Solving the Range Challenge? Range Needs versus Range Preferences for Battery Electric Vehicles with Range Extender

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Abstract
Limited range is a challenge for the widespread adoption of battery electric vehicles (BEVs). Many studies show that customers’ range preferences are substantially higher than average daily driving distances and tend to reflect rather rarely occurring range needs. However, increasing battery size is adversely related to the environmental benefit and the cost-effectiveness of BEVs. Therefore, BEVs with range extender (i.e., extended range electric vehicles, EREVs, e.g. BMW i3 with range extender, also called BEVx) have the potential to become a particularly sustainable option to resolve the range challenge. EREVs allow using smaller battery sizes that can cover usual range needs while the range extender enables to meet also more seldom travel needs. However, in the end the essential question is: Will customers also prefer (i.e., accept) such particularly sustainable vehicle configurations? The objective of the present study was to examine range preferences and range needs of potential EREV customers. Particular effort was made to recruit only participants with sufficient practical BEV experience because research suggests that such a sample is needed to determine truly marketable range configurations in more mature (i.e., near future) markets. In total, 83 potential EREV customers with practical BEV experience could be surveyed. It was shown that the preferred battery range for an EREV was still higher than participants’ average daily driving distance. However, this effect was considerably smaller than the disparity that has been previously reported in the literature for BEVs without range extender. Hence, range extenders can at least reduce the range challenge to some degree. Moreover, participants with high practical BEV experience showed a decreased disparity between range needs and preferences. This highlights the importance of practical experience for EV acceptance and the potential decrease of market demands for higher ranges in future markets due to more practical EV experience of potential customers.

Keywords: battery electric vehicles, range extender, range preferences, range needs, acceptance

1 Introduction

Limited range is a challenge for the widespread adoption of battery electric vehicles (BEVs). A general pattern in research is that range preferences of car drivers are typically markedly above their actual range needs (e.g., [1, 2]) and tend to reflect rather rarely occurring mobility needs (i.e., days with clearly above-average daily range needs) in drivers who have experience with limited-range vehicles [3]. However, larger batteries (i.e., higher-range setups) are related to a larger ecological footprint [4]. The production of a BEV with a range of 150 km consumes more resources compared to a conventional combustion vehicle (e.g., [4, 5]). Only because of the lower environmental impact during vehicle lifetime the BEV turns out to be the more sustainable vehicle concept. Thus, the compensation of the environmental disadvantage of battery production becomes more and more difficult with increasing battery size (e.g., [4, 5]).

One sustainable solution could be extended-range electric vehicles (EREVs; also referred to as BEVx, REEV, REV or REX). This is a vehicle with (1) a relatively small battery to cover all usual trips and (2) a considerable downsized combustion engine that can extend the range to cover the more seldom longer trips. Hence, compared to a plug-in hybrid electric vehicle (PHEV) an EREV is designed to drive purely electric on most trips and has a much smaller combustion engine.

Regarding sustainability and CO₂ reduction, an EREV could be an efficient option for many car drivers. For example, Derollepot et al. [6] segmented longitudinal car use profiles derived from mobility surveys and found that EREVs could satisfy the mobility needs (i.e., travel needs) of a large portion of the population. Thus, from a theoretical point of view an EREV is a very promising solution to establish a sustainable transportation system without the need of a large battery.

However, in the end the essential question is: Will potential EREV customers also prefer (i.e., accept) sustainable EREV configurations with a considerable downsized battery? Or more precisely: Will EREVs (i.e., the availability of a range extender) lead to a reduced disparity between potential customers’ range needs (i.e., travel patterns) and their range preferences in terms of preferred battery range? Thus, will EREVs resolve the range challenge?

2 Present Research

The objective of the present research was to examine battery range preferences and range needs of potential EREV customers.

To this end, we recruited a sample of potential EREV customers who already had experience with BEVs and, therefore, with limited-range mobility. Hence, we did not focus on the general population of car buyers but on the population of potential early adopters of electric vehicles (EVs). This is because our objective was not to estimate the current mass-market potential of EREVs but to examine which EREV range configurations will probably be preferred in near-future markets that consist of more potential customers who already have experience with limited-range mobility.

Moreover, we focused on respondents who already had practical experience with limited range, also because research has shown that such experience can change range preferences considerably [3]. Indeed, it has been argued that studies on range preference should involve experienced BEV users [7]. For inexperienced BEV users, it is difficult to mentally simulate the impact of different BEV characteristics (e.g., the interaction with limited range) on their daily life. Hence, in order for respondents to be able to form accurate estimates of range needs and range preferences that are predictive of customers’ acceptance in more mature markets, it has been suggested that at least some practical experience with BEV range is necessary [3]. For these reasons, we focused on potential early adopters of EREVs who already had practical experience with limited-range mobility.

2.1 Range preferences of potential EREV customers (Q1)

Research has shown that the limited range of BEVs is one of the main barriers for their widespread adoption (e.g., [8]). However, with regard to sustainability the optimal battery size of an EREV should be as small as possible (i.e., sufficient for usual trips). For a successful integration of EREVs into the market, it is important to investigate the user perspective in terms of range preferences. Hence, the first research question is:

(Q1) How much battery range of an EREV do potential EREV customers prefer?

2.2 Range disparity (Q2)

Several studies found a large disparity between range needs (i.e., travel patterns) and range
preferences, especially in people without experience in limited-range mobility (e.g., [1, 2]). Franke and Krems [3] showed that this disparity is smaller in experienced BEV users. An EREV could be one possibility to finally eliminate this disparity completely.

An EREV has two different ranges – a battery range (that covers the usual daily driving distances) and a full power range (that covers the seldom longer driving distances). Ideally, customers’ preferred battery range should be equal to their usual daily driving distance or at least equal to their longest daily driving distance in a typical week (i.e., customers usual range needs). Hence, the second research question is:

(Q2) Can the disparity between range needs and range preference be resolved by an EREV (i.e., by adding a range extender to a BEV)? Hence, is there any disparity between the preferred battery range and the average daily driving distance?

2.3 Effect of experience (Q3)

Research has shown that experience with limited-range mobility leads to more rational views (e.g., a stronger link between range needs and range preferences, see [3]). Hence, there should be a smaller disparity between range needs and range preferences in more mature markets (i.e., markets containing potential early adopters of EREVs with practical experience with limited-range mobility). Therefore, the third research question is:

(Q3) Is experience related to a smaller range disparity?

3 Method

The present study was conducted within the framework of the EVREST project (Electric Vehicle with Range Extender as a Sustainable Technology), which was funded by the German Federal Ministry of Economics and Technology, the French Environment and Energy Management Agency and the Austrian Federal Ministry for Transport, Innovation and Technology within the European call Electromobility*. One aim of the project was to investigate in how far EREVs would be accepted by potential early adopters. To assess the user perceptions of critical aspects of EREVs, a questionnaire study was setup.

3.1 Participants

For the present research we focused on potential early adopters of EREVs with practical BEV experience. BEV experience was determined based on the total km driven with a BEV. Participants were required to have a minimum of 100 km of BEV driving experience; most had substantially more experience (see below). Currently, it is difficult to find such experienced BEV drivers in European markets. However, we had access to the contact data of experienced BEV drivers from a German BEV field study (applicants and participants of the field study “BMW ActiveE Leipzig – long-distance commuters”; labelled LDC trial in the following, for details see [9]). This project was publicly funded. Hence, the recruitment was focused on the general population of early adopters of BEVs and the subsidized full-service leasing rate of 450 € respectively 370 € (leasing rate reduced during field trial) was relatively similar to that of other mainstream BEVs. Furthermore, we recruited potential early adopters of EREVs with practical BEV experience via a newsletter for people interested in electric mobility (electrive.net newsletter, more than 6,000 daily recipients). It can be expected that daily readers are highly interested in EVs, and therefore, may be potential early adopters of EREVs.

Moreover, to really receive a sample of potential early adopters of EREVs we included two filter questions in the beginning of our questionnaire which assessed participants’ general appreciation of the BEV and the EREV concept (see section 3.3.1). Only participants who indicated a general appreciation of EREVs were included in the analysis for the present paper.

The final sample consisted of 83 participants, 11% females and 89% males, with an average age of $M = 43.45$ years ($SD = 10.69$). 68% of the participants had a university degree. 73% reported a monthly net household income above 3,000 Euro (based on the $N = 75$ who answered this question). This is a very typical distribution of early adopters of EVs [10, 11]. On average, the general BEV driving experience (for details on assessment see section 3.3.5) was $M = 4,976$ km ($SD = 9,132$, $Min = 100$, $Max = 70,000$; $N = 82$ because of one missing value on this variable).

3.2 Definition of the EREV Concept

At the beginning of the questionnaire the EREV concept was explained in detail based on three modules. Module (1) provided general information about the EREV concept. It was pointed out that an EREV has an additional combustion engine, which can recharge the battery, and therefore, extends the range. For that reason, the RE is intended to be utilized only for the rare occasions in which the
driver requires substantially more range than is typical. In module (2), the essential differences between an EREV and (a) a hybrid electric vehicle (HEV) as well as (b) a BEV were described. In this part, the degraded mode as a specific feature of the EREV was introduced. The degraded mode is active when the battery is completely empty. Then, only the RE remains to propel the vehicle. In this mode the vehicle power is reduced (e.g., maximum speed only 90 km/h). Furthermore, in this module it was pointed out that the characteristic driving experience of a BEV is mostly retained. Module (3) explicated implications of the use of an EREV in everyday life using four different possible scenarios. Participants received the following descriptions: (1) You can drive your daily trips within the battery range completely without the RE. Hence, you drive purely electric. (2) If the trip becomes longer unexpectedly (e.g., due to a detour), an activation of the RE will extend the driving range. (3) If you want to take a long trip, you will be able to activate the RE at the beginning of the trip and consequently have the maximum available range (full power range). And (4) if the battery is completely discharged, the car will not stop instantly. Instead, you are able to reach the next charging opportunity within degraded mode.

3.3 Questionnaire Scales

3.3.1 Appreciation of EREVs

To filter our sample for potential EREV customers (see section 3.1) we used a single-item indicator from our questionnaire asking for participants’ appreciation of EREVs in general: “I appreciate EREVs”. Participants rated this statement on a 6-point Likert scale from 1 (= completely disagree) to 6 (= completely agree). A second item asked participants for their appreciation of BEVs (“I appreciate BEVs”). However, this item was not relevant for the present analyses.

3.3.2 Range preferences

Two open-ended, stated preference items asked users to directly indicate their preferred range value underlying two different levels of the utility function. The item text was: (1) “Which battery range would you consider to be quite short, but just acceptable?” (minimum acceptable range, labelled “BRacceptable”, conceptually similar to a reservation price), and (2) “Which battery range would you consider to be just right and, therefore, appropriate?” (appropriate range, labelled “BRappropriate”). Participants were instructed that all range values indicated real-life values (i.e., real available range under everyday conditions) and not technical range (i.e., based on driving cycle results). For contexts where incentive-aligned methods are not applicable, it has been shown that single-item, open-ended question formats can be as valid as choice-based conjoint analyses [12].

3.3.3 Range needs

To assess range needs, four open-ended items were included into the questionnaire. The participants were asked to estimate their average daily driving distance on a workday (termed “MWorkday”), their average daily driving distance on a weekend day (termed “MWeekendday”), their maximum daily driving distance in a typical week (termed “MaxWeekday”) and their longest distance driven in one day over the last month (termed “MaxLastMonth”). To get the average daily driving distance of a typical weekday (termed “MwholeWeekday”), we computed the sum of MWorkday multiplied by five and MWeekendday multiplied by two, divided by seven (i.e., a weighted average of the two variables).

We are aware of the fact that such key mobility figures are difficult to estimate for participants. However, this kind of questions was developed and pilot tested across several studies that we conducted over the last few years. In addition, we used plausibility tests (see section 4) as well as clear instructions and frames of reference to reduce the risk of misunderstanding.

3.3.4 Proportion variables

The proportions between range needs and range preferences were calculated to quantify the range disparity. Eight proportion variables were computed relating the four range needs variables (MWorkday, MwholeWeekday, MaxWeekday, MaxLastMonth) to the two range preference variables (BRacceptable, BRappropriate). Hence, for example, for each individual MWorkday was divided by BRacceptable (e.g., 75 km / 100 km = 75%). This individual proportion score was then entered into the analysis.

3.3.5 Extent of practical BEV experience

To assess the extent of practical BEV experience (i.e., total km driven with a BEV) different approaches had to be used. The respondents recruited from the list of applicants of the LDC trial and the respondents recruited via the
Results

To answer our research questions, we analyzed our data using descriptive statistics, t-tests and correlation analyses with an alpha of .05. Moreover, we calculated effect sizes (Cohen’s \( d \), Pearson’s correlation coefficient \( r \), and Spearman’s rank correlation coefficient \( \rho \)) for our tests.

For all range preference and range needs variables data were checked for plausibility. Because of that, additional variables, which were not relevant for the further analyses, were used to examine plausibility of values: the acceptable full power range (FPRacceptable), the appropriate full power range (FPRappropriate), and the total km driven within the last year (SUMlastYear).

First, BRacceptable had to be less than (or at most equal to) BRappropriate and less than (or at most equal to) FPRacceptable. Second, BRappropriate had to be less than (or at most equal to) FPRappropriate. If one of these conditions was not met (five cases), the correspondent case was completely eliminated from the dataset; thus, \( N = 78 \).

Moreover, MWorkday and MWeekendDay had to be less than (or at most equal to) MaxWeekday. Finally, MaxWeekday multiplied with 52 weeks a year had to be equal to or less than SUMlastYear. If one of these conditions was not met, the value for MaxWeekday was excluded from further analyses. In total, 17 further data points of MaxWeekday were excluded, resulting in \( N = 61 \).

4.1 Range preferences (Q1)

Regarding Q1, results of the descriptive analysis showed that participants preferred a relatively high minimum acceptable battery range (BRacceptable) of about 139 km (see Table 1). This corresponds approximately to the real-life battery range of a current typical BEV. However, in relation to participants’ average daily driving distance on a workday (MWorkday) the minimum acceptable battery range (BRacceptable) was not very high (see also section 4.2). Furthermore, there was a remarkable difference between the minimum acceptable (BRacceptable) and the appropriate battery range (BRappropriate) indicating that potential EREV customers with practical BEV experience would still ideally like to have a relatively large battery range.

4.2 Range preferences versus range needs (Q2)

Regarding Q2, results of the descriptive analysis showed that range preferences were generally higher than the average daily driving distance on a workday (MWorkday) and on an average weekday (MwholeWeekday), see Table 1. Inspecting the computed proportion variables it becomes apparent that the range needs on an average day can only explain 71-75% of the minimum acceptable battery range. Regarding the appropriate battery range this value even drops down to about 45-48%.

In addition, we computed t-tests to directly examine the differences between range needs and range preferences (i.e., in a way that allowed direct comparison of our results with the previous analysis of the disparity between range needs and preferences in BEV drivers, see [3]). There were problems with normal distribution for most variables (see Table 2). However, t-tests are known to be relatively robust to this violation of assumptions. Results of t-tests showed that the minimum acceptable and appropriate battery range values were significantly higher than the average daily driving distance (MWorkday, MwholeWeekday), revealing strong effects (see Table 2). These disparity effects are substantially smaller than the ones found for BEV range preferences (\( d = 1.24 \) for minimum acceptable range and \( d = 1.81 \) for appropriate range, see data from [3]). Hence, the range disparity can be resolved to a considerable extent by adding a range extender.

**Table 1: Descriptive Statistics for Range Preferences, Range Needs, and Proportion Variables**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Descriptive Statistics for Range Needs and Range Preferences</th>
<th>Mean for Proportion Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( N )</td>
<td>( M )</td>
</tr>
<tr>
<td>BRacceptable</td>
<td>78</td>
<td>138.78</td>
</tr>
<tr>
<td>BRappropriate</td>
<td>78</td>
<td>233.46</td>
</tr>
<tr>
<td>MWorkday</td>
<td>78</td>
<td>94.82</td>
</tr>
<tr>
<td>MwholeWeekday</td>
<td>78</td>
<td>86.55</td>
</tr>
<tr>
<td>MaxWeekday</td>
<td>61</td>
<td>196.15</td>
</tr>
<tr>
<td>MaxLastMonth</td>
<td>78</td>
<td>381.73</td>
</tr>
</tbody>
</table>
Furthermore, there was no substantial disparity when comparing range preferences to the maximum daily driving distance in a typical week (MaxWholeWeekday). Indeed, BRAcceptable was even smaller than MaxWholeWeekday. Compared to the effects found for BEV range preferences \((d = -0.11\) for minimum acceptable range and \(d = 0.41\) for appropriate range, see data from [3]) this supports the notion that the EREV concept contributes to a reduction of the range disparity.

Finally, the range preferences (BRAcceptable, BRappropriate) were considerably below the longest daily driving distance in the last month (MaxLastMonth) indicating that participants oriented clearly on their usual (and not maximum) range needs for constructing their preferences for battery range of an EREV. Figure 1 finally depicts the differences between range needs and range preferences graphically.

### 4.3 Relationship of practical BEV experience with range disparity (Q3)

Regarding Q3, we computed correlations between participants’ practical BEV experience and the proportion variables (maximum \(N = 77\) because of one missing value of the experience variable). Because there were problems with normal distribution of the variables we used a logarithmic transformation of the variables which partly solved the problems (see Table 3). As an alternative solution to deal with the violation of normality we additionally computed Spearman’s rank correlations.

Results of the correlation analyses revealed (see Table 3) that the higher the practical experience with BEV range, the lower the disparity between range needs and range preferences. Hence, participants with high practical BEV experience showed a decreased disparity between range needs and range preferences.

#### Table 2: t-Tests for Range Preferences versus Range Needs

<table>
<thead>
<tr>
<th>Variables</th>
<th>(N)</th>
<th>(M)</th>
<th>(SD)</th>
<th>(t)</th>
<th>(df)</th>
<th>(p)</th>
<th>(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRAcceptable = MWorkday</td>
<td>78</td>
<td>43.96</td>
<td>74.17</td>
<td>5.23</td>
<td>77</td>
<td>&lt;.001</td>
<td>0.59</td>
</tr>
<tr>
<td>BRAcceptable = MWholeWeekday</td>
<td>78</td>
<td>52.23</td>
<td>73.82</td>
<td>6.25</td>
<td>77</td>
<td>&lt;.001</td>
<td>0.71</td>
</tr>
<tr>
<td>BRappropriate = MWorkday</td>
<td>78</td>
<td>138.64</td>
<td>132.27</td>
<td>9.26</td>
<td>77</td>
<td>&lt;.001</td>
<td>1.05</td>
</tr>
<tr>
<td>BRappropriate = MWholeWeekday</td>
<td>78</td>
<td>146.91</td>
<td>131.16</td>
<td>9.89</td>
<td>77</td>
<td>&lt;.001</td>
<td>1.12</td>
</tr>
<tr>
<td>BRAcceptable = MaxWeekday</td>
<td>61</td>
<td>-49.51</td>
<td>186.45</td>
<td>-2.07</td>
<td>60</td>
<td>.042</td>
<td>-0.27</td>
</tr>
<tr>
<td>BRappropriate = MaxWeekday</td>
<td>61</td>
<td>45.98</td>
<td>203.44</td>
<td>1.77</td>
<td>60</td>
<td>.083</td>
<td>0.23</td>
</tr>
<tr>
<td>BRAcceptable = MaxLastMonth</td>
<td>78</td>
<td>-242.95</td>
<td>262.04</td>
<td>-8.19</td>
<td>77</td>
<td>&lt;.001</td>
<td>0.93</td>
</tr>
<tr>
<td>BRappropriate = MaxLastMonth</td>
<td>78</td>
<td>-148.27</td>
<td>287.77</td>
<td>-4.55</td>
<td>77</td>
<td>&lt;.001</td>
<td>0.52</td>
</tr>
</tbody>
</table>

Notes. \(p\)-values are two-tailed. Kolmogorov–Smirnov (KS) test did not indicate problems with normal distribution (\(p < .05\)). \(b = \) Lilliefors test indicated problems with normal distribution (\(p < .05\)). Furthermore, KS test did not indicate problems with normal distribution for the logarithmized BEV experience variables, but Lilliefors test did.

#### Table 3: Pearson and Spearman’s Rho Correlations of Proportion Variables and BEV Experience

<table>
<thead>
<tr>
<th>Variables</th>
<th>(N)</th>
<th>(r)</th>
<th>(p)</th>
<th>(\rho)</th>
<th>(r)</th>
<th>(\rho)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prop MWorkday / BRAcceptable</td>
<td>77</td>
<td>.312</td>
<td>.006</td>
<td>.325</td>
<td>.002</td>
<td>.004</td>
</tr>
<tr>
<td>Prop MWorkday / BRappropriate</td>
<td>77</td>
<td>.345</td>
<td>.002</td>
<td>.397</td>
<td>.001</td>
<td>.000</td>
</tr>
<tr>
<td>Prop MWholeWeekday / BRAcceptable</td>
<td>77</td>
<td>.279</td>
<td>.014</td>
<td>.291</td>
<td>.010</td>
<td>.009</td>
</tr>
<tr>
<td>Prop MWholeWeekday / BRappropriate</td>
<td>77</td>
<td>.331</td>
<td>.003</td>
<td>.344</td>
<td>.002</td>
<td>.002</td>
</tr>
<tr>
<td>Prop MaxWeekday / BRAcceptable</td>
<td>61</td>
<td>.203</td>
<td>.117</td>
<td>.209</td>
<td>.107</td>
<td>.107</td>
</tr>
<tr>
<td>Prop MaxWeekday / BRappropriate</td>
<td>61</td>
<td>.282</td>
<td>.028</td>
<td>.278</td>
<td>.030</td>
<td>.030</td>
</tr>
<tr>
<td>Prop MaxLastMonth / BRAcceptable</td>
<td>77</td>
<td>.022</td>
<td>.851</td>
<td>-.018</td>
<td>.879</td>
<td>.879</td>
</tr>
<tr>
<td>Prop MaxLastMonth / BRappropriate</td>
<td>77</td>
<td>.101</td>
<td>.381</td>
<td>.055</td>
<td>.635</td>
<td>.635</td>
</tr>
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</table>

Notes. \(p\)-values are two-tailed. Kolmogorov–Smirnov (KS) test did not indicate problems with normal distribution for all variables. \(b = \) Lilliefors test indicated problems with normal distribution (\(p < .05\)). Furthermore, KS test did not indicate problems with normal distribution for the logarithmized BEV experience variables, but Lilliefors test did.

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5 Discussion and Conclusion

5.1 Summary of Study Findings and Implications

The present research represents a first attempt to understand potential EREV customers’ battery range preferences. It was shown that potential EREV customers prefer an average EREV battery range of about 139 km as minimum acceptable range (Q1). This value was higher than respondents’ average daily driving distance on a workday but still indicated a smaller range disparity compared to what previous research has shown for BEV range preferences. Hence, it was shown that the range disparity can be reduced considerably by adding a range extender (Q2). Hence, an EREV can resolve the range challenge to some degree. Moreover, practical BEV experience seems to play a significant role in this relationship (Q3). Potential EREV customers with high practical BEV experience showed a smaller disparity between range needs and range preferences. This highlights the importance of practical experience with limited-range mobility for EV acceptance and indicates a potential decrease of marked demands for higher ranges in future markets due to more practical EV experience of potential customers.

5.2 Critical Evaluation and Further Research

Special effort was made to recruit potential early adopters of EREVs with practical BEV experience. Thus, respondents could more easily imagine how the new features of EREVs could affect driving (e.g., the implication of different ranges). Indeed, this sample might not be representative of the German population of car buyers because of self-selection biases. However, the aim of the study was to investigate potential early adopters because we were interested in the EREV range configurations that will be preferred in near-future markets. It is very likely that such markets will consist of more potential customers who already have experience with limited-range mobility. For that reason, potential early adopters are an appropriate sample for estimating optimal battery size of EREVs in near-future markets. However, it must be mentioned that several respondents of the study were people who had relatively high daily range needs. Although it is particularly relevant to examine range preferences of individuals with high range needs, further research with potential customers who have, for instance, mostly urban mobility travel patterns is clearly needed.

Acknowledgments

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