
## 2. Review of Denmark Electricity Grids and Frequency Regulation

### 2.1. Electricity grid

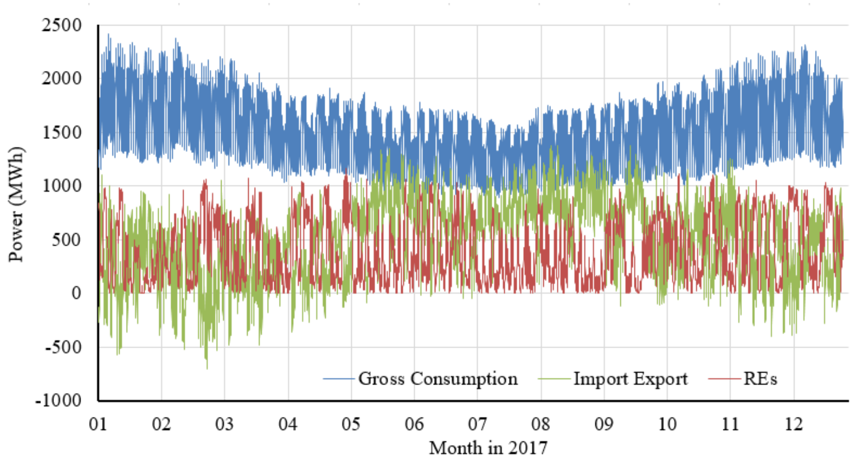
Denmark is one of the leader in the adoption of renewable energy into its grid. According to literature [22], the share of renewable energy, mostly wind energy, in 2016 was about 38%, leading to very high energy security. Denmark planned to accelerate the share of renewable energy, especially the wind, to 50% by 2020 [23]. Currently, the highest peak load in Denmark is only about 6.5 GW, with high marginal capacity of interconnections to cover the fluctuation due to renewable energy. In addition, Denmark has two synchronous grid networks: DK1 (Western Denmark, west of the Great Belt) and DK2 (Eastern Denmark, east of the Great Belt). DK1 is connected to several neighbouring countries including Germany, Norway, and DK2. On the other hand, DK2 is also connected to Germany, DK1, and Sweden. High interconnecting capacity has let Denmark to be able to balance its electricity although with high penetration of renewable energy. However, as the penetration of renewable energy is predicted to further increase in the future, domestic balancing capability becomes very important.

Figure 2 shows the consumed electricity, imported and exported electricity, and generated electricity in Denmark, both DK1 and DK2, during 2017. Positive value in the green line represents the imported electricity from interconnected grid networks, and vice versa. In DK1, the highest and lowest peak loads were about 3.5 and 2.5 GW, which occurred during winter and summer, respectively. On the other hand, in DK2, the highest and lowest peak loads were lower compared to DK1, about 2.3 and 1.7 GW, which also occurred in winter and summer, respectively.

Regarding the share of renewable energy, the highest share was obtained in DK1, which can be higher than the total consumption in the same grid network. However, in DK2, there was no such phenomenon, and the value of generated electricity by renewable sources was smaller than the total consumption. Therefore, the amount of the exported electricity to the surrounding grid networks was larger in DK1 than one in DK2. The highest generated electricity from renewable sources could achieve about 4 GW in DK1 and about 1.2 GW in DK2, which happened in several times in a year. It is clear that, in general, the penetration of renewable energy was very high in both grid networks. However, compared to DK2, the penetration of renewable energy (ratio of renewable energy to total consumption) in DK1 is also significantly larger. The highest ratio was achieved during the midnight, which was about 180%. This phenomenon occurred as the total consumption was very low, while the generated electricity from renewable sources was very high. Furthermore, the imported and exported electricity from and to neighbouring countries/grid networks was largely ranging from -2 GW (export) to 2 GW (import) in DK1, and from -0.6 GW (export) to 1.5 GW (import) in DK2. From the fluctuation of imported and exported electricity, frequent and larger exported electricity was achieved in DK1 than in DK2.




**(a) DK1 (Western Denmark).**




**(b) DK2 (Eastern Denmark).**

**Fig. 2. Electricity consumption, imported-exported electricity, and generated renewable energy in Denmark during 2017.**

## 2.2. Frequency regulation services

Frequency regulation is performed in order to maintain the grid frequency within the defined limits by balancing both supply and demand in a given control area and defined time basis [24]. Frequency regulation in Denmark is basically determined by the Danish TSO, Energinet.dk, for each grid network. In this section, several frequency regulation services, in both DK1 and DK2, which are considered feasible to be performed using EVs are described in brief. In general, there are three classifications of reserves (frequency regulations): primary, secondary, and tertiary reserves. However, this study mainly focuses on the comparison analysis of the primary frequency regulation.

### 2.2.1. Primary frequency regulation

Primary frequency regulation is generally defined as unit (both up and down) which can respond fast within a few seconds as it basically deals with sudden imbalances. Each grid network has different policy for primary frequency regulation. The primary regulation is performed in order to balance between the supply and demand and also stabilize the grid frequency to close to the target/reference frequency, which is 50 Hz. Therefore, it is conducted in both directions of up and down by production (supply) and consumption (demand) units.

In DK1, the primary frequency regulation (frequency containment reserve, FCR) is conducted in the frequency range of ±200 mHz, with an operational deadband of ±20 mHz, relative to reference frequency. The regulation service must be delivered linearly, with the maximum delivery time of 15 s for the first 50% capacity, and 30 s for the rest. In addition, each of up and down regulation services has a different set price, and the service must be able to stand for 15 min, and cool down period of 15 min. On the other hand, in DK2, the primary frequency regulation is called as frequency-controlled normal operation reserve (FCR-N), which is performed in order to stabilize the grid frequency close to the target/reference frequency, which is 50 Hz. It also reduces the number of jumps/dips of frequency. This service will be automatically activated in any frequency deviation of ±100 mHz relative to the reference frequency. It is conducted as a fast-reacting proportional control, and performed symmetrically. Moreover, there is no deadband in FCR-N and the maximum delivery time is 150 s which can be performed continuously. Both primary frequency regulations in DK1 and DK2 are conducted based on a daily auction.

### 2.2.2. Secondary frequency regulation

As the continuance of primary frequency regulation, a secondary frequency regulation is considered as the generator or load which are able to supply and absorb the electricity in response to the frequency change within 5-10 min [20]. This control action can be performed automatically through automatic generation control (AGC) or manually. Secondary reserve serves two objectives: releasing the primary reserve which has been activated, and restoring any imbalances on the interconnections.

The secondary frequency regulation in DK1 (automatic frequency restoration reserve, aFRR) is conducted automatically (load frequency control) and based on monthly contract. In addition, the activation time is ranging from 30 s to 15 min.

Like the primary reserve, this secondary reserve also consists of up and down regulation, but is requested as a combined symmetrical reserve. On the other hand, in DK2, following FCR-N as primary reserve, there is a frequency-controlled disturbance reserve (FCR-D) providing upward regulation. It is activated automatically when the frequency drops in the range of 49.5-49.9 Hz, and will stay active until the balance is restored or the manual (tertiary) reserve takes over the regulation. The service must be able to be delivered in 5 s for the first 50%, and next 25 s for the remaining capacity. Like FCR-N, the market of FCR-D is also based on the daily auction.

### 2.2.3. Tertiary/manual frequency regulation

In tertiary frequency regulation, the units of generation and load respond to the TSO signal in a longer time than the secondary frequency regulation, which is usually in the range of 15-30 min [20]. Tertiary frequency regulation in both DK1 and DK2 is almost similar, and is usually called as manual frequency restoration reserve (mFRR). mFRR is conducted manually and must be able to be supplied fully within 15 min. Moreover, the market of mFRR is based on the daily auction.

## 3. Results and Discussion on Primary Frequency Regulation Service Using EVs

Compared to conventional generators and loads, such as gas and steam turbines, EVs have significant advantages of faster response and high accuracy for power absorption (charge) and discharge [25]. On the other hand, among three above frequency regulations, primary frequency regulation occurs more frequently although its capacity is small. Considering the fast response of EVs and the limitation of available battery capacity, this study focuses on the feasibility analysis and comparison of primary frequency regulation in both DK1 and DK2.

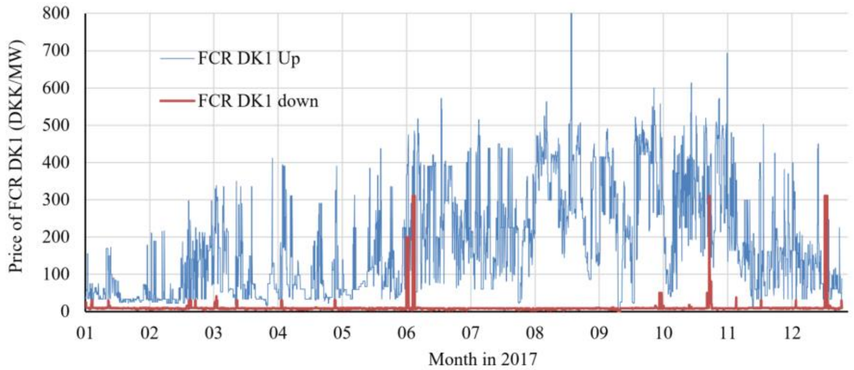
### 3.1. Price of frequency regulation services

The price of primary frequency regulation service in both DK1 and DK2 is basically defined based on the daily auction (one day before the regulation). Figure 3 shows the price comparison of the primary regulations in both grid networks of DK1 (FCR) and DK2 (FCR-N) throughout 2017. It is obvious that primary regulation in DK2 has higher fluctuation compared with the one in DK1. It is important to note that DK1 grid network is connected with the European mainland grid network, including Germany, which is very large in scale. Therefore, fluctuation due to the generated power by renewable energy, currently, can be alleviated (absorbed) smoothly. DK2, which covers Nordic area (mainly Sweden), is significantly smaller than DK1 and the share of renewable energy in the whole grid, including hydro power, wind, and PV, is very large. Therefore, the frequency fluctuation in DK2 is very rigorous.

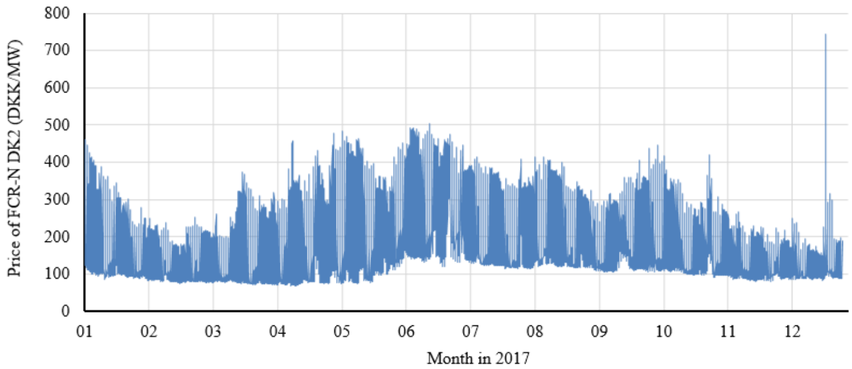
In DK1, up and down regulations are distinguished to each other (blue and red lines for up and down regulations, respectively), and the price between them is significantly different. Up regulation has significantly higher price compared to down regulation. On the other hand, in DK2, as the delivery is combined in symmetrical way in both up and down regulations, the price of both services are same. The annual average prices for up and down regulations in DK1 were about

179 and 10 DKK/MW, respectively. On the other hand, the annual average price in DK2 was 173 DKK/MW, for both up and down regulations.

The advantage of frequency regulation by EVs in DK2 is that, as it is combined in symmetrical way, both electricity absorption (charging of EVs) and electricity supply (discharging from EVs) receive the same revenue. Therefore, depending on the condition, EVs can enjoy charging while receiving relatively high profit. This is significantly different with one in DK1, in which a high revenue is only given to the up regulation, which means discharging electricity from the EVs.




**(a) DK1 FCR.**




**(b) DK2 FCR-N.**

**Fig. 3. Price of primary frequency regulation in each DK1 and DK2 in 2017.**

As the frequency fluctuation in DK2 is significantly higher, the exchanged power and energy during primary frequency regulation in DK2 is considered high. Frequent and high frequency fluctuation, exchanged power, and energy lead to several issues when the service is performed using EVs:

a. High exchanged power and energy means higher revenue which can earned by the EVs. In addition, in symmetrical delivery system (such as in DK2), the state of charge (SOC) before and after the service is almost similar.

b. Frequent charging and discharging lead to higher SOC change of the battery (depth of discharge). It is strongly related to the life time (charging and discharging cycles) of the battery. Therefore, the development of battery having long charging and discharging life cycles is urgently required.

c. High exchanged energy and its fluctuation causes a deeper depth-of-charge of the battery, leading to higher battery degradation. It also influences potentially the battery life time.

Focusing on DK2 grid, higher price of frequency regulation occurs during the night, which is generally starting from midnight until the morning. On the other hand, the grid load peaks during the noon and significantly decreases during the night. The lowest load occurs also from the midnight to the early morning. In addition, power generation in DK2 is mainly composed by thermal power (4.3 GW), wind power (1.03 GW), and solar power (0.18 GW). Furthermore, as DK2 system is also connected to several other grids, including Germany (until 2019), DK1, and Sweden, there is power export and import among the grid systems. It is considered that during the night, the ratio of renewable energy (wind power) is significantly high, leading to the high opportunity of frequency regulation service during the night. Figure 4 shows the relationship among the total grid load, generated renewable energy, and exported and imported power in DK2 in representative one week during summer in 2017.

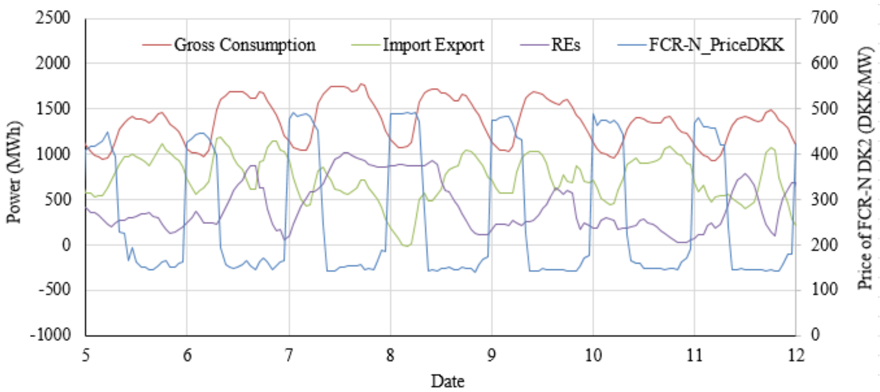



**Fig. 4. Relationship of total grid load, generated renewable energy, and exported and imported power in DK2 in a representative week in June 2017.**

## 3.2. Revenue analysis for different cases

To compare and analyse the revenue which can be earned by EVs in Denmark, several cases have been assumed. Case 1 is the case in which EVs are owned by the office or company as operating vehicles during weekday, therefore, they usually move during noon and parked in the office/company from evening to the next day morning (4 PM to 6 AM), and also during weekend. Case 2 assumes that EVs are owned privately as commuting vehicles, but there is no V2G connection at the office/company. Hence, EVs are basically connected to the grid via V2G-ready charger during the night after commuting until the morning before the departure (8 PM to 6 AM in both weekday and weekend). Moreover, the modified Case 2 with additional V2G connection during noon (8 AM to 6 PM, assuming that commuting takes 2 h for each) at the office/company is assumed as Case 3. Furthermore, Case 4 considers the condition that EVs are only used during weekend, which possibly occurs in several metropolitans with established commuting transportation system. Case 5 is the case that EVs are considered as stationary battery, hence, it is fully devoted for V2G service and connected to the grid for 24 h throughout the year.

In the calculation, several additional assumptions were made: 1) EVs have average battery capacity of 24 kWh, 2) the average maximum charger capacity is 10 kW, 3) considering the power loss in both charging and discharging, the useable capacity of charger is 9.25 kW, 4) the availability of EVs in each case is 90%, 5) the effect of environmental conditions, such as temperature, and SOC to charging and discharging rates is neglected, and 6) there are no consumption and service taxes for ancillary service using EVs.

Table 1 shows and compares the annual revenue by a single EV in several cases which are considered possible in FCR-N DK2. Based on the actual price analysis, the annual revenue which can be earned in Case 1 (EV fleets owned by any office/company) is about 9,800 DKK (1,300 EUR). Furthermore, in Cases 2 and 3 (commuting EVs with and without V2G connection during noon, respectively), the total annual revenues are about 7,200 DKK (960 EUR) and 9,500 DKK (1,200 EUR), respectively. In Case 4 (weekend EV), the possibly earned revenue is about 10,900 DKK (1,460 EUR). At the last, in the V2G-dedicated Case 5, the possible earned revenue is about 12,600 DKK (1,690 EUR).

**Table 1. Possibly earned annual revenue per EV due to participation in primary frequency regulation in DK2 (FCR-N DK2).**

| Cases | Explanation (service time) | Annual revenue (DKK/EV) |
|---|---|---|
| Case 1 | Weekday 4 PM-6 AM, weekend for 24 h | 9,839 |
| Case 2 | Weekday and weekend 8 PM-6 AM | 7,244 |
| Case 3 | Weekday 8 PM-6 AM and 8 AM-6 PM, Weekend 8 PM-6 AM | 9,527 |
| Case 4 | Weekday for 24 h, weekend 8 PM-6 AM | 10,942 |
| Case 5 | Weekday and weekend for 24 h | 12,612 |

For comparison, Table 2 shows the potentially earned annual revenue in the corresponding cases by a single EV in primary frequency up regulation in DK1 (FCR DK1). The potentially earned annual revenues by a single EV in Case 1, 2, 3, 4, and 5 are about 9,100 DKK (1,210 EUR), 5,200 (690 EUR), 9,200 (1,220 EUR), 10,800 (1,440 EUR), and 13,100 (1,740 EUR), respectively.

Compared to revenues possibly earned in FCR DK1, the revenue earned by EV in FCR-N DK2 is generally higher, except for the fully V2G-dedicated case (Case 5). However, Case 5 in FCR DK1 is an impossible case, because EVs will need charging to be able to provide an up regulation service. In addition, all the cases in FCR DK1 are also very hard to be realized due to the limitation of battery capacity and the need of charging for the next departure (commuting). Therefore, a shorter participation duration is expected in FCR DK1, leading to much lower revenue than in DK2.

**Table 2. Possibly earned annual revenue per EV due to participation in primary frequency up regulation in DK1 (FCR DK1).**

| Cases | Explanation (service time) | Annual revenue (DKK/EV/y) |
|---|---|---|
| Case 1 | Weekday 4 PM-6 AM, weekend for 24 h | 9,143 |
| Case 2 | Weekday and weekend 8 PM-6 AM | 5,221 |
| Case 3 | Weekday 8 PM-6 AM and 8 AM-6 PM, Weekend 8 PM-6 AM | 9,202 |
| Case 4 | Weekday for 24 h, weekend 8 PM-6 AM | 10,828 |
| Case 5 | Weekday and weekend for 24 h | 13,099 |

From economic analysis of primary frequency regulation, it is clear that participation in ancillary service market using EVs can improve the economic performance of EVs. However, currently there are several challenges and barriers which must be clarified and solved to facilitate well this kind of grid ancillary service using EVs. As the number of EVs in the near future is predicted to increase gradually, the potential of EVs for ancillary service is also increasing accordingly. The general barriers in V2G are assumed: 1) there is no currently available operating EVs aggregator, especially for the large scale, 2) the ancillary service market using EVs has not been established well yet, 3) the trust in technology and motivation to participate by the early adopters are still low, 4) the policies/regulations, incentives, and tax systems require significant improvement, 5) further developments in technologies and supporting infrastructures, including charger and battery, are urgently required, and 6) several environmental impacts, such as battery recycling due to high battery degradation, must be clarified and solved. To measure the feasibility and answer those above challenges and barriers, a relatively large scale demonstration test is considered required. It is expected that through this kind of demonstration test, all the entities, including government, EV owners, TSO, aggregator, and surrounding communities experience the advantage of EVs utilization in grid ancillary services.

## 4. Conclusion

Utilization of EVs to participate in ancillary service of frequency regulation, especially primary frequency regulation, in Denmark has been economically analysed. There are several important findings from the study, which can be summarised as follow:

- Grid network in Western Denmark (DK1) is significantly larger than one in Eastern Denmark (DK2), as well as the share of renewable energy. However, as the DK1 is connected to the European grid which is very large, the grid is relatively more stable than DK2. This leads to higher price fluctuation of frequency regulation in DK2 (symmetric combined up and down regulations).
- Primary frequency regulation service in DK2 (FCR-N DK2) is more economically feasible compared to the one in DK1 (FCR DK1). The symmetric primary frequency regulation in DK2 leads to higher revenue in total, including up (discharging) and down (charging) regulations. On the other hand, the asymmetric primary frequency regulation in DK1 shows relatively high price for up regulation (discharging) but very low down regulation (charging).

- As the share of renewable energy to the total electricity load is high, it is considered that the potential of frequency regulation by EVs increases accordingly. A frequent fluctuation in frequency, finally, urgently demands a very responsive regulator (service provider), such as EVs or battery.
- Several challenges and barriers related to the utilization of EVs for grid ancillary services need to be analysed and solved urgently as the number of EVs is sharply increasing.
- As the penetration of renewable energy increases significantly, an optimum balancing control using all the available methods and infrastructures are demanded. EVs can behave as one excellent candidate, however, utilization of other technologies, such as hydrogen in power-to-gas technology and pumped hydro, is strongly encouraged.

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