

Provision of regulating- and reserve power by electric vehicle owners in the Dutch market



T.W. Hoogvliet, G.B.M.A. Litjens*, W.G.J.H.M. van Sark

Copernicus Institute of Sustainable Development, Utrecht University, PO Box 80.125, 3508 TC Utrecht, The Netherlands

HIGHLIGHTS

- Simulation of four EVs participating in the secondary reserve during one year.
- Dutch travel patterns, unbalance prices and loads on urban power distribution.
- EVs show significant benefits by participating in the secondary reserve.
- Providing secondary reserve has little effect on the ability to travel.

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ABSTRACT

Recent years have shown a large increase in electric vehicles (EVs), which could make a significant contribution meeting European, national and municipal energy- and climate goals. However, most EVs are not used for about 90% of the time, which makes their batteries available for other purposes. One of these purposes could be the provision of Regulating- and Reserve Power (RRP) to the transmission system operator, a vehicle-to-grid (V2G) concept. The aim of this paper is to determine the potential value that EVs could generate by providing RRP and identify EV user impacts on the provision of RRP. A model was developed to simulate the potential value of four commonly sold EVs under a baseline charging- and RRP dispatch scheme with three user categories for one year. The model used minutely settlement prices of the Dutch RRP market from 2014 to 2015, along with charging- and driving characteristics of Dutch EV drivers. Results show substantial effects of RRP provision in terms of monetary benefits, battery throughput and state-of-charge (SOC) distribution. Provision of RRP resulted in monetary benefits in the range between €120 and €750 annually per EV owner, depending on EV- and user category. This is accompanied by increased battery throughput and lower SOC distributions. However, the latter has little effect on the assumed trip requirements of the EV user. Subsequently, an assessment was made on the sensitivity of the results for changes in user characteristics and fleet sizes, which offered both favourable prospects and limitations. We conclude that the provision of RRP by EVs in the Netherlands shows promising potential.

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1. Introduction

Since its introduction in the Netherlands in 2011 the number of electric vehicles (EVs) has grown to roughly 100,000 in late 2016 [1]. This growth was supported by numerous government policy schemes for electric mobility and charging infrastructure. Most of these electric vehicles are either 100% battery electric vehicles (BEVs), range extended electric vehicles (REVs) or plug-in hybrid electric vehicles (PHEV). While their precise propulsion mecha-

nism differs, all these vehicles can connect to the grid to charge their batteries [2]. However, studies have shown that the time that EVs are parked and connected usually exceeds the time that is required for charging [3–5]. This implies that EVs possess flexibility that can be marketed and since the Dutch government aims to have 1,000,000 EVs on the road in 2025 the amount of flexibility will increase in the coming years [1].

1.1. Markets

There are several markets where EVs could offer their flexibility, namely the Primary Control Reserve (PCR), market for Regulating and Reserve Power (RRP) and the Tertiary Reserve. The purpose

* Corresponding author.

E-mail addresses: tim_hoogvliet@live.nl (T.W. Hoogvliet), g.b.m.a.litjens@uu.nl (G.B.M.A. Litjens), w.g.j.h.m.vansark@uu.nl (W.G.J.H.M. van Sark).

of the PCR is to restore frequency disruption in the entire, internationally interconnected High-Voltage grid. This means that in case of a disruption somewhere in the interconnected grid, all connected generators react to restore system balance. The market for RRP, also known as the secondary reserve market, is operated by the Dutch TSO TenneT to maintain grid balance in its control area in the Netherlands and part of Germany. The tertiary reserve is called upon in case there is insufficient RRP to restore disruptions.

Of all these markets, the market for RRP is most interesting for several reasons. Firstly, RRP is contracted through market bids that apply for one- or multiple 15-min blocks. These bids can be submitted until one hour before dispatch. These short time spans allow parties to accurately place their bids, contrary to the primary reserve, where a bid must apply for a full week, and tertiary reserve, where bids apply for a quarter or full year. Secondly, the tertiary reserve is characterised by a minimum bid size of 20 MW, high availability requirements and dispatch periods that can take several hours. These criteria make the tertiary reserve unsuitable for participation with EVs. The final argument for choosing the secondary reserve is that fact that the primary reserve only pays a capacity price and does not remunerate the volume of energy delivered. In the market for RRP an energy-only fee is applied.

Participation in the market for RRP is realised through symmetrical products where a party offers capacity to provide RRP up and/or down, in order to correct overconsumption and/or overproduction, respectively. Offers of RRP are bundled and dispatched according to a so-called bid ladder. Fig. 1 shows an example of such a bid ladder, where the left-hand side shows bids for RRP down and the right-hand side for RRP up. Each bid represents one bidding party.

Bids for RRP down contain a price per volume that the bidding party is willing to pay to the TSO for taking power from the system. Note that prices for RRP down can be negative, in which case the bidding party will receive payment from the TSO. Bids for RRP up contain a price per volume that the bidding party is willing to receive from the TSO for adding power to the system. In case of an unbalance the TSO will dispatch these bids in an economically efficient manner, i.e., in decreasing order for RRP down and in increasing order for RRP up. The settlement price that each party eventually receives for each MW h of energy delivered is determined by the highest- or lowest bid for RRP up or down, respectively. Taking Fig. 1 as example, this would require that for 500 MW of RRP up parties 1–5 would receive a settlement price

of 50 €/MW h. The rationale behind our study is that EV owners can potentially earn money by providing RRP up and save on charging costs by providing RRP down at a price that is lower than the electricity price paid for charging.

Codani and Petit provided a framework to assess the suitability of TSO market design for reserve power provision by EVs [7]. They describe two key sets of rules that are important for the potential of V2G: the rules towards aggregation of distributed energy sources and the rules defining the payment scheme of V2G services. These are described in Table 1 and are compared to the rules employed by the Dutch TSO. This shows that Tennets market design is favourable for RRP provision by EVs, as it complies to rule 3, 4 and 5. Although the market design does not fully comply to Rules 1, 2 and 6, these conditions are still relatively favourable. Codani and Petit also used this framework to assess TSOs in Denmark, France and the US. If Tennets market design was included in their analysis it would have been in their top three of most favourable market designs.

1.2. Literature review

The requirement of a symmetrical product means that EVs have to be capable to charge and discharge power from and to the grid. This concept is also known as vehicle-to-grid (V2G) and was first described in [8], who argued that an increasing share of electric mobility comes with a large volume of potential battery capacity available for ancillary services [9]. Since then numerous studies have been conducted on the potential of V2G for balancing power systems and supporting the integration of renewable energy [10]. Many of these studies focus on the dispatch of EVs in the primary reserve where participants usually receive a capacity price which differs from a bid ladder system such as employed by the Dutch TSO [4,5,11,12].

Sortomme and El-Sharkawi conducted their analysis based on 10,000 EVs in Houston, TX and estimated annual revenues between \$161 and \$635 per EV [13]. In addition, Sortomme and El-Sharkawi pointed out that the mass roll out of public charging facilities under the eVgo network made V2G adoption realistic. In the Netherlands similar developments were seen as municipalities have actively supported the roll out of public charging infrastructure, thereby creating potential for V2G applications. The work of Codani et al. [7], for instance, focused on the primary reserve in France and concluded that under alternative TSO market designs EV owners could potentially earn between €193 and €593 per year, which is in line with the findings of Sortomme and El-Sharkawi.

Some studies have also been conducted related to the secondary reserve. Pavić et al. [14] presented the participation of EVs in the secondary reserve in the UK. Their results show that not only the EV driver, but also the entire system reaps benefits when EVs are used for balancing power systems. This was also concluded by Fernandes et al. [15], who assessed the impact of V2G on power system operation costs in Spain under different scenarios for EV- and renewables penetration. They report savings in reserve costs between €122 and €540 per EV, which would potentially flow back to EV users. Another study found benefits from balancing ranging between £150 and £400 depending on number of EVs and installed wind capacity for the UK [16]. In another study, Jargstorf and Wickert [17] assessed the potential of EVs in the German secondary reserve market and concluded that the average revenues for EV drivers are low (less than €60 per year per EV) due to strict regulations.

1.3. Research aim

The studies mentioned in the literature review acknowledge that EVs can create value by participating in reserve markets. How-

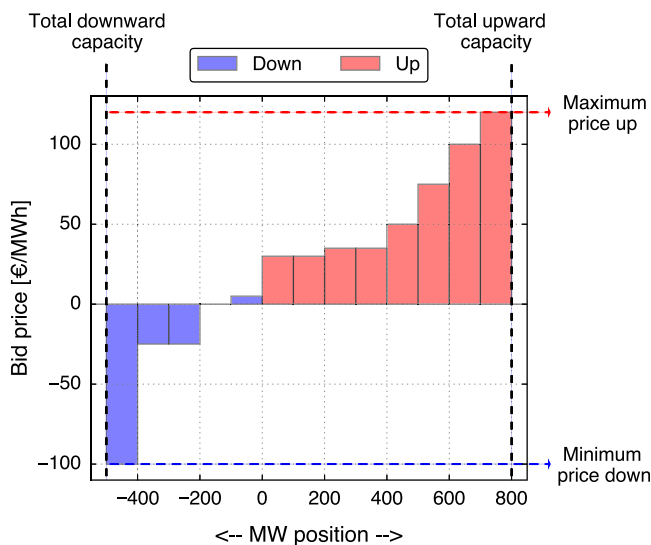


Fig. 1. Illustrative price bid ladder for TenneT, after [6].

Table 1
Overview of ideal market design and compared with the RRP market of the Netherlands.

Type	Rules	Description	Conditions Codani et al. [7]	RRP market Tennes
Aggregation	1. Minimum bid size	Minimum capacity of RRP bid. Generally, TSOs employ minimum bid sizes between 0.1 MW and 10 MW. Smaller minimum bid sizes are more favourable for the aggregation of EVs	0.1 MW	4 MW
	2. Interoperability between DSOs	TSO rules must allow for aggregation over multiple areas to increase odds of reaching the minimum bid size	Yes	No ^a
	3. Type of aggregation	Telemetry vs. financial. Telemetry allows for combining bids and power flows from different locations. Financial only allows for the combining of bids	Telemetry	Telemetry
Payment	4. Nature of payment scheme	Market based vs. regulated. In market-based payment schemes all parties eligible for RRP provision can bid. In regulated payments schemes TSOs dispatch based on historical load share	Market-based	Market-based
	5. Completeness of payment scheme	The extent to which regulation services are remunerated	Complete	Complete
	6. Bonus for intense flexibility	The extent to which fast responding sources are rewarded	Yes	Considerably ^b

^a Netherlands has only six DSOs with large service areas. This in contrary to Denmark and Germany, which have 65 and 900+ DSOs. Therefore, less interoperability is required for the Netherlands.

^b The energy capacity fee favours fast responding resources, such as fleets of connected EVs.

ever, none of these studies extends the assessment beyond the financial benefits towards the impact it has on the EV user. Moreover, an assessment aimed on the Netherlands is lacking, while this is a particularly interesting market, as the Netherlands are, together with Norway, frontrunner in Europe regarding EV uptake [18]. Secondly, Table 1 showed that the Dutch market design is favourable for RRP provision. Additionally, Dutch policies maintain to support intermittent, renewable power, which will create increasing demand for flexibility and reserve power that could be supplied by EVs.

Therefore, the aim of this paper is to assess the potential value of RRP provision by EVs in the Netherlands. The impact of RRP provision on the EV and EV user is analysed extensively by assessing the battery state of charge (SOC) and the users ability to travel. The potential value and user impacts were assessed by using minutely settlement prices together with charging-and driving characteristics of four EVs.

The remainder of this paper is organised according to the following structure. Section 2 describes the model and its inputs. Section 3 presents the dispatch scenarios and performance indicators. Section 4 presents model results. In Section 5 the methodology and results of this study are discussed. Section 6 will conclude this paper and provides recommendations for further research.

2. Model description and inputs

To determine the potential of RRP provision by EVs in the Netherlands a model has been developed where four different EVs participate in the Dutch RRP market on a minutely basis for the years 2014 and 2015. The EVs are simulated under three different user types based on Dutch EV user characteristics. In this section the model structure and inputs will be discussed. Fig. 2 presents an overview of the model. When the EVs are parked and plugged into charging facilities (CF) they are connected with the high-voltage (HV) grid through a series of cables and substations. Transferring power between the low-voltage grid and high-voltage grid results in transmission losses that have to be accounted for. In line with the Dutch average [19], we assume a transmission power loss of 8%.

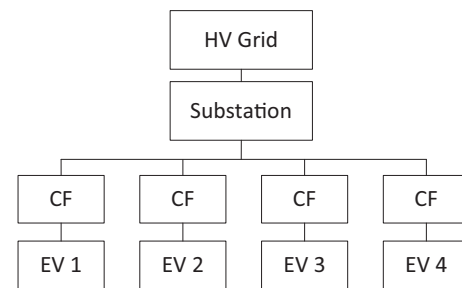


Fig. 2. Model structure, representing physical connections between different components, i.e., the high-voltage grid via substations to various charging facilities (CFs) and EVs connected to these.

2.1. EVs and user types

The four most commonly sold EVs in the Netherlands were used in the model. Two types of EV were used, the Battery Electric Vehicle (BEV) and the Hybrid Electric Vehicle (PHEV). The Tesla Model S and Nissan Leaf were the most sold BEVs in the Netherlands in 2014 and 2015, while the Mitsubishi Outlander PHEV and the Opel Ampera were the most sold PHEVs. These EVs differ with respect to battery- and charging capacity. It is assumed that these EVs always charge and discharge according to (dis)charging capacities stated in Table 2 [20], and that these EVs are technically capable of bi-directional charging. However, EVs do not have the full battery capacity at their disposal as discharging to a SOC of 0% is not possible. Therefore, a minimum SOC of 20% is assumed, similar to [21,22]. A conversion efficiency of 90% is assumed for both charging and discharging, leading to a round-trip efficiency of 81%.

To determine the use of the abovementioned EVs, previous studies on the characteristics of Dutch EV drivers are used [3,23,24]. These studies show that Dutch EV drivers can be divided into three user types, i.e., Resident (R), Commuter (C) and Resident-Commuter (RC) types, who all have very consistent travel patterns and energy consumption during weekdays. RC users charge their EV during each parking session, while R-users only charge at night and C-users only during office hours. Based on these findings start- and stop times of charging sessions are constructed for each user

Table 2
Overview of electric vehicle specifications.

	Tesla	Leaf	Outlander	Ampera
Battery capacity (kW h)	85	24	12	16
Charging capacity (kW)	11	6.6	3.7	3.7
Distance per trip (km)	43	49	–	30
Energy cons. (kW h/km)	0.200	0.137	–	0.229
SOC reduction (%/trip)	10	28	28	28

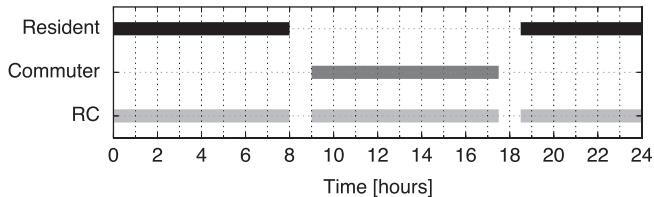


Fig. 3. Connection times during weekdays of different user types used in the simulations.

type (Fig. 3). These times only apply for weekdays. In weekends the EVs are simulated as parked and not connected due to variable travel patterns.

The study by Helmus and Van den Hoed [3] also presents statements regarding the energy consumption of trips made by Dutch EV drivers, which are used in our model. For R-users they show a mean daily energy consumption amounting to 48% of the total capacity of the battery, irrespective of battery capacity. For C-users this is 64% and for RC-users a combination of both. To separate the effect of connection time and driving distance before charging, a daily energy consumption of 56% of the battery capacity is assumed for all user types. If we assume an EV driver undertakes two trips per day, this means that each trip consumes 28% of the battery capacity. However, for the Tesla a daily energy consumption of 10% is used as the Tesla has a considerably larger battery than other EVs. Assuming an energy consumption of 28% of battery capacity per trip for the Tesla would yield travel distances that exceed the national average. The distance per trip, average energy consumption per km, and expected SOC reduction are shown for each EV in Table 2 [25]. Note that for the Outlander no distance per trip is presented as it uses the combustion engine as main source of propulsion and therefore the distance per trip cannot be estimated based on electricity consumption alone.

2.2. Prices

In this study two types of prices are used. Firstly, the electricity price, which is the price that an EV driver pays for charging his EV at a charging facility without providing balancing services to the TSO. The pricing structure of EV charging differs substantially between different charging service providers. Additionally, these prices also include network and taxes, which are not applied to the settlement prices on the market for RRP. It is therefore chosen to use the electricity-only price, which is set in our model at 0.10 €/kW h after [26].

Settlement prices of 2014 and 2015 are used to calculate costs and benefits that are obtained by providing RRP. These are published by TSO as the balance delta with prices, which lists the highest price for activated RRP up and lowest price for activated RRP down [27]. By using these prices each transaction yields maximum benefits and would require perfect knowledge regarding the amount of RRP that will be dispatched in order to place bids perfectly. Fig. 4 presents the distribution of balancing prices in 2014 and 2015, both of which were used in simulations. Considering that RRP down is profitable if the settlement price is lower than

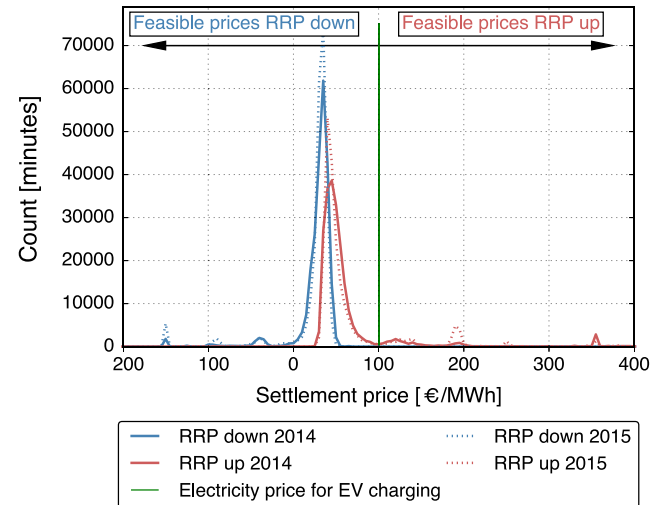


Fig. 4. Distribution of settlement prices in 2014 and 2015.

the electricity price, provision of RRP down is always profitable. In contrast, the bulk of prices for RRP up are far below the electricity price, meaning that RRP up provision will be profitable less often.

3. Dispatch scenarios and performance indicators

To determine potential monetary benefits and battery impacts two dispatch scenarios are developed and applied on four EVs. These scenarios consist of a series of assessments that lead to a model outcome and corresponding calculations.

The first scenario is a baseline scenario where EVs are modelled as they are currently used. The second scenario is a RRP dispatch scenario where EVs are modelled providing RRP up and down. These dispatch scenarios are presented schematically in Fig. 5. The charging sessions that can occur in each of the scenarios are also shown in the top part of the figure. In the baseline scenario the charging pattern is clearly predictable: continued charging until the battery is fully charged. In the RRP scenario the charging pattern can vary depending on settlement prices for RRP to create value for the EV driver. This pattern is constrained by the limits of the battery and the driver departure time, depicted by the required SOC line in Fig. 6. This figure addresses the decision that an EV driver has to make, namely forgoing a predictable charging pattern for one that is variable within certain limits however yielding financial benefits. Sections 3.1 and 3.2 will elaborate upon each dispatch scenario.

3.1. Baseline scenario

3.1.1. Determine EV connection

The first step assesses whether an EV is connected to the charging facility (Eq. (1)).

$$t \in t_c \quad (1)$$

where t is time and t_c is time connected (see e.g. Fig. 3). If the EV is not connected this means that the EV is on a trip, or parked and not connected. During a trip the battery is depleted at the rate of the power consumption P_{drive} of the EV (Eq. (2)). If disconnected and not on a trip the SOC remains unchanged.

$$\text{SOC}(t + 1) = \text{SOC}(t) - P_{\text{drive}} \cdot \Delta t \quad (2)$$

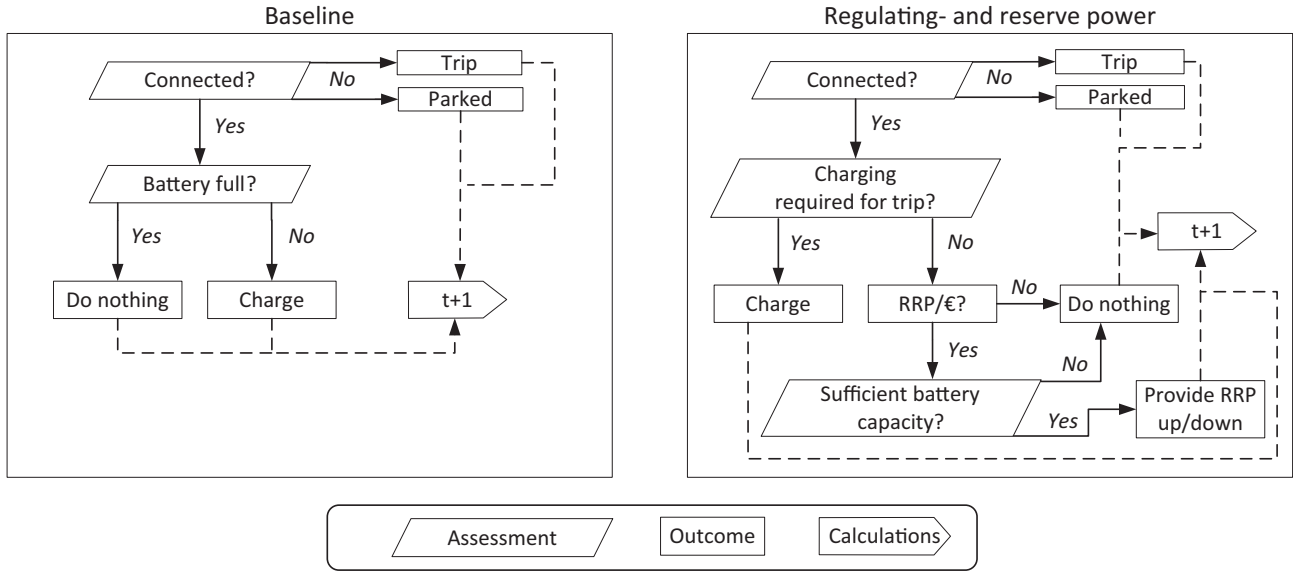


Fig. 5. Schematic model overview of the baseline (left) and RRP scenario (right).

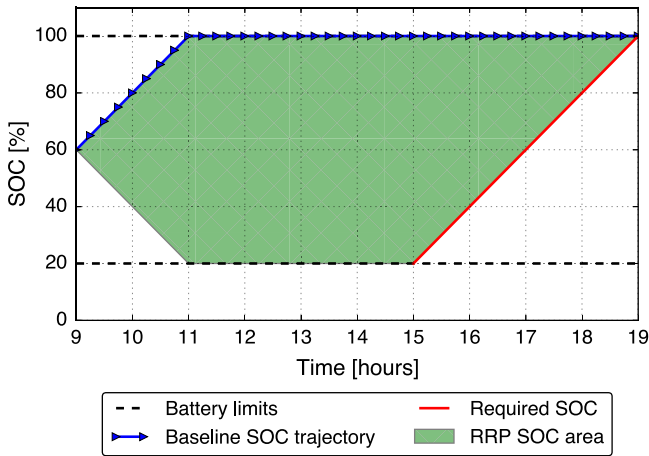


Fig. 6. State of charge trajectory for the baseline and trajectories for the RRP scenario.

3.1.2. Determine if charging is required

If the EV is connected to the grid, it is assessed if charging is required. In the baseline scenario charging takes place if the SOC at time step t ($SOC(t)$) is less than the maximum battery capacity (SOC_{max}) (Eq. (3)).

$$SOC(t+1) = \begin{cases} SOC(t) + P_{cf} \cdot \eta_{cf} \cdot \Delta t & \text{if } SOC(t) < SOC_{max} \\ 0 & \text{if } SOC(t) \geq SOC_{max} \end{cases} \quad (3)$$

The change in SOC depends on the vehicle charging power capacity (P_{cf}), efficiency (η_{cf}) and duration of the time step (Δt). The resulting ($SOC(t+1)$) is taken as input for the next time step (one minute later). The volume of energy charged to the battery is calculated according to Eq. (4). In the baseline scenario this volume is equal to the energy consumed for driving (E_{driven}). The energy needed for driving is identical in the baseline- and RRP scenarios.

$$E_{charged,t} = SOC(t+1) - SOC(t) \quad (4)$$

The profit is calculated according to Eq. (5). In the baseline scenario the profit π will be negative or zero, as only costs for charging (p_{el}) will occur or no costs at all, respectively. As a user pays for the

amount of energy it takes from the grid, the volume $E_{charged}$ has to be divided by the charging efficiency before multiplying with p_{el} .

$$\pi_{t,baseline} = \frac{E_{charged,t}}{\eta_{cf}} \cdot p_{el} \quad (5)$$

3.2. RRP scenario

In this dispatch scenario charging and discharging is based on settlement prices from the RRP market and trip requirements of the driver, meaning that energy is only transferred if settlement prices are profitable and no charging is required to meet energy needs for the next trip.

3.2.1. Determine EV connection

The first parallelogram, see (Fig. 5), is identical to the baseline scenario and associated calculations.

3.2.2. Determine if the EV has flexibility

This assessment checks if the EV has the flexibility to provide RRP. An EV will be used for transport at time step t_{trip} at which point the user requires a certain SOC to take that trip ($SOC_{trip}(t_{trip})$) [21,28]. This value does not necessarily represent the technically required SOC for a trip, but could also take on a value preferred by the EV user. A certain amount of time is needed to reach $SOC_{trip}(t_{trip})$, depending on the charging capacity of the EV. The red line in Fig. 6 illustrates this and represents the minimal SOC (SOC_{req}) of the battery that is necessary at each time step t in order to achieve an SOC of 100% at the time of departure t_{trip} . When the SOC at time step t , $SOC(t)$, is equal to or smaller than $SOC_{req}(t)$ then the EV has to charge (according to Eq. (2)) and therefore possesses no flexibility to provide RRP. The conditions for flexibility are summarised in Eqs. (6) and (7). If these conditions are met it then has to be assessed if providing RRP is profitable.

$$SOC(t) > SOC_{req}(t) \quad (6)$$

$$SOC_{req}(t) = SOC_{trip}(t_{trip}) - P_{cf} \cdot \eta_{cf} \cdot (t_{trip} - t) \quad (7)$$

3.2.3. Assessment of RRP provision and profitability

In this step the model checks which form (up, down) of RRP is desired by the TSO and whether prices are at such a level that

RRP provision is profitable. The provision of RRP up is considered profitable if the settlement price for RRP up is higher than the electricity price. RRP down is considered profitable if the settlement price for RRP down is lower than the electricity price. If prices do not lead to a profit no RRP is delivered.

3.2.4. RRP feasibility assessment and calculation

This step assesses if the selected option does not exceed the minimum- or maximum capacity of the battery. Providing RRP up discharges the battery according to Eq. (8). If RRP up is selected, then it can only be provided if the resulting SOC is more than both the minimum SOC and required SOC of the battery. The amount of RRP up delivered to the TSO is calculated according to Eq. (9). Note that delivering power to the low-voltage grid in this case avoids the need to deliver power from the high-voltage grid. The transmission of energy from high- to low voltage grid is accompanied by transmission losses ($\eta_{\text{transmission}}$). However, in case of RRP up, transmission loss can be considered as an advantage as a unit of power delivered at the low-voltage grid translates to a higher amount of power delivered to the high-voltage grid.

$$\text{SOC}(t+1) = \text{SOC}(t) - P_{cf} \cdot \Delta t \quad (8)$$

$$E_{\text{RRP,up,t}} = \begin{cases} \frac{(\text{SOC}(t+1) - \text{SOC}(t)) \cdot \eta_{cf}}{\eta_{\text{transmission}}} & \text{if } \text{SOC}(t+1) \geq \text{SOC}_{\min} \\ & \wedge \text{SOC}(t+1) \geq \text{SOC}_{\text{req}} \\ 0 & \text{else} \end{cases} \quad (9)$$

In case RRP down was selected it could only be provided if the resulting SOC was less than the maximum SOC of the battery, as RRP down requires charging of the battery. The amount of RRP delivered to the TSO is calculated according to Eq. (10). In the provision of RRP down transmission losses have the opposite effect as they result in more power taken from the high-voltage grid.

$$E_{\text{RRP,down,t}} = \begin{cases} \frac{(\text{SOC}(t+1) - \text{SOC}(t))}{\eta_{cf} \cdot \eta_{\text{transmission}}} & \text{if } \text{SOC}(t+1) \leq \text{SOC}_{\max} \\ 0 & \text{else} \end{cases} \quad (10)$$

If RRP could be delivered, profits are calculated according to Eq. (11). Note that for RRP down the profits are mostly negative as money had to be paid to the TSO, although negative settlement prices (p_{settle}) that result in positive profits occurred as well.

$$\pi_{t,\text{RRP}} = E_{\text{RRP}} \cdot p_{\text{settle}} \quad (11)$$

3.3. Performance indicators

The performance of the dispatch scenario are evaluated on battery throughput (BT), monetary benefits and SOC distribution. Battery throughput is defined as the volume of energy that passes through the battery (Eq. (12)).

$$E_{\text{in}} = \sum_{t=1}^T (E_{\text{charged,t}} + E_{\text{RRP,down,t}}) \quad (12a)$$

$$E_{\text{out}} = \sum_{t=1}^T (E_{\text{driven,t}} + E_{\text{RRP,up,t}}) \quad (12b)$$

$$BT = E_{\text{in}} + E_{\text{out}} \quad (12c)$$

The monetary benefits are defined as the difference between the baseline scenario and the RRP scenario (Eq. (13)).

$$\pi = \sum_{t=1}^T (\pi_{t,\text{RRP}} - \pi_{\text{baseline,t}}) \quad (13)$$

The SOC distribution is defined as the percentage of total time that a certain SOC value occurs. This provides implications regarding the users ability to undertake trips.

4. Results

4.1. Battery throughputs

Both dispatch scenarios were run for each of the years for which the settlement prices were available (2014 and 2015) for each user type and EV. The results are structured as follows. We first present a figure showing a breakdown of the performance indicators for 2014, followed by a table where results for 2014 and 2015 are summarised and compared.

Fig. 7 presents the different components of battery throughput that occurred in the simulations. In the baseline scenarios driving is the only activity that results in battery throughput. Because driving energy is similar for all user types, no distinction is made for different user types. A Leaf occupied by an RC user drives the same distances as a Leaf used by a C user type and therefore has identical battery throughput. In the RRP scenario, RRP up becomes an extra determinant for throughput. Different throughputs can be seen for each user type because RRP up provision depends on connection time. Note that the increase in throughput is identical to the amount of RRP up provided.

From Fig. 7 two main observations can be made. Firstly, it can be seen that longer connection times lead to higher throughputs, as the RC user has the highest throughput, followed by the R- and C user. This is explained by the fact that longer connection times increase the odds on favourable prices for RRP up provision, which in turn determines throughput. Secondly, it can be observed that RRP down provides the most energy to the battery, thereby reducing the need for charging. The increase in throughput that this causes in comparison to the baseline is presented in Table 3. The simulation on the settlement prices of 2015 results in battery throughputs that have a very similar composition compared to the 2014 results, i.e. a large amount of RRP up and small amount of RRP down. However, the settlement prices were more favourable in 2015 as feasible prices for RRP up occurred 40% more often. Feasible prices for RRP down occurred 3% more often, but were 16% lower. As a result, higher battery throughputs are calculated for 2015.

4.2. Monetary benefits

When the power flows of Fig. 7 are translated to monetary flows it can be seen that the large amount of energy that is charged to the battery through RRP down comes at relatively small costs, indicated by the blue columns in Fig. 8. Alternatively, the small amount

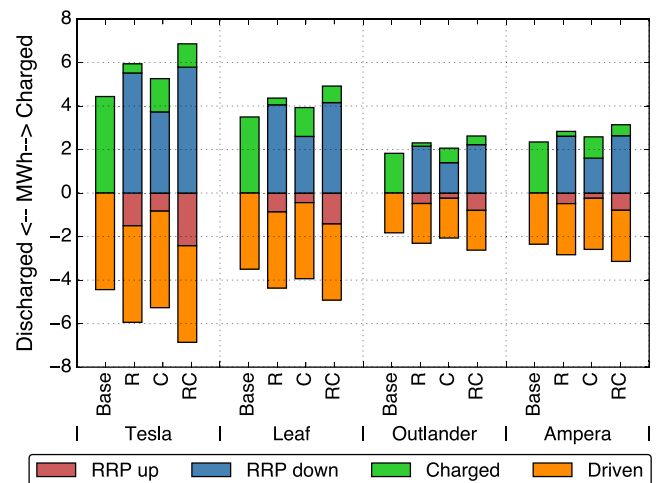


Fig. 7. Annual battery throughputs per EV, user type and dispatch scenario in 2014.

Table 3

Increase in annual battery throughput under the RRP scenario compared to baseline scenario of each EV for 2014 and 2015. Also the relative differences between the years are shown.

		Tesla	Leaf	Outlander	Ampera
2014 (%)	R	34	25	26	21
	C	19	12	13	10
	RC	55	41	44	34
2015 (%)	R	41	30	32	25
	C	27	17	18	14
	RC	69	52	55	43
2015–2014 (pp)	R	+7	+6	+6	+63
	C	+8	+5	+5	+4
	RC	+14	+11	+12	+10

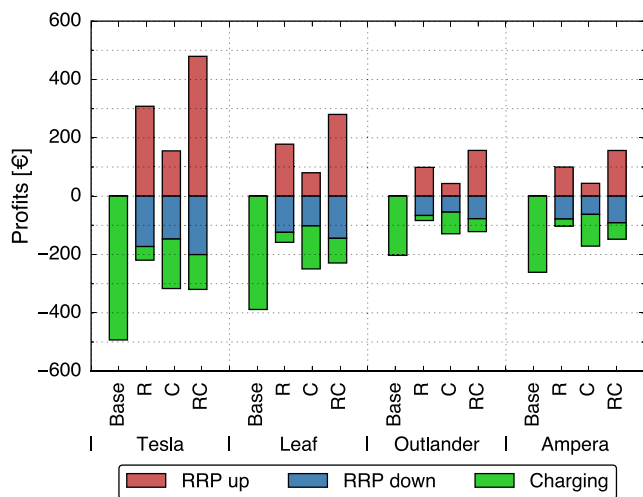


Fig. 8. Breakdown of profits per EV, user type and dispatch scenario in 2014.

Table 4

Total annual profits for 2014 and 2015, and the absolute difference.

		Tesla	Leaf	Outlander	Ampera
2014 (€)	Base	−493	−389	−203	−261
	R	89	20	15	−3
	C	−162	−169	−86	−128
	RC	160	51	35	9
2015 (€)	R	116	41	27	10
	C	−69	−108	−52	−89
	RC	250	109	67	44
2015–2014 (€)	R	+27	+21	+12	+13
	C	+93	+62	+34	+39
	RC	+90	+58	+31	+36

of RRP up leads to significant benefits as shown by the red columns. Summing these together with charging costs yields the net annual profit, presented in Table 4. As prices were more favourable in 2015, higher total annual profits are possible as can be seen.

Fig. 9 presents the monetary benefits, as defined in (Eq. (13)), for 2014 and 2015. It shows that all EVs experience monetary benefits from the provision of RRP, regardless of their user type. However, EVs with higher battery- and charging capacities benefit more from the settlement prices. Due to its large battery- and charging capacity the Tesla has a larger RRP SOC area than the Leaf. Consequently, increasing the odds that a transaction with the RRP market is technically possible and thereby allowing for more RRP provision and forthcoming revenues for the Tesla.

4.3. Users ability to complete unexpected trips

A commonly voiced concern surrounding V2G applications is that drivers could experience insufficient battery SOC in case of unexpected trips. To address that issue the SOC distribution was constructed for 2014, which shows the relative occurrence of SOC values in Fig. 10. The figure shows the SOC distribution under baseline circumstances through the solid line and under the RRP scenario as the dotted line. The first observation is that under the RRP scenario all users experience a lower SOC distribution. This is due to two reasons. Firstly, EVs charging does not necessarily start immediately after connecting the EV, as demand for RRP down can be absent, in contrast to the baseline scenario where EV charging starts immediately after connection. Secondly, EVs also provide RRP up, resulting in lower SOC values. This means that the EV batteries experience longer times at lower SOC values. If the Nissan Leaf under the RC user is assessed in the baseline scenario the user has a full battery for 90% of the time. Under the RRP scenario this drops to $\approx 55\%$ of the time. This is not necessarily an unfavourable effect if users can still complete their trips. A more important question is whether users can complete unexpected trips.

To address this issue it is assumed that an unexpected trip consumes as much energy as a regular trip. When assessed in the figure the EVs remain capable of making these trips for a large share of the time as only a few occurrences of a battery SOC below 48% are seen for the Leaf, Outlander and Ampera and none for the Tesla. The share of time that an EV can make an unexpected trip is shown in Table 5. Simulations for 2015 again yielded similar numbers (<0.1% deviation compared to 2014). This shows that users will experience a limited impact on their ability to complete unexpected trips when they choose to participate in RRP provision.

4.4. Sensitivity analysis

Results presented in Section 4.2 are obtained using a set of assumptions regarding user preferences and characteristics. Additional analysis was conducted to assess how changes in these assumptions impact annual benefits. These results are shown for the 2014 settlement prices.

4.4.1. Alternative battery preferences and trip duration

Simulations were run under alternative user preferences for the minimum SOC, required SOC and trip duration to investigate the impact these have on the annual benefits. Results of these simulations are presented in Fig. 11. The leftmost graph presents the results for simulations with lower required SOC settings. Note that the Teslas required SOC setting can be lowered to 30% as its only needs 10% of its SOC for a trip, while the other EVs need an SOC of 48%. Lowering the required SOC setting yields an increase in benefits due to reduced need for charging and increase in SOC area. This increase can be visualised by lowering the SOC_{req} line in Fig. 6, such that the SOC at time of departure equals the alternative SOC setting. The analysis shows that a user who is aware of his energy requirements for trips and willing to tailor his EVs charging to this can increase annual benefits. For this increase in annual benefits the user risks a larger probability that an unexpected trip cannot be completed.

The middle graphs present results for a higher minimum SOC setting. At a minimum SOC setting of 50% the EVs will have equal ability to make unexpected trips as in the baseline scenario, while forgoing little (Resident, Commuter) to no (Resident-Commuter) annual benefits. At higher minimum SOC settings annual benefits do decrease due to the decrease in available SOC area. This can be visualised by shifting the SOC_{min} line in Fig. 6 upwards. This

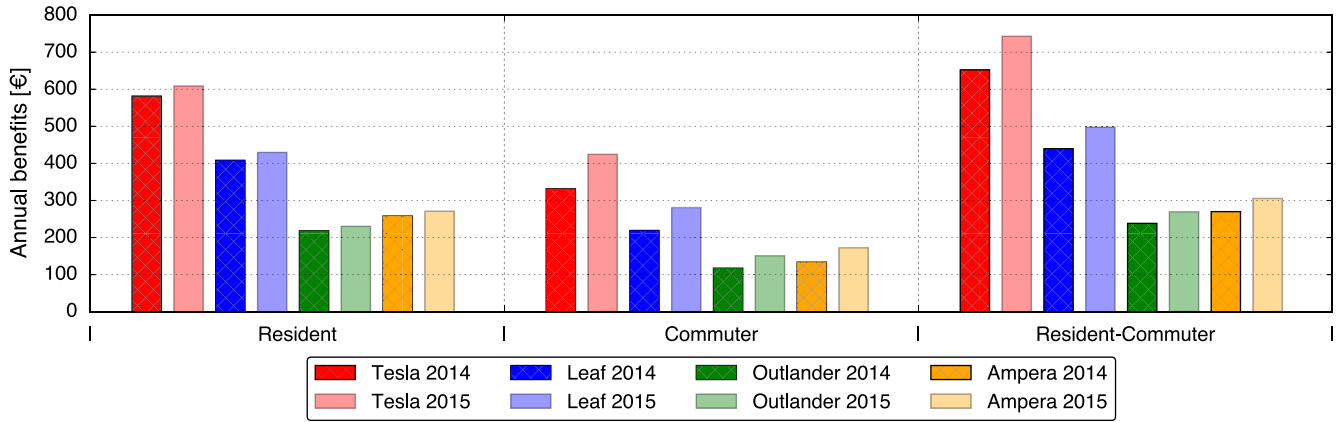


Fig. 9. Monetary benefits per EV and user type for 2014 and 2015.

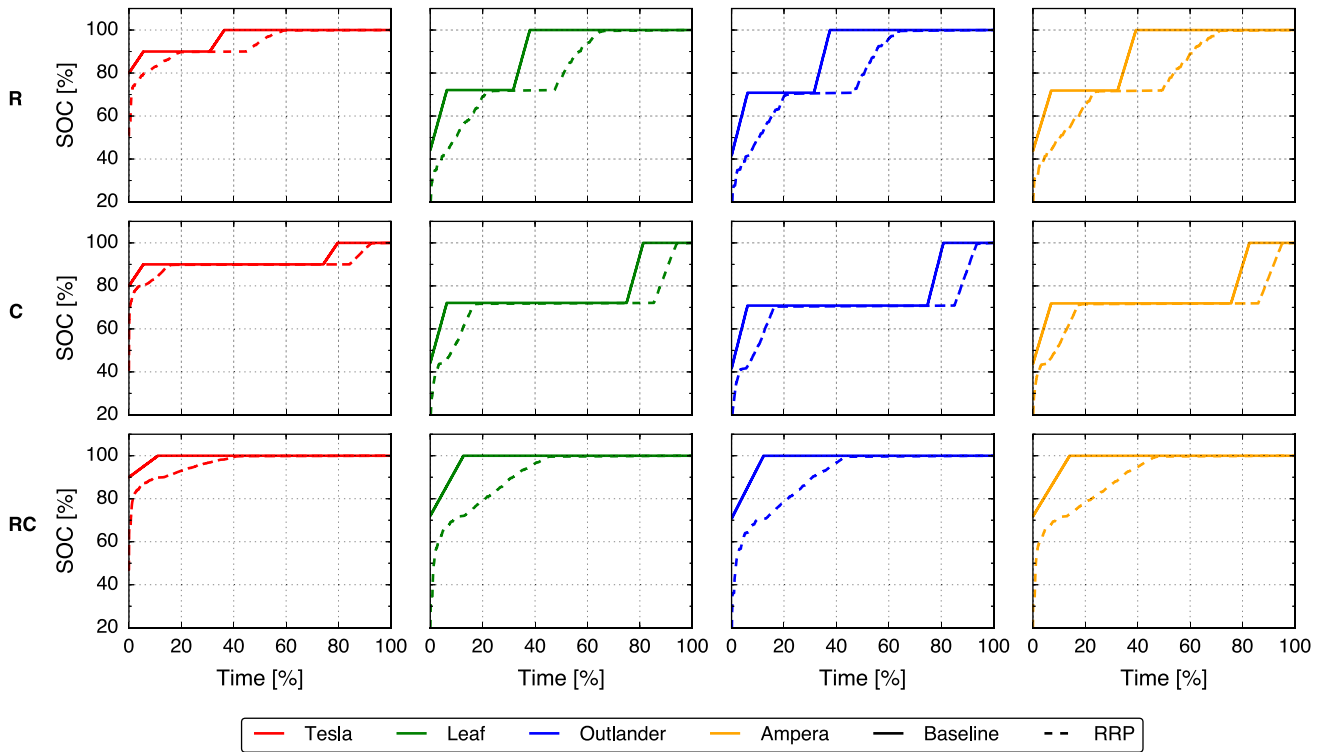


Fig. 10. SOC distribution of each EV and user type under the baseline- and RRP scenario for 2014.

Table 5
Share of time to make an unexpected trip for each dispatch scenario and user type in 2014.

	Tesla	Leaf	Outlander	Ampera
Base (%)	100	98	98	99
R (%)	100	88	88	86
C (%)	100	90	90	90
RC (%)	100	99	98	99

analysis shows that users can minimise the risk of not being able to complete a trip and still profit from the provision of RRP. The right-most graph shows the impact of changes in trip duration. Shorter trips result in longer availability to provide RRP and therefore higher annual benefits. The opposite holds for longer trips.

4.4.2. Effect of RRP provision in weekends

Previous research has shown that travel patterns become less predictable during weekends [3]. Therefore, weekends were omitted from the initial simulations. To give an indication of the impact of weekends the model was run for weekends only under settlement prices of 2014 and assuming all user types conduct a trip between 10:00 and 12:00. During the rest of the time EVs are parked and connected. Under these assumptions the EVs receive additional monetary benefits ranging between €85 and €223 which adds between 34% and 76% (in this case) to the benefits on annual basis (shown in Table 6). This would mean that users who plan to use their EV in the weekend could enjoy a significant amount of extra monetary benefits, especially for the user type commuter.

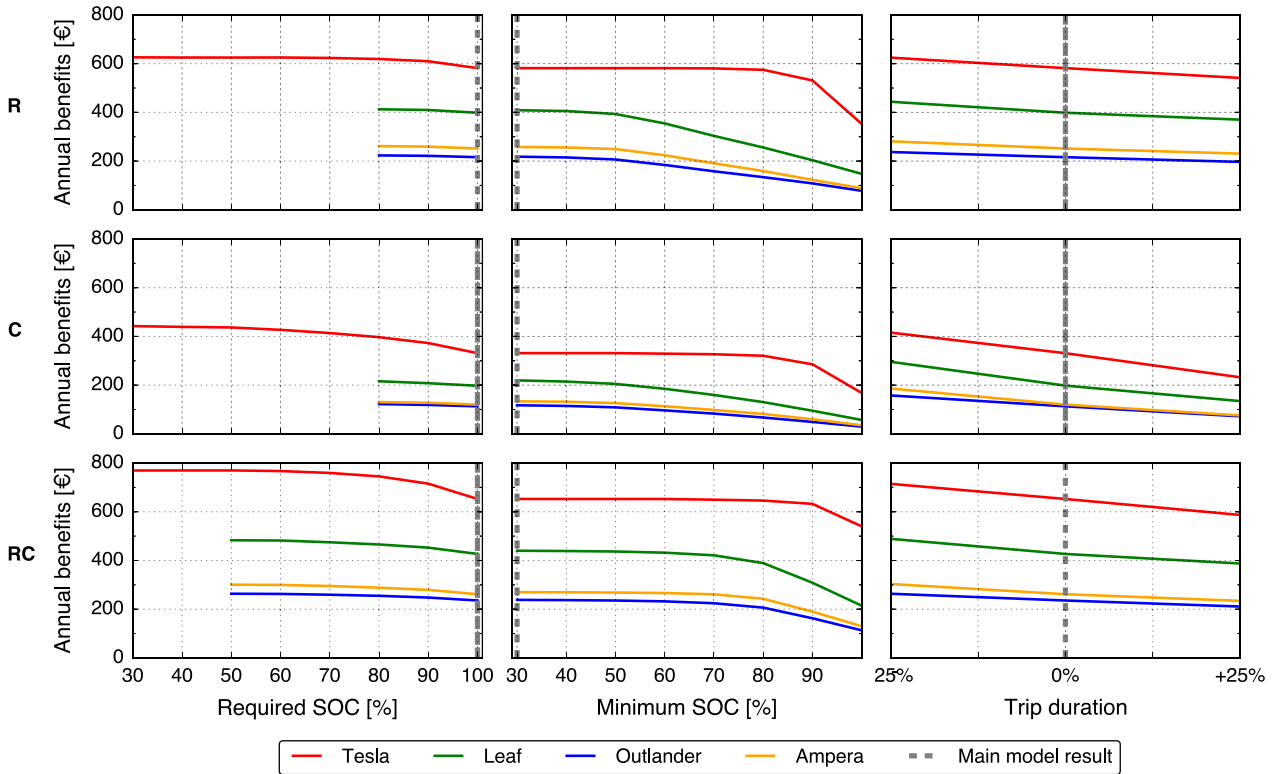


Fig. 11. Total annual benefits under alternative user preferences and -characteristics.

Table 6
Additional benefits for the weekends in 2014. For each user type the relative benefits compared to the weekdays are given.

	Tesla	Leaf	Outlander	Ampera
Benefit (€)	223	160	85	102
R (%)	+38	+39	+39	+39
C (%)	+67	+73	+72	+76
RC (%)	+34	+36	+35	+38

4.4.3. Effect of different daily energy consumption

The work of Helmus and Van der Hoed [3] presents different daily energy consumptions for each user type, while in the simulations a fixed daily energy consumption was taken for all user types. To explore the effect this has on monetary benefits, simulations were run using the input data found in [3] and presented in Table 7). Note that these new settings affect only the R- and C-user types as the RC user types daily energy consumption is the same as used in the initial simulations. The analysis shows that R-users are better off than C-users due to the fact that R-users have a start each session with a higher SOC, which provides them with more flexibility to provide RRP.

5. Discussion

5.1. Market saturation

The market for RRP has limitations as there is a limited amount of RRP available at settlement prices that comply with the prof-

Table 7
Change in monetary benefits when accounting for different daily energy consumption between user types.

	Tesla	Leaf	Outlander	Ampera
Residents (%)	+7	+4	+3	+6
Commuter (%)	-16	-22	-16	-21

itability requirements. To make a rough estimate of the size of the market all settlement prices and activated RRP in 2014 were assessed on a minute basis. This shows that in 2014 the amount of RRP that could economically be delivered by EVs was 45.8 GW h and 167.7 GW h, for RRP up and down respectively. To give an indication of amount of EVs that could participate, the findings of Fig. 7 were used. For each EV the volume of feasible RRP up or down was divided by the volume RRP up or down provided by the EV. Per EV type this yields the number of vehicles that could participate in RRP provision. Table 8 shows results of this analysis for the RC and C user type in thousands of EVs. This gives an estimation of the higher- and lower boundary of number of EVs. When this assessment is applied to 2015 different values are found. In 2015 the feasible amount of RRP up and down were somewhat higher at around 67 GW h and 182 GW h, respectively. Considering that at the time of writing there are 100,000 EVs in the Netherlands it can be stated that in terms of volume the RRP market would already be saturated if all EV drivers are RC users and would provide RRP.

Aside from abovementioned technical limits, an increasing number of EVs will push down settlement prices for RRP up and increase prices for RRP down, thereby reducing the profitability of RRP provision by EVs [16]. However, quantification of this effect lies beyond the scope of this research. In Druitt (2012) such quantification was made based on the UK and showed benefits declining with 66% in case two million vehicles participated.

Table 8
Estimated EV participation before RRP market saturation (in thousands).

		Tesla	Leaf	Outlander	Ampera
C (-10 ³)	Up	55	104	191	192
	Down	44	63	117	102
RC (-10 ³)	Up	19	32	58	58
	Down	28	39	74	62

5.2. Impact on substations

A concern surrounding large-scale integration of EVs in general is the overcharging of the distribution infrastructure [29]. Therefore, the effect of RRP provision by EVs on the distribution grid loads was analysed. A load profile was constructed for an average urban neighbourhood in the Netherlands consisting of 140 apartments and 60 commercial buildings. This profile was constructed using measurement data of two commercial buildings and modelled data of 400 residential buildings. The residential profiles are modelled using the Flex Street model and explained by Claessen et al. [30]. To this profile the loads that are induced by EVs were added for both baseline and RRP scenario. With regard to grid capacity it is assumed that the transformers in the substation are the limiting factor. A likely maximum capacity for a transformer in an urban area is around 360 kW.

Fig. 12 shows the impact of increasing the fleet used in the simulations by a factor of 1–5. For each of these fleets the highest and lowest load that occurred during the simulations is presented. It can be seen that RRP up provision increases the maximum occurred load on the substation. In the baseline scenario substation overcharging would occur if the fleet exceeds 20 EVs. In the RRP scenario this occurs for a fleet of 16 EVs under the RC and commuter user type. Note for the resident user type no difference is seen between baseline and RRP due to the fact that residents connect at night when no peak loads occur. For RRP down it can be

seen that negative loads occur, meaning that the substation has to transport power to higher voltage grid sections. This does induce additional aging of the transformers [31].

This analysis implies that RRP could contribute to existing peak loads in urban distribution grids. Simultaneously it shows that the current infrastructure would experience this anyway as in the baseline scenario four additional EVs are required to obtain the same effect. The issue of increased peak loads due to EV charging has also been discussed in Verzijlbergh et al. [32], who emphasised the need for controlled EV charging. A charging scheme should be implemented that not only generates profits, but also avoids grid overcharging.

5.3. Maximum SOC of electric vehicle

In this research it is assumed that EV drivers prefer a full battery at the time of departure. However, Tesla drivers are advised not to fully charge their EV battery unless it is necessary and employ a max SOC setting of 90%. For other EV no such recommendations were found. Nissan states that such a lower SOC setting is only required in case the vehicle will not be used for an extensive amount of time.

To assess the impact of a 90% maximum charge setting on the Tesla, a maximum SOC setting of 90% of the total capacity was set for the simulations. This leads to slightly decrease of monetary benefit for all users, namely for R users 5%, for C and for RC users 7%.

5.4. Considerations regarding implementation

This study provides a first exploration of the monetary benefits and user impacts that occur when Dutch EV users participate in RRP provision. However, for EVs to successfully participate a couple of conditions must be met. Firstly, an aggregator is required to combine individual EVs to groups that comply with the minimum bid size set by the TSO [7,28]. Secondly, supporting technologies are needed to communicate user preferences and the EVs battery SOC to the aggregator. This could for example be achieved through an app where EV drivers enter minimum SOC, required SOC, current SOC and departure time. In addition, charging facilities need to become bi-directional. These adaptations require high investment costs and could present a barrier for the implementation of V2G [33,34]. Thirdly, and most importantly, for successful implementation of this concept it is required that EV users are willing to plan their trips more consciously [34]. The extent to which users are willing to do this should be taken in consideration when designing V2G based propositions [35]. Hidrue and Tan also mention user adversity towards battery degradation as potential barrier for V2G. The benefits that users derive from V2G services should outweigh the barriers listed in the abovementioned studies.

5.5. Comparison with previous studies

The results of this research are in line with findings from previous research, see Table 9. The differences that can be seen between the different countries can be attributed to the local market conditions and remuneration type. Because these studies are executed for different countries and years a precise comparison is difficult, only a qualitative comparison can be made. Nevertheless, the key take away is that all studies show potential value in V2G services.

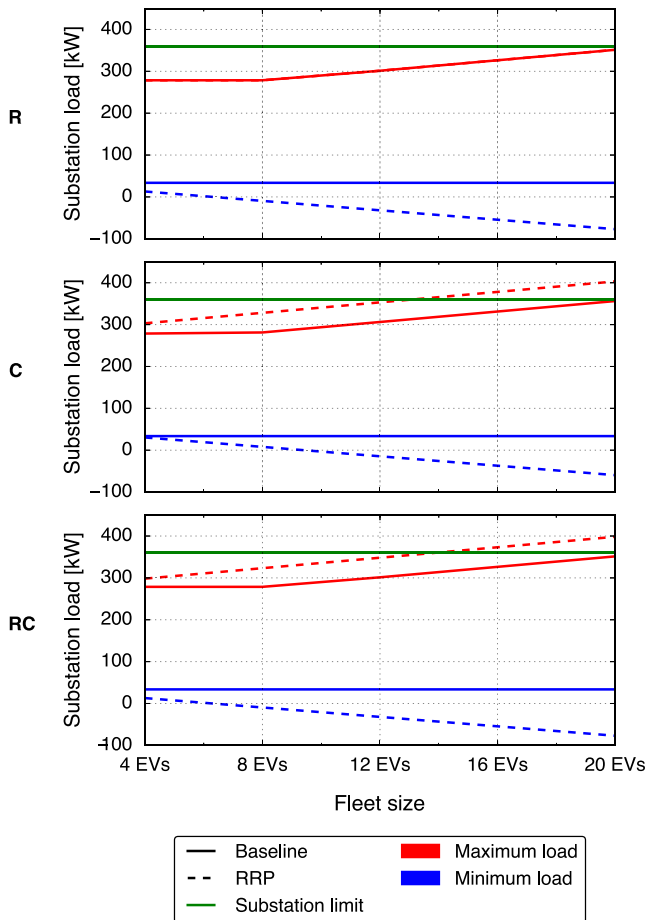


Fig. 12. Maximum and minimum loads in the baseline (solid line) and RRP (dashed line) for increasing fleet sizes.

Table 9
Comparison of results with previous studies.

Study	Location	Value range per EV	Service studied	Remuneration
This research	Netherlands	€120–€750	Secondary reserve	Energy price
Kempton et al. [4]	California (USA)	\$311–\$720	Primary reserve	Capacity price
Codani et al. [7]	France	€193–€593	Primary reserve	Capacity price
Sortomme and El-Sharkawi [13]	Houston (USA)	\$161–\$635	Energy sales, primary reserve, secondary reserve	Capacity price
Fernandes et al. [15]	Spain	€122–€540	Reduction of system costs	Unspecified
Druitt and Früh [16]	UK	£150–£400	Storage and secondary reserve	Energy price
Jargstorf and Wickert [17]	Germany	€8–€108	Secondary reserve	Capacity- and energy price

6. Conclusion

This research has shown the potential value EVs could generate by providing RRP, with focus on the Netherlands. An in-house developed simulation model was used to simulate four commonly sold EVs in an urban area in the Netherlands under a baseline charging- and RRP dispatch scheme, for different user types. With this model the monetary benefits, EV battery throughputs and impact on users mobility that result from RRP provision by EVs are simulated.

The simulations show that providing RRP yields monetary benefits ranging between €120 and €750 per EV, depending on EV- and user type. RC users who drive an EV with a high battery- and charging capacity are relatively better off than users with a shorter connection time and EVs with a lower battery- and charging capacity.

These benefits do result in higher battery throughputs ranging between 10% and 55%, which will have an adverse effect on the battery. Quantifying this effect in technical and monetary terms is recommended for further research. The simulations also showed that EV owners would barely sacrifice the ability to make unexpected trips. The ability to make trips with a Tesla is not affected by providing RRP. This latter finding has interesting implications as it shows that the benefits described above result in relatively little impact on mobility needs.

This study also has some limitations that should be addressed. In the simulations it is assumed, based on previous research, that all EVs charge a daily energy volume of 56% of the maximum capacity of their battery. When this research was conducted, the Dutch EV fleet mainly consisted of PHEVs which limits the applicability of these assumptions for FEVs. For future studies it is recommended to tailor energy consumption per trip more specifically to the type of EV (PHEV/BEV). The proposed methods within this study are suitable for these studies.

This study offers an exploration of the potential value that EVs could generate by providing RRP. However, implementation of this technology is presently hampered by non-existent supporting infrastructure and services that are necessary to facilitate users in offering their EVs. But when successful it could provide a valuable complement to a more intermittent, yet more sustainable energy system.

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