What influences uptake of private battery electric cars in cities? A case study of Stuttgart, Germany

INTRODUCTION
Cities continue to play a major role in the transition to battery electric vehicles (BEVs). In Germany, around 38% of the more than 237,000 total new private BEV registrations in 2022 were in urban regions. However, only roughly one third of the urban regions saw private BEV registration shares above the national average of 25% in 2022, suggesting that some cities have a higher uptake of BEVs than others. The shift from internal combustion engine vehicles (ICEVs) to BEVs plays an important role in reducing air pollutants and greenhouse gas (GHG) emissions, therefore benefitting the health of city populations.

To better support the shift to electric vehicles in cities, it is necessary to understand which factors might influence BEV uptake at a more granular neighborhood level, as this relationship is currently not well-researched. Some reports provide general observations about the typical German BEV purchaser and owner: predominantly middle-aged men with a higher education who are employed full time, have a higher income compared to an ICEV user, are married, have children, and often live in either a one- or two-family house. Women in Germany were more likely to own smaller and petrol-fueled cars compared to men, who more often own electric cars and larger

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vehicles. Also typical for BEV owners is having a higher environmental awareness about ICEVs and the use of electricity from renewable energy sources. Moreover, a previous ICCT report assessing German districts and district-free cities found a high correlation between new BEV registration shares and environmental awareness, access to public charging infrastructure, and economic well-being.

This paper evaluates the potential correlations between the share of private BEVs—as indicated by total new vehicle registrations in city neighborhoods—with sociodemographic factors, environmental awareness, and charging infrastructure access. While investigating which factors influence BEV uptake in cities, this study further assesses if members of marginalized groups are given equitable access to the transition from ICEVs to BEVs. To evaluate this question, we assume that the access of a group to the transition is indicated by the BEV share of new vehicle registrations. When referring to marginalized groups, we generally mean those that experience disadvantages due to the interplay of different factors such as income, education, age, ethnicity, gender, or disability. Equity can be understood as the state in which different levels of support are provided, based on the needs of an individual or group, in order to obtain fair and equal outcomes. An equitable transition from ICEVs to BEVs is one where support is given based on a group’s specific needs, accounting for any barriers that may exist, to achieve access to BEVs for those who need them. An overview of the motivation, equity focus, and outcomes of this study is shown in Figure 1.

Figure 1
Motivation, equity focus, and outcome of this paper

<table>
<thead>
<tr>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>To evaluate potential correlations between the share of private BEVs in total new vehicle registrations across city neighborhoods and selected variables such as income, access to charging infrastructure, age, etc.</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Equity Focus</th>
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<tbody>
<tr>
<td>We center the perspective of marginalized groups i.e., those which might be at risk of facing higher barriers to participate in the transition from internal combustion engine cars to battery electric cars due to certain sociodemographic factors—such as income, age, living conditions in terms of residency type, citizenship—or due to other aspects such as charging infrastructure opportunities</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outcome</th>
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<tbody>
<tr>
<td>Policy recommendations for local authorities, beyond state and national policies, to move towards an equitable transition from internal combustion engine cars to battery electric cars</td>
</tr>
</tbody>
</table>

The scope of this analysis is new registrations by private individuals, as these accounted for 50% of new BEV registrations in Germany in 2022. As a case study, we chose the city of Stuttgart. The city had a 13% BEV share of total new passenger registrations in 2021.

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3 Wappelhorst et al., Elektromobilität und soziale Teilhabe.
similar to the German average of 14% in the same year. Stuttgart is the sixth largest city in Germany by population, a major auto manufacturing hub, and has a long history of local and regional policies to support BEV uptake.

We start by analyzing the share of BEVs in total private passenger car registrations across the 23 districts and 152 neighborhoods of Stuttgart. Due to the lack of available high-resolution data from 2022 onward, only the years 2017–2021 are considered. We perform a multivariable linear regression to better understand the correlation between private BEV uptake and selected sociodemographic factors, environmental awareness, and access to charging infrastructure across neighborhoods. A discussion and spatial visualization of these results are also shown. We also provide an overview of local policies that are in place or were previously implemented and suggest recommendations focusing on how cities could improve equitable access to BEVs.

NEW REGISTRATIONS OF PRIVATE BEVS IN STUTTGART FROM 2017 TO 2021

Before investigating which factors might influence BEV uptake, we first assess the development of private BEV uptake in Stuttgart’s 23 districts and 152 neighborhoods, based on data from the Statistical Office of the City of Stuttgart. Figure 2 shows the total new passenger car registrations by private individuals between 2017 and 2021 and the share of BEVs for the city of Stuttgart. Total registrations peaked in 2019 at around 20,000 new vehicles before falling in 2020 to around 15,000 and to just over 10,000 in 2021. The decline in new passenger car registrations in 2020 was likely due to the COVID-19 pandemic outbreak in the same year. Despite this market disruption, the BEV share of new private passenger car registrations, referred to here as the private BEV share, has steadily grown in Stuttgart since 2017. The city-wide private BEV share went from 1% in 2017, 2018, and 2019, to 7% in 2020, and then doubled to 14% in 2021. The uptake in BEVs has occurred in tandem with the development of the charging infrastructure network. Across the city, there were about 750 normal and fast charging points in 2020 and almost 800 in 2021, translating to about 1.2 charging points per 1,000 inhabitants.
At the district level in 2021, private BEV shares ranged from 7% in the district Mühlhausen in the north of the city to nearly 20% in the district Nord, which is situated north of the city center, revealing disparities in uptake (Figure 3). Eight of the 23 districts, mostly located in the center and south of the city, were above the city-wide private BEV share of 14% in 2021. These eight districts were Nord, Plieningen, Mitte, Degerloch, Sillenbuch, West, Obertürkheim, and Vaihingen. The BEV registration shares in four districts were the same as the city-wide share of 14% and 11 were under the city-wide share, typically located in the northern part of the city.
As the data shows, spatial disparities exist in the private BEV shares at the broader district level. For a more granular analysis, it is important to also look at the neighborhood level, as neighborhoods within districts can have significant differences in terms of sociodemographics or access to charging infrastructure. Additionally, more granular-level data can help pinpoint which factors might be significant in the uptake of private BEVs. The private BEV shares across the Stuttgart neighborhoods from 2017 to 2021 are shown in Figure 4. For seven of the 152 neighborhoods (displayed in gray in the figure), data are unavailable or the population is at or near zero, leaving 145 neighborhoods for our analysis. The same scale of shades, ranging from below 5% to above 20%, is used for all years.
Figure 4
BEV share of new private passenger car registrations in Stuttgart neighborhoods from 2017 to 2021
The figure shows that the private BEV shares have steadily risen in Stuttgart among most neighborhoods. In 2017, only one neighborhood had a private BEV share higher than 5%, here used as the lowest bracket. This grew to four neighborhoods in 2018 and seven in 2019. The uptake in private BEVs was more widespread in 2020 when 92 out of 145 neighborhoods had private BEV shares above 5% and 29 neighborhoods had shares above 10%. However, this gradual growth has been uneven, particularly between 2017 and 2019, when neighborhoods with higher private BEV uptake were concentrated in and around the city center (Mitte). Additionally, some neighborhoods in the city did not record private BEV shares above 5% as of 2021.

In 2021, the distribution of private BEVs displayed a wide range in uptake levels, varying from 0% to 66%. The neighborhoods with the highest share of private BEV registrations in 2021 were Tränke in the southern district of Degerloch with 66%, Pragstraße (Bad Cannstatt district in the north-east) with 50%, and Rotenberg (Untertürkheim district in the west) with 40%. Nineteen neighborhoods saw shares above 20% in 2021, 10 of which were in and around the city center, namely in the districts of Mitte, Nord, and Süd. However, six of the 19 neighborhoods with private BEV shares above 20% occurred in districts on the outskirts of the city center (Bad Canstatt, Plüningen, Untertürkheim, Vaihingen, and Zuffenhausen). Twelve of the neighborhoods had a BEV share of less than 5%. Overall, there was no clear spatial distribution pattern shown in the low- or high-uptake neighborhoods. The variations over the years give a first indication of the uneven uptake across Stuttgart’s neighborhoods and the potential inequities in BEV adoption among private individuals.

QUANTITATIVE ASSESSMENT OF VARIABLES CORRELATING WITH BEV SHARES ACROSS NEIGHBORHOODS

As described in the previous section, disparities exist in the BEV share of total new private vehicle registrations distributed across the districts and neighborhoods within Stuttgart. These disparities underscore the complex interplay of factors that influence private BEV adoption.

In this section, we conduct a quantitative analysis using a multilinear regression to identify factors that might contribute to the varying BEV adoption rates across Stuttgart neighborhoods. This method allows us to investigate the relationships between the dependent variable, private BEV uptake, and several independent variables, such as sociodemographics, the availability of charging infrastructure, and environmental awareness.

It is important to note that while a multilinear regression can provide valuable insights, it also comes with certain limitations. The relationships between variables are often complex and nonlinear, and there may be interactions between variables that a linear model cannot fully capture. Furthermore, the results of the regression analysis are based on the available data and the selected variables, and there may be other unmeasured factors influencing BEV adoption that are not included in the model. Despite these limitations, this analysis provides a useful starting point for understanding the factors contributing to the observed disparities in BEV shares across different neighborhoods of Stuttgart.

VARIABLE SELECTION

The dependent variable—the private BEV share—is defined as the share or percentage of BEVs in total new private passenger car registrations. It is calculated using data on new private battery electric passenger car registrations and total new private
passenger car registrations in the 152 neighborhoods of Stuttgart in 2021, which is provided by the Statistical Office of Stuttgart.¹⁰

According to the literature, we identified eight potential factors, or independent variables, that may have influenced the shift in the BEV share in Stuttgart. These potential influencing factors, described below, fall into three categories: sociodemographics, charging infrastructure accessibility, and environmental awareness. Depending on data availability, we created variables for each potential influential factor to reflect those factors or serve as a proxy.

**Sociodemographic variables**

» Net income index (Stuttgart average = 100): The net income index measures the average net income per person within a neighborhood and compares it to the city-wide average income for the specific reference year (2017, the most recent data available), which stood at €30,645. Any index value above or below 100 signifies the percentage difference of that specific neighborhood. For example, a neighborhood with an index value of 110 would have an average net income that is 10% higher than the city-wide average. Income is a significant factor influencing vehicle purchases, and higher-income individuals are generally more capable of affording the higher upfront costs of new BEVs. A recent report using 2020 data found that the average disposable income per capita is significantly and positively correlated with BEV shares in Germany.¹¹

» Population density (persons per km²): Higher population densities could potentially foster BEV uptake due to shorter travel distances and the resulting lower level of range anxiety. The empirical evidence regarding the role population density plays is mixed. Some studies have found a negative correlation between population density and the BEV share while others have found inconclusive results.¹² With more granular data at the neighborhood level, we can examine this question with a higher degree of precision.

» Share of family households (%): This variable measures the percentage of families (households with children under the age of 18) in all households using data from 2021. Family households, particularly in developed economies, are more likely to own multiple vehicles due to higher transportation requirements. Research indicates that multicar households are considerably more likely to have a BEV.¹³ Access to both powertrain types can provide families with more flexibility to choose between driving their BEVs or ICEVs, thereby reducing potential range anxiety. This flexibility can make BEV ownership more advantageous in terms of total costs.¹⁴

» Share of residents 65 years old and older (%): We calculate this metric, which is the percentage of residents aged 65 and above, based on data from 2021. Age can play a role in BEV adoption, as various age groups may differ in their environmental awareness, familiarity with the technology, and financial capabilities. Some studies have identified that individuals over 65 years of age tend to adopt BEVs at a lower rate.¹⁵ We examine whether neighborhoods with a larger proportion of senior residents show lower BEV adoption rates.

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¹⁰ Landeshauptstadt Stuttgart Statistisches Amt, Dataset.
¹¹ Wappelhorst et al., Electric Vehicles for Everyone?
¹³ Brückmann, Willibald, and Blanco, “Battery Electric Vehicle Adoption.”
¹⁵ Brückmann, Willibald, and Blanco, “Battery Electric Vehicle Adoption.”
Share of residents without German citizenship (%): To quantify the proportion of immigrants within neighborhoods, we utilize the metric representing the percentage of residents without German citizenship from the total population, based on data from 2021. An equitable transition to clean transportation is one of the key goals of the German government.\textsuperscript{16} To realize this equitable transition, it is crucial to examine the BEV adoption rates among potentially marginalized groups, which includes immigrants. These groups might face extra challenges in accessing BEVs due to policy disparities after accounting for economic constraints and other sociodemographic barriers discussed above.

**Accessibility of charging infrastructure variables**

Density of public charging points (unit per km\(^2\)): Density of public charging points is used as a proxy for access to public charging infrastructure, which research shows is an important factor influencing BEV adoption.\textsuperscript{17} For our analysis, the density of public charging points in Stuttgart is calculated using the total number of public charging points (fast and normal) by location in 2021 from Eco-Movement and the land area of each neighborhood using 2017 statistics from Datenkompass Stuttgart.\textsuperscript{18} There are alternative metrics for this factor, such as public charging points per vehicle or public charging points per capita for each neighborhood. Here, we use public charging points per area to reflect both availability as well as accessibility by distance. This variable for the density of public charging points includes charging points that are always accessible to the public and semi-accessible public charging points. Semi-accessible public charging points are located on private property and subject to specific but nondiscriminatory access restrictions such as compliance with opening and closing times.

Share of one- and two-family houses (%): The share of one- and two-family houses, or the share of detached and semi-detached houses of all residential buildings, is used here as a proxy for potential accessibility to home charging. Most Germans live in multifamily houses with up to 10 apartments. Residents of one- and two-family houses are more likely to have access to private charging infrastructure, which is a significant factor in choosing to purchase a BEV.\textsuperscript{19}

**Environmental awareness variable**

Share of votes for the Greens in the 2021 German federal election, second vote (%): The share of votes for the Green party in the German federal election second vote (which is for a specific party, rather than an individual candidate) is used as a proxy for environmental awareness. Previous research, which used similar methods, has shown that a preference for the Green party increases the adoption probability of BEVs.\textsuperscript{20} For this metric, we use the most recent publicly available data from the Stuttgart Statistical Office from November 2022.\textsuperscript{21}

Table 1 gives an overview of the final independent and dependent variables used for the regression analysis and relevant data sources. All variables are at the neighborhood level.

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\textsuperscript{20} Brückmann, Willibald, and Blanco, “Battery Electric Vehicle Adoption.”

level except for the share of votes for the Greens in the German elections, which is at the district level. All variables are collected using 2021 data except for the net income index, for which the most recent available data is from 2017.

Table 1
Overview of variables and data sources selected for this analysis

<table>
<thead>
<tr>
<th>Category</th>
<th>Variable</th>
<th>Level</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dependent variable</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BEV registrations</td>
<td>Share of battery electric cars in new passenger car registrations by private individuals (%), 2021</td>
<td>Stuttgart neighborhoods</td>
<td>Landeshauptstadt Stuttgart a</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Independent variables</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sociodemographic</td>
<td>Average net income index (benchmarked to Stuttgart average = 100), 2017</td>
<td></td>
<td>Landeshauptstadt Stuttgart b</td>
</tr>
<tr>
<td></td>
<td>Population density (persons per km²), 2021</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Percentage of residents aged 65 and over in relation to all residents (%), 2021</td>
<td>Stuttgart neighborhoods</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Percentage of families in all private households (%), 2021</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Share of residents without German citizenship (%), 2021</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accessibility to charging infrastructure</td>
<td>Share of one- and two-family houses (%), 2021</td>
<td></td>
<td>Eco-Movement d</td>
</tr>
<tr>
<td></td>
<td>Density of public charging points (fast and normal, unit per km²), 2021</td>
<td></td>
<td>Landeshauptstadt Stuttgart *</td>
</tr>
<tr>
<td>Environmental awareness</td>
<td>Share of votes for the Greens in the German election, second vote (%), 2021</td>
<td>Stuttgart districts</td>
<td>Landeshauptstadt Stuttgart c</td>
</tr>
</tbody>
</table>

Table 2 provides summary statistics of the selected variables along with the private BEV share. These statistics provide valuable background information about Stuttgart and put the following multivariable linear regression analysis into perspective. The mean shows the average value for each variable, and the minimum and maximum values give information about the presence of extreme values. The 25th percentile, 50th percentile, and 75th percentile figures are helpful to assess the distribution and dispersion of values. Finally, the coefficient of variation illustrates if the values of a variable differ greatly across neighborhoods. When the coefficient of variation is higher, it indicates a greater level of dispersion around the mean.

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Table 2
Summary statistics for the selected variables

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>25th percentile</th>
<th>50th percentile</th>
<th>75th percentile</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEV share of new private passenger car registrations (%)</td>
<td>14</td>
<td>0</td>
<td>67</td>
<td>9</td>
<td>13</td>
<td>17</td>
<td>0.7</td>
</tr>
<tr>
<td>Net income index per capita</td>
<td>100</td>
<td>45</td>
<td>144</td>
<td>91</td>
<td>99</td>
<td>108</td>
<td>0.2</td>
</tr>
<tr>
<td>Population density (persons per km(^2))</td>
<td>5,112</td>
<td>141</td>
<td>21,738</td>
<td>1,794</td>
<td>3,736</td>
<td>7,273</td>
<td>0.9</td>
</tr>
<tr>
<td>Share of family households (%)</td>
<td>18</td>
<td>1</td>
<td>43</td>
<td>16</td>
<td>18</td>
<td>20</td>
<td>0.3</td>
</tr>
<tr>
<td>Share of residents 65 years old and older (%)</td>
<td>18</td>
<td>2</td>
<td>49</td>
<td>14</td>
<td>18</td>
<td>22</td>
<td>0.4</td>
</tr>
<tr>
<td>Share of residents without German citizenship (%)</td>
<td>27</td>
<td>8</td>
<td>89</td>
<td>17</td>
<td>24</td>
<td>33</td>
<td>0.5</td>
</tr>
<tr>
<td>Share of one- and two-family houses (%)</td>
<td>45</td>
<td>0</td>
<td>100</td>
<td>24</td>
<td>47</td>
<td>65</td>
<td>0.5</td>
</tr>
<tr>
<td>Density of public charging points (fast and normal, unit per km(^2))</td>
<td>7</td>
<td>0</td>
<td>109</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td>2.2</td>
</tr>
<tr>
<td>Votes for the Greens in German federal election (%)</td>
<td>24</td>
<td>14</td>
<td>35</td>
<td>20</td>
<td>24</td>
<td>27</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The summary statistics show that the mean value in 2021 for the private BEV share was 14%, though it ranged from 0% to 67% across Stuttgart’s neighborhoods. Most neighborhoods had private BEV shares ranging from 9% to 17% (the 25th and 75th percentiles). These statistics show that the private BEV share was not evenly distributed across neighborhoods in Stuttgart. This observation can be further validated by a relatively large coefficient of variation for the private BEV shares of 0.7.

For the average net income index in the neighborhoods, the mean value was 100 in 2017, ranging from 45 to 144. In the 25th and 75th percentiles, the income index ranged from 91 (25th percentile) to 108 (75th percentile), which indicates a narrow income gap between the middle 50% of neighborhoods. However, the minimum and maximum values are much further away from the mean, indicating the existence of very high- and low-income neighborhoods in Stuttgart relative to the city average.

In terms of the sociodemographic variables, population density had the largest spread in distribution across the neighborhoods in 2021, with a coefficient of variation of 0.9. The degree of variation is followed by the share of residents without German citizenship (0.5), the share of one- and two-family houses (0.5), and the share of residents 65 years and older (0.4). The least variation across neighborhoods was the share of family households and the net income index, with a coefficient of variation of 0.2.
When examining indicators for charging accessibility, the share of one- and two-family houses, or the percentage of detached and semi-detached houses in all residential buildings, is used as a proxy for potential home-charging access. This averaged 45% in 2021 across all neighborhoods in Stuttgart. The range spanned from 0% to almost 100%, with the middle 50% of neighborhoods falling between 24% and 65%. The availability of public charging points, represented by the density of public charging points per square kilometer, varied considerably across neighborhoods. The average was around seven public charging points per square kilometer, with points ranging between zero and 109 depending on the neighborhood. Half of the neighborhoods had three or fewer public charging points per square kilometer, indicating a highly skewed distribution. In fact, both indicators for charging accessibility display relatively high coefficients of variation, implying an uneven distribution across the neighborhoods. However, public charging accessibility showed a greater degree of imbalance in its distribution compared to home-charging potential accessibility (2.2 versus 0.5 in terms of the coefficient of variation). This underlines the spatial disparities in public charging infrastructure across different neighborhoods.

The environmental awareness indicator is constructed using the share of votes for the Greens at the 2021 German elections at the district level. This variable is more evenly distributed than most of the other selected indicators. The average share was 24% across all districts in Stuttgart, ranging from 14% to 35%. The share of votes for the Greens in the middle 50% of districts ranged from 20% to 27%.

Overall, the independent variables with a high dispersion in terms of minimum and maximum values, compared to the mean across neighborhoods, include the net income index, population density, availability to public charging points, and potential access to home charging.

**MULTIVARIABLE LINEAR REGRESSION ANALYSIS**

We use a multivariable linear regression analysis to investigate the relationship between the variables described above and the private BEV shares at the neighborhood level in Stuttgart. A multivariable linear regression is a statistical method that can be used to summarize and study relationships between potential influencing factors (independent variables) and an outcome variable (dependent variable). The model assumes a linear relationship between the dependent variable and each independent variable. By including a combination of independent variables, the regression analysis can help understand how each correlates with the private BEV registration shares when all other independent variables are held constant. The simple assumption of the linear relationship has great interpretability; the estimated coefficient for each independent variable can be interpreted as the percentage change of the new private BEV registration share associated with a 1-unit change in the independent variable, when the other independent variables are kept unchanged.
We carry out the multivariable linear regression analysis to investigate the correlation between the private BEV registration shares and the selected variables. Equation 1 is used in this regression:

\[ S_j = \alpha + \beta \times Income_j + \theta \times PopDen_j + \gamma_1 \times PercFam_j \\
+ \gamma_2 \times Perc65_j + \gamma_3 \times PercNonDE_j + \omega_1 \times PercHouses_j \\
+ \omega_2 \times ChargerDen_j + \delta \times PercGreenvote_j + \epsilon_j \]

Where:

- \( S_j \) denotes the dependent variable of the private BEV shares in the new private passenger car registrations in 2021 for each neighborhood \( j \) in Stuttgart;
- \( Income_j \) denotes the net income index for neighborhood \( j \);
- \( PopDen_j \) denotes the population density in persons per square kilometer for neighborhood \( j \);
- \( PercFam_j \) denotes the share of families in neighborhood \( j \);
- \( Perc65_j \) denotes the share of residents of 65 years old and older in neighborhood \( j \);
- \( PercNonDE_j \) denotes the share of residents without German citizenship in neighborhood \( j \);
- \( PercHouses_j \) denotes the share of one- and two-family houses in neighborhood \( j \), which serves as a proxy for accessibility to home charging;
- \( ChargerDen_j \) denotes the density of public charging points (both fast and normal) per square kilometer in neighborhood \( j \), which serves as a proxy for accessibility to public charging;
- \( PercGreenvote_j \) denotes the share of votes for the Greens at German elections first vote for neighborhood \( j \);
- \( \alpha \) denotes the constant term of the multivariable linear regression model; and
- \( \epsilon_j \) is the error term, which captures all the other factors that are not considered here that might affect the private BEV shares but are not included in our study.

Table 3 illustrates the results of the regression. Variables with a statistically significant positive correlation are shaded in green. The deeper green indicates a higher significance of correlation. Statistical significance is measured by the p-value, which measures how likely the correlation is non-zero. The smaller the p-value, the more likely that a correlation exists. A p-value below 0.01 means that there is less than 1% probability that we detect the correlation by chance. A p-value below 0.1 indicates that there is less than 10% probability that we identify the correlation by chance. The notation used above is consistent throughout the paper.
### Table 3
Linear correlation factors of the selected independent variables with BEV share of new private vehicle registrations in Stuttgart in 2021

<table>
<thead>
<tr>
<th>Independent variables</th>
<th>Change of dependent variable private BEV share in percentage points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average net income index (Stuttgart average = 100)</td>
<td>0.25**</td>
</tr>
<tr>
<td>Population density (persons per km²)</td>
<td>-0.0002</td>
</tr>
<tr>
<td>Share of family households (%)</td>
<td>-0.2</td>
</tr>
<tr>
<td>Share of residents 65 years old and older (%)</td>
<td>0.02</td>
</tr>
<tr>
<td>Share of residents without German citizenship (%)</td>
<td>0.4</td>
</tr>
<tr>
<td>Share of one- and two-family houses (%)</td>
<td>0.17***</td>
</tr>
<tr>
<td>Density of public charging points (total, unit per km²)</td>
<td>0.083**</td>
</tr>
<tr>
<td>Share of votes for the Greens in 2021 German elections, second vote (%)</td>
<td>0.2</td>
</tr>
<tr>
<td>Sample size</td>
<td>135</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.3</td>
</tr>
</tbody>
</table>

*** p < 0.01, ** p < 0.05, * p < 0.1  
Notes: Values in the table show the estimated coefficients. The p-value indicates the statistical significance of each variable. For fields with a p-value below 0.1, green shading represents a statistically significant positive correlation, while there is no statistically significant negative correlation in this table. Fields that are not highlighted have p-values larger than 0.1. R-squared shows the goodness of fit of the regression model.

**Statistically significant positive linear correlations**

» Neighborhoods with higher average income levels tend to see a higher private BEV share. We find a significant and positive correlation between the net income index (relative to the city average of 100) and the private BEV share. This is the only sociodemographic factor that shows a significant correlation. As shown in Table 3, the coefficient of the net income index is 0.25, which means that on average, a 1-unit rise of the income index correlates with a private BEV share that is 0.25 percentage points higher. The results indicate that income inequity could influence inequity in BEV uptake among neighborhoods. Between the highest- and lowest-average-income neighborhoods there is a difference of 99 in the income index. This income gap might explain the 24.8 percentage-point difference in the private BEV shares in 2021 (99 * 0.25 = 24.8).

» Neighborhoods with better access to home charging (proxied by the share of one- and two-family houses) tend to see a higher private BEV share. The coefficient for share of one- and two-family houses is 0.17. The correlation is positive and significant. The results indicate that each percentage-point increase in the share of one- and two-family houses correlates with a private BEV share that is 0.17 percentage points higher, after taking into account the effect of other variables.

» Neighborhoods with better access to public charging (proxied by public charging-point density) tend to see higher private BEV shares. The regression analysis shows that the density of public charging points, measured as charging points per square kilometer, also shows a significant positive correlation with the share of BEVs in new private passenger car registrations. The coefficient of the public charging-point density is 0.083, indicating that, on average, a one-unit increase in public charging-point density corresponds to a 0.083 percentage-point increase in the private BEV share.
No statistically significant linear correlations

The independent variables—population density, share of family households, share of residents 65 years and older, share of residents without German citizenship, and the share of votes for the Greens in German elections as a proxy for environmental awareness—do not show a statistically significant linear correlation with private BEV registration shares.

**Figure 5**
Summary of quantitative assessment results

**Neighborhoods with a higher average income**
Every one unit rise in the income index (Stuttgart average = 100) correlates with a 0.25 percentage point increase in the private BEV registration share (P-value = 0.25)

**Neighborhoods with higher access to public charging**
Every 1 unit increase in public chargers per km² correlates with a 0.083 percentage point increase in the private BEV registration share (P-value = 0.083)

**Neighborhoods with higher access to at-home charging**
Every 1 percentage point increase in the share of one- and two-family houses correlates with a 0.17 percentage point increase in the private BEV registration share

**Spatial distribution of the significant dependent variables correlating with the private BEV registration shares**

In this section, we show the spatial distribution of the dependent variables that are correlated with a higher private BEV registration share across Stuttgart neighborhoods. The net income index showed one of the highest significant positive correlations with new private BEV shares in the linear regression analysis. Figure 6 shows the private BEV shares in blue and the net income tax levels as yellow dots. Thirteen neighborhoods with private BEV shares above 20% had income levels above the Stuttgart index of 100. This contrasts with 11 neighborhoods that had private BEV shares under 5% and income index levels below the Stuttgart index. The figure
also displays that there is no clear spatial pattern between this relationship. Some neighborhoods show high private BEV shares despite income index levels below the Stuttgart average value of 100; we find this pattern also the other way around. Low private BEV shares and below Stuttgart average-income-level neighborhoods can be found across the city, but particularly on the outskirts. These neighborhoods may require further assessment to determine if targeted measures are necessary to promote equity.

**Figure 6**
Private BEV share of new private passenger car registrations in Stuttgart by neighborhood in 2021 and net income index levels in 2017
Public charging infrastructure also showed a significantly high positive correlation with private BEV shares. Figure 7 shows the distribution of total public charging stations and the private BEV shares in Stuttgart in 2021. Each location on the map can denote multiple charging points. When looking at the distribution of public charging infrastructure versus private BEV shares, there is also no clear spatial pattern. Some neighborhoods had a private BEV share of over 20% but no public charging stations, others had low BEV uptake but a high number of charging stations. This could be attributed to other factors highlighted in the regression analysis, such as income levels or the potential for at-home charging, which might also influence the share of private BEVs.

**Figure 7**
Charging station distribution and BEV share of new private passenger car registrations in Stuttgart by neighborhoods in 2021

The share of one- and two-family houses as a proxy for potential home charging access showed a significantly high positive correlation with private BEV shares; the spatial distribution is shown in Figure 7. The yellow dots represent the share of one- and two-family houses, which is typically lower in neighborhoods within the city center. This is in comparison to a higher share mostly occurring outside of the city center. The

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Note: Map locations can denote multiple charging points; fast and normal charging points can overlap.

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22 Normal charging points are considered charging points that give less than or equal to 22 kilowatts (kW) and fast charging points are considered chargers that give more than 22 kW.
figure also shows no clear spatial distribution pattern, which might be due to housing structures varying within neighborhoods. Despite this, the map can help identify areas with a low share of one- and two-family houses and low private BEV uptake where additional measures—such as funding access to public charging infrastructure—might support those who lack charging opportunities.

**Figure 8**  
Private BEV share of new passenger car registrations in Stuttgart by neighborhood in 2021 and the share of one- and two-family houses by percent of total residences in Stuttgart neighborhoods in 2020

**EXISTING POLICIES AND RECOMMENDATIONS FOR AN EQUITABLE UPTAKE OF PRIVATE BEVS IN STUTTGART**

The results above suggest potential inequities at the neighborhood level and the potential inaccessibility of marginalized groups to participate in the transition to BEVs. Here we briefly touch upon some local measures implemented in Stuttgart and how they could address access to BEVs for private individuals in an equitable way. Based on the results of the regression analysis, we focus on income-dependent policy actions and access to charging infrastructure. This section focuses solely on local-level measures and does not include state or national instruments.
The city of Stuttgart offers some social- and income-based policies aimed at encouraging a shift to alternative modes of transportation. This includes financial aid for the purchase or leasing of an electric cargo bike or an electric trike, with increased grants for families and single parents with lower incomes. Similar policies for the acquisition or lease of an electric car do not exist in Stuttgart.

The installation of private charging infrastructure is supported as part of the city’s funding guidelines for private charging aimed at building owners, tenants, leaseholders, and service providers. In cases where it is possible to connect the charging infrastructure to photovoltaics, projects can receive grants from the "Stuttgart Solar Offensive." As both programs also target tenants who typically do not have access to private charging facilities, this can be considered an approach to make public charging infrastructure available in an equitable manner for those who are not living in one- and two-family houses.

The city of Stuttgart supports private investors by facilitating the installation of publicly accessible charging points in public spaces. The city is also supporting new public charging locations across neighborhoods without taking into account equity aspects. However, the consideration of neighborhood income levels and other sociodemographic factors can be important; one study in the U.S. state of California indicates a lower distribution of public charging infrastructure in housing communities with on-average lower incomes.

Based on the findings and selected policies in Stuttgart, the following high-level recommendations could be made for Stuttgart:

- Introduce income-based programs for BEV purchases or leases. Income-based subsidies offered for the purchase of electric cargo bikes and trikes are a good example of a socially oriented electromobility policy. A similar scheme could be adopted for new and used BEV purchases and leases, targeted at marginalized groups dependent on a car. If a support scheme is introduced that benefits those who cannot afford a BEV by providing them with subsidies, the current low-emission zone could be made more stringent, as the transition toward BEVs would then include a larger part of the city population. This would improve air quality while simultaneously promoting equitable access to BEVs. Such subsidies have been shown to improve the effectiveness of low- and zero-emission zones across other European cities.

- Support access to public charging infrastructure in marginalized neighborhoods. Some studies from the United States indicate that public charging is more likely to be deployed in wealthier communities.

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of equitable public charger deployment across neighborhoods and the need for relevant planning at city levels. In terms of potential home-charging access, our results show a highly significant correlation between private BEV shares and one- and two-family houses. Conversely, the results imply marginalized groups may not have access to charging based on their place of residence, i.e., living in multiple-dwelling buildings. Funding for tenants living in multiple-dwelling buildings could therefore be one measure to help spur further private BEV adoption.

CONCLUSIONS

As the transition from ICEVs to BEVs continues in regions across Germany, ensuring equitable access to BEVs is crucial to ensure that groups are not left behind. Stuttgart experienced an increase in private BEV shares in new passenger car registrations from 1% in 2017 to 14% in 2021. However, the transition to BEVs has not been equal across the city, with certain neighborhoods and districts recording higher shares of new private BEV registrations than others. Certain factors could contribute to this unequal uptake. Income, public charging availability, and the share of one- and two-family houses, as a proxy for potential access to home charging, show a positive correlation with new private BEV registration shares. Based on our analysis the following high-level conclusions can be made:

» *Private BEV shares of new passenger car registrations vary across Stuttgart’s neighborhoods.* Between 2017 and 2021, the private BEV registration share rose in Stuttgart, but there were large discrepancies in BEV uptake across individual neighborhoods. In 2021, the distribution of new private BEV shares ranged from 0% to 66% across the 145 Stuttgart neighborhoods for which data was available. Some neighborhoods had consistent levels of uptake and some never registered new private BEV shares above 5% between 2017 and 2021.

» *The average income level of a neighborhood shows a positive correlation with private BEV shares in new passenger car registrations.* Income remains a statistically significant variable and is correlated with new private BEV registration shares across Stuttgart neighborhoods. On average, a change in the income index by one point correlates with a 0.25 percentage-point change in the private BEV share. The results suggest that income remains an important factor for BEV uptake.

» *Access to both home charging and public charging infrastructure shows a positive correlation with private BEV shares in new passenger car registrations across Stuttgart’s neighborhoods.* A 1-unit increase in the number of public chargers per km² showed a 0.083 percentage-point increase in the private BEV registration share. When the share of one- and two-family houses is used as a proxy for access potential to home charging, there was a statistically significant correlation with the BEV share as well. For every 1 percentage-point increase in the share of one- and two-family houses, there was a 0.17 percentage-point increase in the private BEV registration share. Other factors, such as population density, number of households with children, share of seniors, and votes for the Greens, as a proxy for environmental awareness, do not show a statistically significant correlation.

As the transition from ICEVs to BEVs continues, equitable access must be kept in mind, as barriers to BEV uptake exist. Solutions that account for income barriers, as well as for gaps in public charging infrastructure, could benefit marginalized groups the most. Despite having beneficial policies that promote BEVs, Stuttgart has seen an uneven distribution of private BEV shares in new passenger car registrations thus far. Continued efforts that focus on equitable access are necessary to ensure the transition to BEVs does not leave anyone behind.
This study is based on a selection of variables reflecting sociodemographic, environmental awareness, and charging infrastructure availability factors, and does not reflect all aspects that can interplay in the adoption of BEVs. In terms of mobility services more broadly, other potential unobserved variables may also influence the transition, such as the availability of public transport or electric carsharing services, which could be a topic of future city-level research.