

Using electric vehicles as flexible resource in power systems: A case study in the Netherlands

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Abstract—Electromobility is expected to experience a significant uptake in the coming years, particularly in the Netherlands, where the possibility to ban combustion engine car sales by 2025 is under discussion. This paper aims at evaluating the impact of an increased penetration of battery electric vehicles (BEV) on the Dutch power system, using the Dispa-SET unit commitment and optimal dispatch model. The analysis starts with an extensive dataset of charging transactions for the year 2015 in the Netherlands, recorded from about one third of all public charging stations in the country. This dataset is used to generate the charging load profile of the current BEVs fleet, and to compute the connected BEVs battery capacity at each hour of the year, to be used for modelling a Vehicle-to-Grid (V2G) option in the system. Different hypotheses are then formulated regarding the future penetration of this technology. The corresponding charging profiles and available battery capacities are generated. These time series are then input into Dispa-SET to simulate the Dutch power system under different hypotheses of BEV and variable renewable energy deployment. Two different BEV charging cases are distinguished: an *immediate charging* strategy, and the use of BEVs battery capacity as variable storage unit. For each scenario, aggregated indicators are computed, including average electricity price, cycling of power plants, electricity mix in each country, or level of curtailment. Results indicate that the effect of BEVs is negligible at the current deployment levels. It becomes significant if BEVs constitute the largest share of the vehicles fleet. In this case, the additional consumption is absorbed by the power system at the expense of higher electricity generation costs. If BEVs are used for V2G, they can positively impact the power system, thus increasing system flexibility and significantly reducing the level of curtailment in case of high shares of renewables.

I. INTRODUCTION

The European Union (EU) is actively encouraging member countries to phase out traditional oil-fuelled cars in cities in favour of Electric Vehicles (EV) as a solution for increasing efficiency, contributing to ensure security of supply, decrease CO₂ emission and decrease local (especially urban) air pollution coming from the transport sector [1] [2]. With the increasing associated charging infrastructure deployment all over European countries, the demand coming from these technologies might impact the power system and potentially offer a source of flexibility through variable charging profiles and battery storage capacity options [3].

In the recent years, the Dutch government has adopted several policy support mechanisms for EVs uptake, which made the Netherlands the country with the highest market share of electric cars in 2015 in the EU, and the second-highest share

worldwide after Norway [3]. This country is therefore a unique case study for the analysis of EVs charging demand and impact of the power sector.

The recent uptake of EVs provides a significant amount of historical data regarding charging profiles, connection times or utilisation patterns pertaining this technology. This paper aims at exploiting such data to evaluate the current and future impact of electric vehicle deployment on the power system. To that end, historical data from 2015 are used in conjunction with the Dispa-SET model, a unit commitment and power dispatch model developed at the Joint Research Centre (JRC) of the European Commission. This aims at investigating the impact of Battery Electric Vehicle (BEV) charging demand on the current Dutch power system, under different hypotheses for BEV technology penetration and renewable energy deployment (i.e. wind and solar) in the country. In addition, looking at the entire connection periods when vehicles are plugged to the grid, the battery capacity connected to the system is estimated, based on commercial BEV battery characteristics. This total capacity is finally used as variable storage unit in the model, in order to investigate the impact that Vehicle to Grid (V2G) strategies could have on the optimal use of power resources available, with particular attention to Variable Renewable Energy (VRE).

II. INPUT DATA AND DATA PROCESSING

In this section, the methodology used to analyse the historical data, to compute the aggregate charging demand curves, and to characterize the variable storage unit available is described. In addition, the Dispa-SET model and the scenarios tested for this study are presented.

A. Input data

The raw data is provided by ElaadNL. It consists of two different datasets of historic charging transactions, recorded from January 2012 till May 2016. The first Transactions dataset consists of more than 1 million records from 1747 charging stations managed by EVnetNL in the Netherlands. It includes information concerning:

- ID code of the charging station and the specific connector where the transaction took place;
- reference ID (RFID) code of the card used by the customer to start and end the transaction;
- date and time when the transaction was started and stopped;

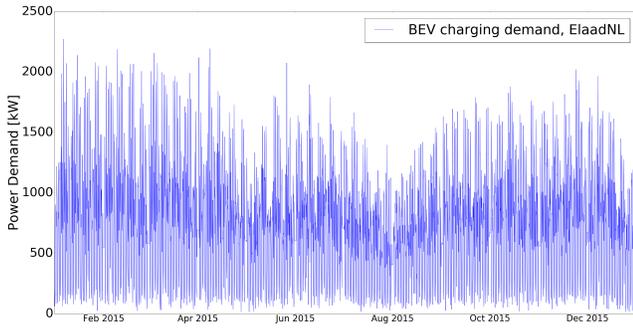


Fig. 1. Aggregate charging load for selected IDs, 15-min time resolution.

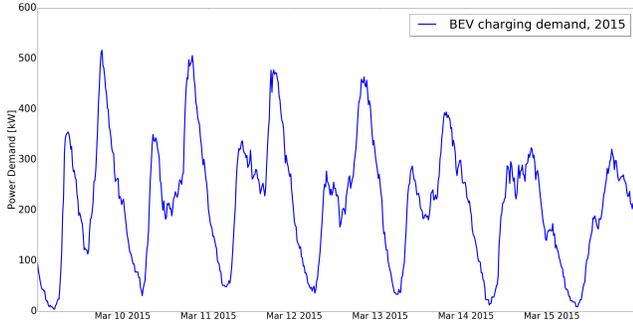


Fig. 2. Aggregate charging load for selected IDs, 15-min time resolution (1 week, March 2015).

- meter values at the beginning and at the end of the transaction, expressed in Watt-hour [Wh];
- connection time, equal to the difference between starting and ending time of the transaction;
- charging time, expressed as the time period during which the energy transfer took place;
- idle time, as the time period when the EV was plugged but no energy transfer was recorded;
- geographic coordinates of the charging station where the transaction took place.

The second database consists average power values recorded with a 15 minute time resolution for each transaction. Because this database does not include the idle connection times (i.e. the time period during which the vehicle is connected but not charging), its data is only used for cross-validation between the two databases, when computing the aggregate EV charging demand curve.

B. Computing the aggregate charging demand curve

From the Transactions dataset, the records that took place from January till end of December 2015 are considered in this study. The selected data are analysed by individual charging connector and by single charging ID card recorded. Each ID card corresponds to one electric vehicle, which will be referred to as "ID" in the further developments of this paper. It is worth mentioning that these ID cards can be used also at different charging stations not managed by EVnetNL, or at private charging points. Therefore, the data available might not



Fig. 3. IDs clusters for, based on EV battery characteristics.

be representative of the total yearly charging demand of each ID. Two new 15 minutes time resolution databases are created out of the original dataset: the time series of the charging power per ID, and the time series of the connection status for each ID.

To separate charging transactions pertaining to BEV from those related to Plug-in Hybrid EV (PHEV), the usable energy and charging power battery characteristics of the main EV models sold in the Netherlands between years 2010 and 2015 are considered. Two clusters are visually identified for BEV, based on the maximum values of total energy and charging power recorded for each ID:

- Maximum Charging Power ≤ 4 kW and Maximum Total Energy charged < 12 kWh;
- Maximum Charging Power > 4 kW.

The two clusters are shown in Fig. 3, where each dot represents one ID in the Transactions dataset.

In addition, the selected data are further refined by considering only IDs with more than 10 transactions recorded at ElaadNL charging points over the entire year. This aims at identifying frequent users that could better characterize typical charging patterns.

Finally, a total of 2215 cards are considered. For every single card, a new 15 minutes time resolution database of the average power demand for each of the recorded charging periods is computed, out of the ElaadNL 2015 Transactions records.

The aggregate charging demand curve is finally obtained as the sum of all IDs charging databases (Fig. 1, weekly detail in Fig. 2). The total computed demand is equal to 6388,2 MWh, with a peak demand of 588,34 kW corresponding to the maximum value of curve.

C. Scaling up the aggregate charging demand

In order to investigate the impact of future BEV deployment on the Dutch power system, the computed aggregate charging demand curve is scaled up. It is assumed that all current passenger cars will be fully replaced in the future with BEVs. It should be noted that this hypothesis is unrealistic in the short term, but it aims at providing an upper bond of the possible effect of electric vehicles deployment. Furthermore, it is in line with the current political willingness of the Dutch government to start banning all diesel and gas cars sales in the country by

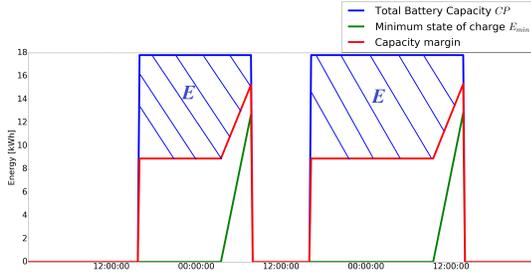


Fig. 4. Storage capacity for single ID.

2025 [4].

The aggregate load is scaled up according to the reference input data of the JRC-EU-TIMES model [5]. The considered parameters are presented in Table I.

The total new aggregate charging demand is calculated as follow:

$$\frac{d}{\varepsilon} \cdot v_{tot} = D \quad (1)$$

The corresponding scaled demand curve is obtained through a proportion between the total charging demand and the relative aggregate charging pattern computed out of the 2015 data. Therefore, the total scaled charging demand D is equal to 19,85 TWh, the a peak demand of 6984,44 MW that corresponds to the maximum value of the computed scaled curve.

D. Computing the aggregate storage capacity

To investigate the BEV potential for electricity storage when allowing V2G in the system, it is necessary to compute the total connected battery capacity. However, the total available storage capacity cannot be computed as the sum of all individual connected capacities. The constraints linked to the individual minimum state of charges must be taken into account, since the battery charge should always ensure the customer to have sufficient energy for the upcoming trips. The most optimistic available capacity therefore corresponds to the following hypotheses:

- Perfect foresight, where the user is fully aware of the time and duration of all future displacements;
- Just-in-time charging, where the minimum state of charge constraint is only defined just before the time of departure, and its value is the required energy for the upcoming trip.

TABLE I
REFERENCE INPUT DATA OF JRC-EU-TIMES MODEL

Parameter		Value
Average distance travelled by each car [km/veh]	d	13201.69
Average energy consumption of EVs [Bkm/PJ]	ε	1.43
Total number of passenger cars [veh]	v_{tot}	7735912

These constraints are illustrated in Fig. 4 the minimum level of charge is defined by the energy consumed in the subsequent transaction (assumed to be equal to the energy spent during the trip plus the losses), and by the charging time to satisfy the constraint. Since this corresponds to the most optimistic constraint, a security margin is defined:

$$E = (CP - E_{min}) * (1 - \xi) \quad (2)$$

Where E is the battery capacity made available to the system, CP is the total battery capacity, E_{min} is the minimum state of charge and ξ is the security margin (cfr Fig. 4). CP is assumed equal to the maximum value of the total energy per charging transaction over the year, whereas ξ is set equal to 0.5. For every single ID, a new 15 minutes time resolution database of E values for each connection period is calculated. The resulting curve is obtained as the sum of all computed IDs database, and it represents the aggregate capacity available during the year.

III. THE POWER SYSTEM MODEL

The power system is simulated using Dispa-SET, a unit commitment and power dispatch model. It includes a detailed representation of the operation of large scale power systems over short-term periods of operation. The system is considered to be centrally managed by an operator provided with complete technical and economic information, including the generation units available, the demand in each node and the transmission network constraints. Dispa-SET is can be freely downloaded and is released with an open-source license to ensure transparency and reproducibility [6].

The model solves the unit commitment problem across the European interconnected power system, minimizing the total generation cost. It is formulated as a mixed-integer linear program (MILP) and solved with the optimization software package CPLEX Optimizer [7].

For the purpose of this study, the model is applied to the Dutch power system only, based on installed capacity data originating from the ENTSO-E Transparency platform and the Platts database.

A. Characterizing the variable storage unit in the model

The aggregate curve representing the available BEV storage capacity is used to define an hourly non-dimensional *Availability Factor* (AF_{st}). This factor is defined as a time series accounting for the fraction of the storage capacity available at each time step. It is an exogenous input in the Dispa-SET model.

The storage capacity unit is characterised by a total capacity $CP_{st,max}$ equal to the peak value of the aggregate storage capacity curve, and a maximum charging power $P_{st,max}$ equal to the peak value of the BEV aggregate charging demand curve. These values are then multiplied by the AF_{st} to account for the temporal variations of the storage availability throughout the day, as explained below:

$$CP_{st} = CP_{st,max} \cdot AF_{st}(h) \quad (3)$$

$$P_{st} = P_{st,max} \cdot AF_{st}(h) \quad (4)$$

B. Scenarios description

Seven different scenarios are tested in the model. In the reference scenario, the total demand is defined based on the ENTSO-E data of hourly load values for the Netherlands [8]. Concerning the BEV charging demand, the following three cases are considered:

- BEV charging demand as from ElaadNL data for year 2015, without possibility of storage;
- Scaled BEV fleet, without smart charging;
- Scaled BEV fleet, with optimal V2G management.

The optimal V2G storage management is defined under the hypothesis that the available storage capacity is centrally dispatched (e.g. through an aggregator) and participates to the day-ahead and reserve markets, in such a way to minimize the operational costs of the system.

For the three cases listed above, the model is run with two different hypotheses regarding the penetration of VRE in the Dutch power system, as from power plants data:

- No increased penetration of VRE;
- Increased penetration of VRE (namely, solar and wind) by a factor of four.

The main parameters for the considered scenarios are provided in Table II.

IV. SIMULATION RESULTS

In Fig. 5 and 6, the three different total load curves input in the model, over the entire year and for one week in March respectively, are presented. Fig. 7 instead, shows an example of the computed power dispatch in Dispa-SET along one week in March 2015, for the base scenario with 2015 BEV demand. It allows to see which of the resources available in the system contribute to supply the demand in each hourly time step modelled. The power generation units are aggregated per type of fuel. The right axis refers to the aggregated battery state of charge.

Table II shows the main results obtained in Dispa-SET. Finally, Fig. 8 and Fig. 9 presents the different power generation mixes and number of power plants start-ups respectively, computed by the model for each of the scenarios tested.

A. Comparing the base scenarios

The model results for the reference scenario, based on the 2015 load curve from the Netherlands, are compared with the outputs obtained considering both the 2015 BEV demand and the scaled demand. The impact of the 2015 BEV demand

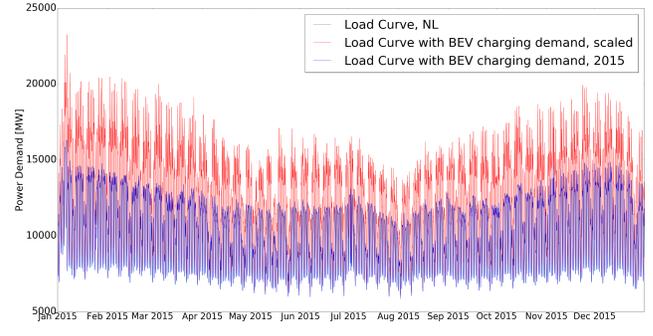


Fig. 5. Load curve inputs for the Dispa-SET model, hourly resolution.

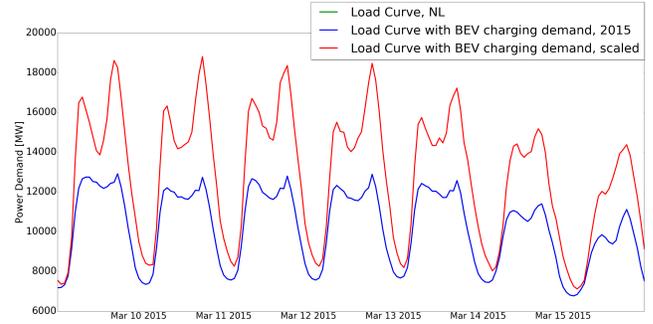


Fig. 6. Load curve inputs for the Dispa-SET model, hourly resolution (1 week, March 2015).

TABLE II
MAIN RESULTS FROM THE DISPA-SET MODEL

	Nr. BEVs	VRE installed capacity [MW]	V2G (Y/N)	$CP_{st,max}$ [MWh]	$P_{st,max}$ [MW]	Total consumption [TWh]	Peak load [MW]	Net imports [TWh]	Total curtailment [TWh]	Average electricity generation cost [EUR/MWh]
Reference scenario	0	4786	N	-	-	87.93	16286	8.90569	0.16088	27.18706
2015 BEV demand	2215	4786	N	-	-	87.93	16288	8.90569	0.15704	27.19223
Scaled BEV demand	7735912	4786	N	-	-	107.78	23253	8.90569	0.42749	30.04118
BEV + increased VRE	2215	19144	N	-	-	87.93	16288	8.90569	2.52743	18.42140
Scaled BEV + increased VRE	7735912	19144	N	-	-	107.78	23253	8.90569	2.88743	22.37219
Scaled BEV + storage	7735912	4786	Y	31340.21	6984.44	107.78	23253	8.84448	0.14293	28.48301
Scaled BEV + storage + increased VRE	7735912	19144	Y	31340.21	6984.44	107.78	23253	8.84448	0.98967	20.48347

results to be negligible in relation to the total load curve of the country. The total consumption and the peak load are the same for both cases, as well as the average electricity generation cost, as shown in Table II. This can be noticed also in Fig 5 and Fig 6, where the two curves match in the plots.

In the case of the scaled BEV demand added on top of the Dutch load curve instead, a significant higher peak load (+42%) and total consumption (+22%) is demanded to the system. This causes a consistent increase in gas generation (+117%, from 15,4 TWh up to 33,4 TWh) and in number of start-ups for both gas- and coal- power plants (cfr Fig. 8 and Fig. 9). Also, with increased BEV demand a higher average electricity generation cost is computed by the model.

B. Scenarios with increased electricity production from VRE

With an increased share of VRE available in the system, the model opts for significantly decreasing electricity generation from fossil fuels, particularly gas, while increasing consistently the start-up frequency of power plants. Gas generation goes from 15.4 TWh down to 6,5 TWh, when the 2015 BEV demand is considered. 33.4 TWh to 18,8 TWh respectively, when the 2015 BEV demand and the scaled demand are considered. In addition, the average electricity generation cost decreases whereas power curtailment increases, particularly when considering the 2015 demand.

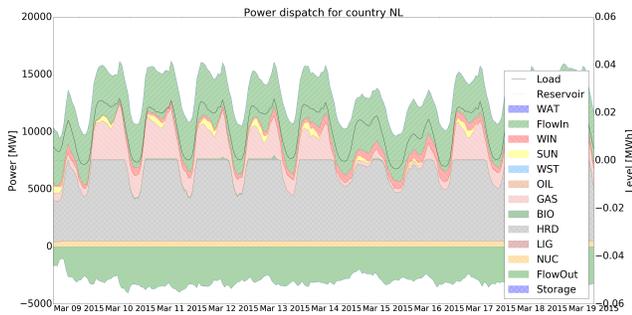


Fig. 7. Example of power dispatch output from Dispa-SET for the base scenario with 2015 BEV demand (1 week, March 2015). WAT: Hydro energy; FlowIn: Importations; BIO: Biomass; WIN: Wind energy; HRD: Hard Coal; SUN: Solar energy; LIG: Lignite; WST: Waste energy; NUC: Nuclear energy; FlowOut: Exportations

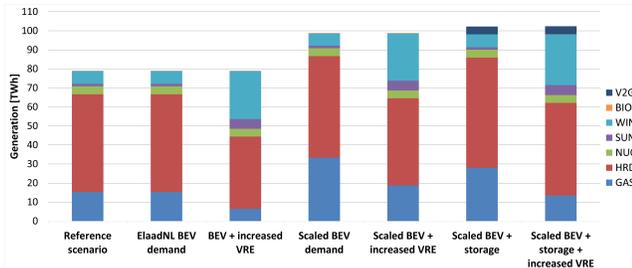


Fig. 8. Power Plants generation mix, per modelled scenario.

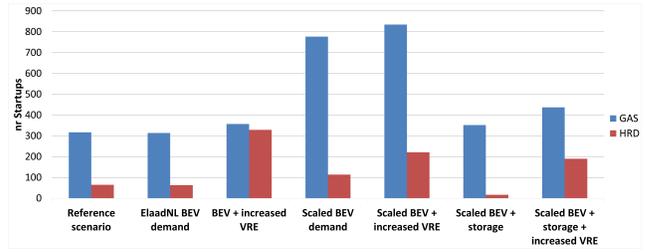


Fig. 9. Number of start-ups for gas- and coal-based power plants, per modelled scenario.

C. Scenarios with V2G

When the system is allowed to store and withdraw electricity to and from vehicles' batteries plugged to the grid, no significant contribution is registered, if only the BEV storage capacity as from 2015 data is considered. Looking at the scaled demand instead, for both scenarios with and without increased share of renewable energy sources (RES), the model suggests that the battery storage option can contribute to further reduce electricity generation and start-ups frequency of gas power plants. In fact, gas generation is reduced by 28% (from 18.8 TWh to 13.5 TWh) and by 15.8% (from 33.4 TWh to 28 TWh), for scenarios with and without increased VRE respectively. A limited increase of around 6% and 8% in coal generation is also stated, from 45.7 TWh to 48.6 TWh and from 53.4 TWh to 57,85 TWh. At the same time, there is a significant reduction in power curtailment (about 66%) and average electricity generation cost, particularly when increased generation from RES is available (about 8%). Finally, a slight increase in solar and wind generation is registered, allowing the system to integrate 26.7 TWh, corresponding to approximately 26% of the total computed electricity generation in the Netherlands. This is the higher amount of wind generation computed by the model among all the scenarios tested.

V. DISCUSSION

As mentioned above, the consistent increase in demand coming from full electric vehicles, as envisaged in this study, is representative of an extreme situation. The Dutch power system seems to rely mainly on coal and natural gas to satisfy the demand. When comparing the results for the scenarios with scaled BEV demand, with and without increased VRE, it is interesting to notice that the total curtailment increases by about 2,7%. Also the number of start-ups for both gas and coal power plants increases, thus impacting the lifetime of the power plants. This suggests that a higher share of RES does not optimally supply the BEV, because of the mismatch between VRE generation and BEV consumption. It is however worthwhile to note that renewable sources contribute to lower the average electricity generation cost in all the scenarios. This is explained by their zero marginal cost, in contrary to fossil fuel technologies. Renewable sources contributes in lowering the average electricity generation cost in all the scenarios tested, which is explained by a lower fossil-fuel based electricity generation [9].

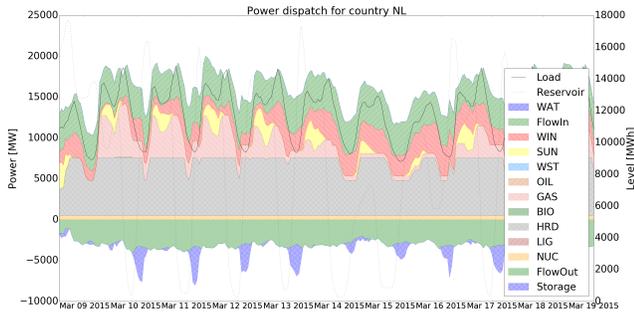


Fig. 10. Power dispatch output from Dispa-SET for the V2G scenario with increased VRE (1 week, March 2015).

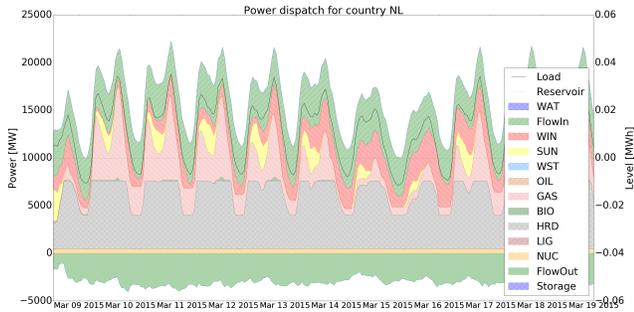


Fig. 11. Power dispatch output from Dispa-SET for the scenario with scaled BEV demand and increased VRE (1 week, March 2015).

A. Allowing V2G

When considering the availability of V2G storage option in the system with scaled BEV charging demand, the results show a significant reduction in power curtailment by about 66%, both with and without additional VRE. This result suggests V2G as viable option for increasing flexibility in the system, allowing for a better match between supply and demand sides. If power dispatch computed by the model (cfr Fig. 10) is compared to the same weekly output when no storage option is provided (cfr Fig. 11), it looks clear how the storage availability acts in balancing the peak load and levelling the overall demand curve. Also, the reduced start-up frequency computed for both gas- and coal- power plants suggests that storage availability provides benefits on the lifetime of traditional power plants, while helping in balancing demand fluctuation. Finally, the average electricity generation cost is also reduced when V2G is considered. In the scenarios with scaled BEV demand, the cost varies from 30 EUR/MWh to 28.5 EUR/MWh, when only the storage option is considered. When a higher share of RES is assumed, the cost goes from 22.4 EUR/MWh to 20.5 EUR/MWh. These outcomes suggest that there might be some margins for economic benefits to the end users.

VI. CONCLUSION

This study first analyses the real time charging patterns of electric vehicles in the Netherlands. It focuses particularly on frequent transactions that are identified as characteristic of

typical full electric passenger cars sold in the country during year 2015. Looking at the datasets provided by ElaadNL as main input for this study, the aggregate charging demand curve for the selected transactions is computed with a 15 min time resolution, together with the aggregate curve of the battery capacity available during connection periods. The aggregate charging demand curve is then scaled up, assuming that in the future the current Dutch passenger cars fleet will be entirely replaced with BEV. The two BEV charging demand curves are then added on top of the load curve of the country and used as input to the Dispa-SET model. The impact of BEV demand on the power system of the Netherlands is investigated for both cases, with and without increased VRE. The outputs from the model suggest that a significant increase in BEV charging demand would cause a higher variability of the load curve. This can lead to increased coal and gas electricity generation and start-up frequency of traditional power plants, thus also affecting their lifetime. Therefore, more flexibility is needed to ensure a better match between supply and demand in the Dutch power system, allowing for an optimal exploitation of the VRE capacity. Finally, when testing V2G in the model, power curtailment and average electricity generation cost are significantly reduced, thus suggesting that this option can effectively allow for a more efficient use of the resources available by increasing the level of flexibility of the system.

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REFERENCES

- [1] OECD/IEA, *Energy Policies of IEA Countries: European Union 2014 Review*. Paris: IEA Publications, 2014, oCLC: 899764304.
- [2] European Commission, "Electric vehicles," 2017. [Online]. Available: https://ec.europa.eu/transport/themes/urban/vehicles/road/electric_en
- [3] OECD/IEA, *Global EV Outlook 2016: Beyond one million electric cars*. Paris: IEA Publications, 2016.
- [4] D. Madson, "The Netherlands Moving to Ban Diesel and Gas Cars," Aug. 2016. [Online]. Available: <http://www.yaleclimateconnections.org/2016/08/netherlands-moving-to-ban-diesel-and-gas-cars/>
- [5] S. Gago Da Camara Simoes, W. Nijs, P. Ruiz Castello, A. Sgobbi, D. Radu, P. Bolat, C. Thiel, and E. Peteves, "The JRC-EU-TIMES model - Assessing the long-term role of the SET Plan Energy technologies," Publications Office of the European Union, EUR - Scientific and Technical Research Reports, 2013.
- [6] S. Pfenninger, J. DeCarolis, L. Hirth, S. Quoilin, and I. Staffell, "The importance of open data and software: Is energy research lagging behind?" *Energy Policy*, vol. 101, pp. 211 – 215, 2017.
- [7] S. Quoilin, I. Hidalgo Gonzalez, and A. Zucker, "Modelling Future EU Power Systems Under High Shares of Renewables: The Dispa-SET 2.1 open-source model," Publications Office of the European Union, EUR - Scientific and Technical Research Reports, 2017.
- [8] European Network of Transmission System Operators for Electricity (ENTSO-E), "Total Load - Day Ahead / Actual," 2017. [Online]. Available: <https://transparency.entsoe.eu/load-domain/r2/totalLoadR2/show>
- [9] M. Mulder and B. Scholtens, "The impact of renewable energy on electricity prices in the Netherlands," *Renewable Energy*, vol. 57, pp. 94–100, Sep. 2013.