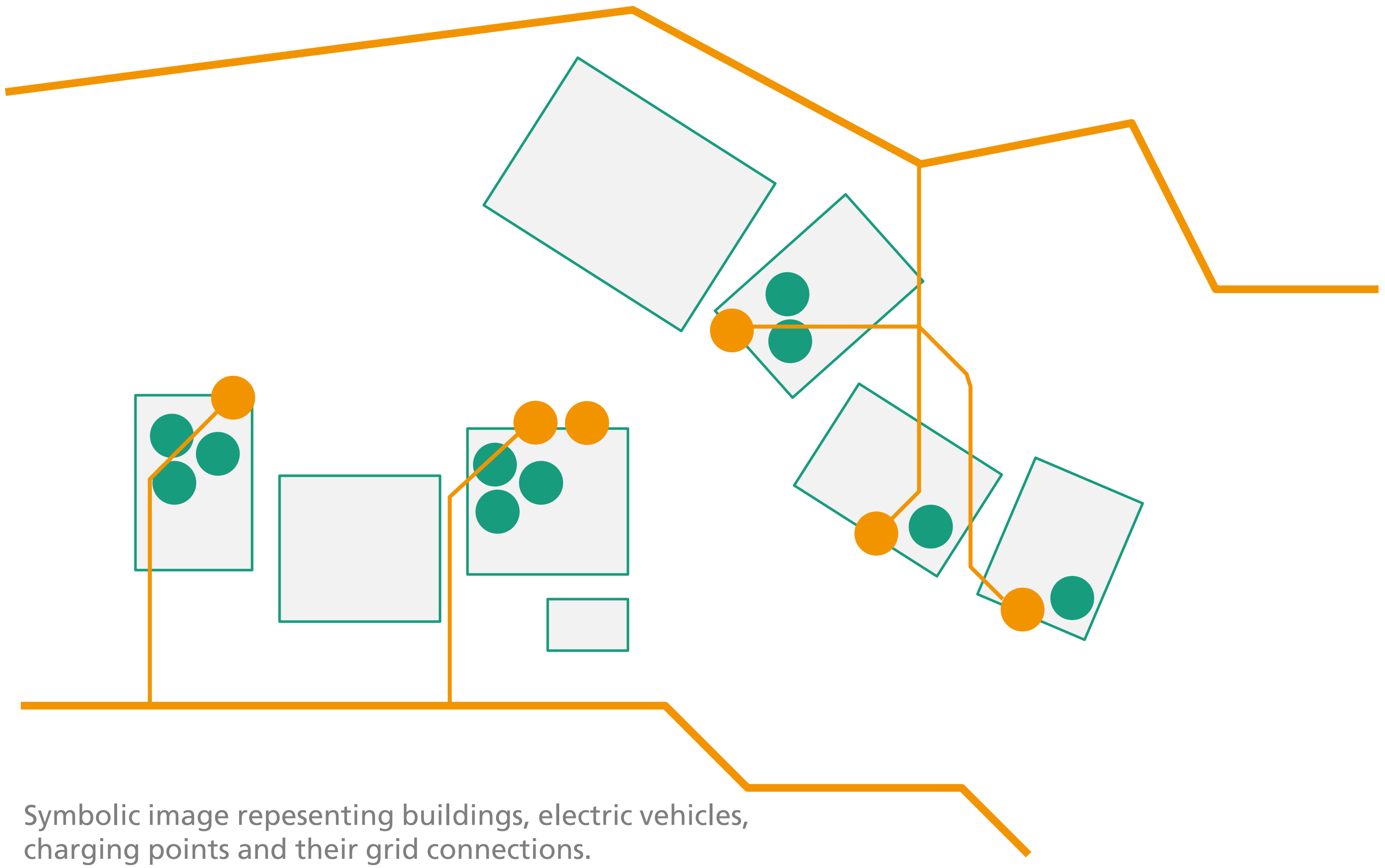
MODELING SPATIAL AND TEMPORAL CHARGING DEMANDS FOR ELECTRIC VEHICLES FOR SCENARIOS WITH AN INCREASING SHARE OF RENEWABLE ENERGIES



Symbolic image repesenting buildings, electric vehicles, charging points and their grid connections.

With this text block the authors try to describe the presented contents, graphics and diagrams in the best possible way, even if a text block is a weak substitute for a talk.

You are welcome to contact us during the live chat or afterwards (by e-mail or phone) for questions, suggestions and discussions.

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The presented work is a part of the project Ladeinfrastruktur 2.0 ("charging infrastructure 2.0")

Supported by:

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Philip Gauglitz

Jan Ulffers

Gyde Thomsen

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Jan Ulffers is a research associate at the Fraunhofer Institute for Energy Economics and Energy System Technology IEE and the University of Kassel, where he is also working on his PhD. His main research focus is planning methods for distribution grids in the context of renewable energies and electro-mobility.

Gyde Thomsen studies Energy- and Environmental Management at the University of Flensburg.
At Fraunhofer Institute she works on her master's thesis focusing on spatial allocation of electric vehicles.

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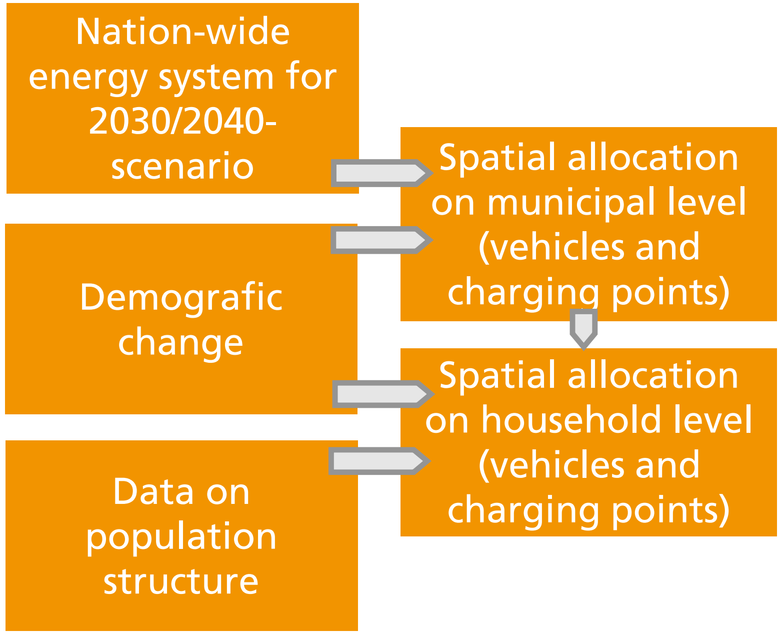
MOTIVATION

- Electric vehicles can significantly contribute to reduce carbon emissions in the mobility sector.
- This transformation will be very dynamic, which poses a technical and economical challenge.
- The necessary charging infrastructure is a new element in our energy systems, that we will have to integrate into our electric grids.
- Therefore, spatial and temporal modelling of future charging behaviour is essential.
- An important area of application is grid planning, as challenges may arise especially in distribution grids.

Overall Model Structure



A nation-wide scenario for 2030 / 2040 provides a realistic and consistent framework for the energy mix, vehicle expansion, etc.

In the first stage of spatial allocation, the corresponding charging power and number of vehicles are divided up at municipal level. For the allocation of the number of vehicles, various criteria are used such as the number of inhabitants, the number of commuters, and the number of cars registered.

The second step of spatial distribution at household level represents the central model core. Taking into account population structure data (incl. income levels, household types, assigned building types, ...), the municipality-wide vehicle numbers are assigned to households with house specific geocoordinates.

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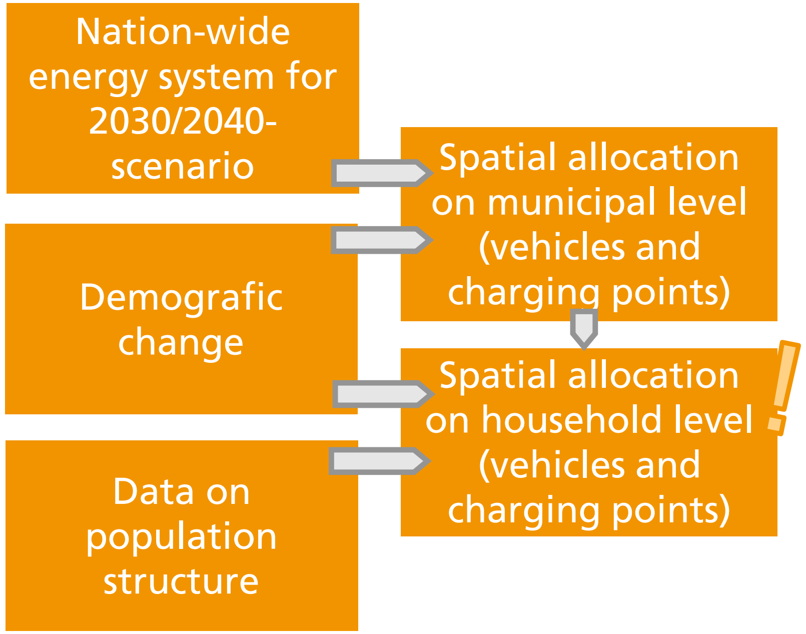

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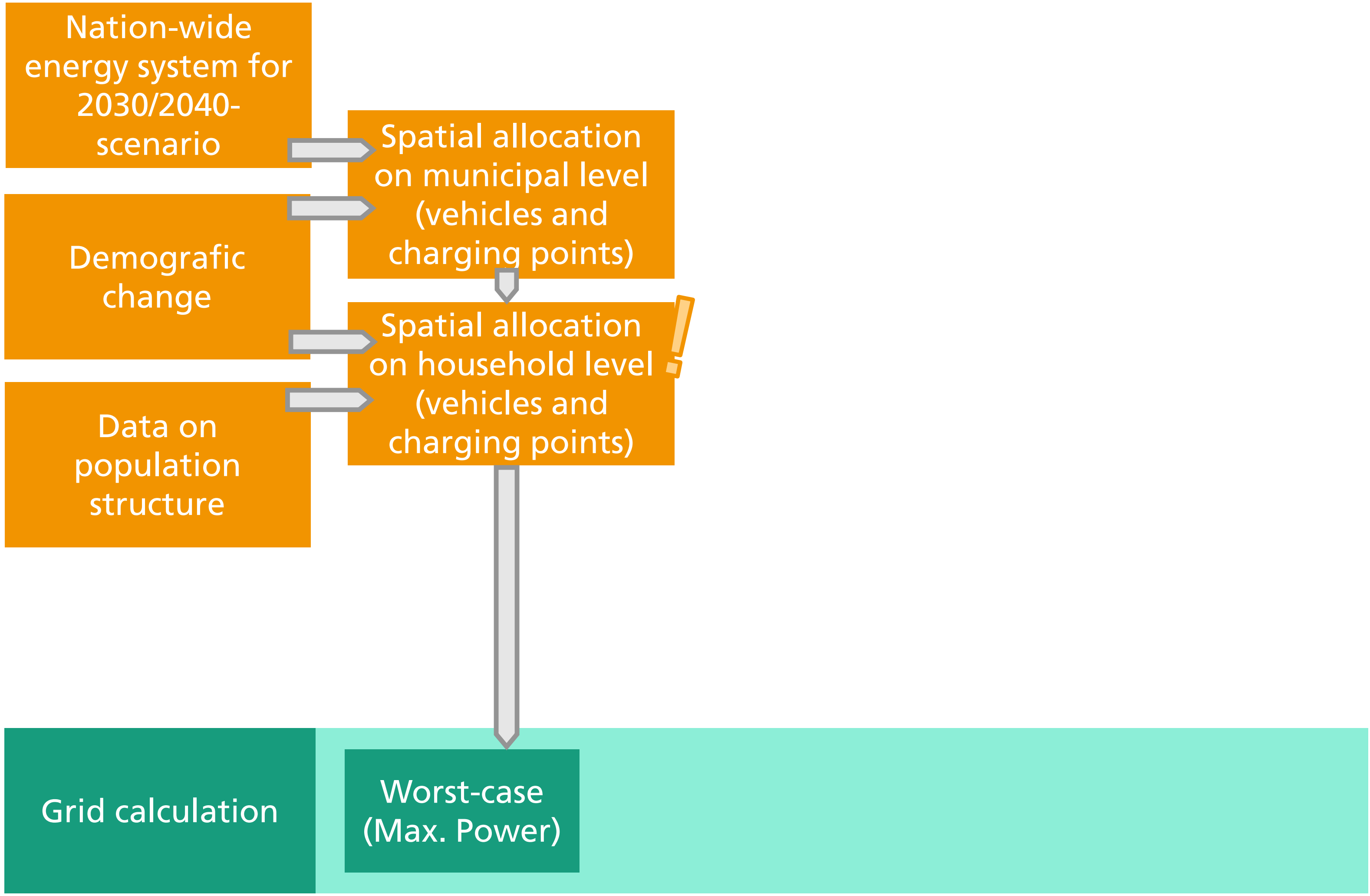

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This spatial allocation is used for worst-case grid analyses and provides a high added value compared to less detailed approaches.

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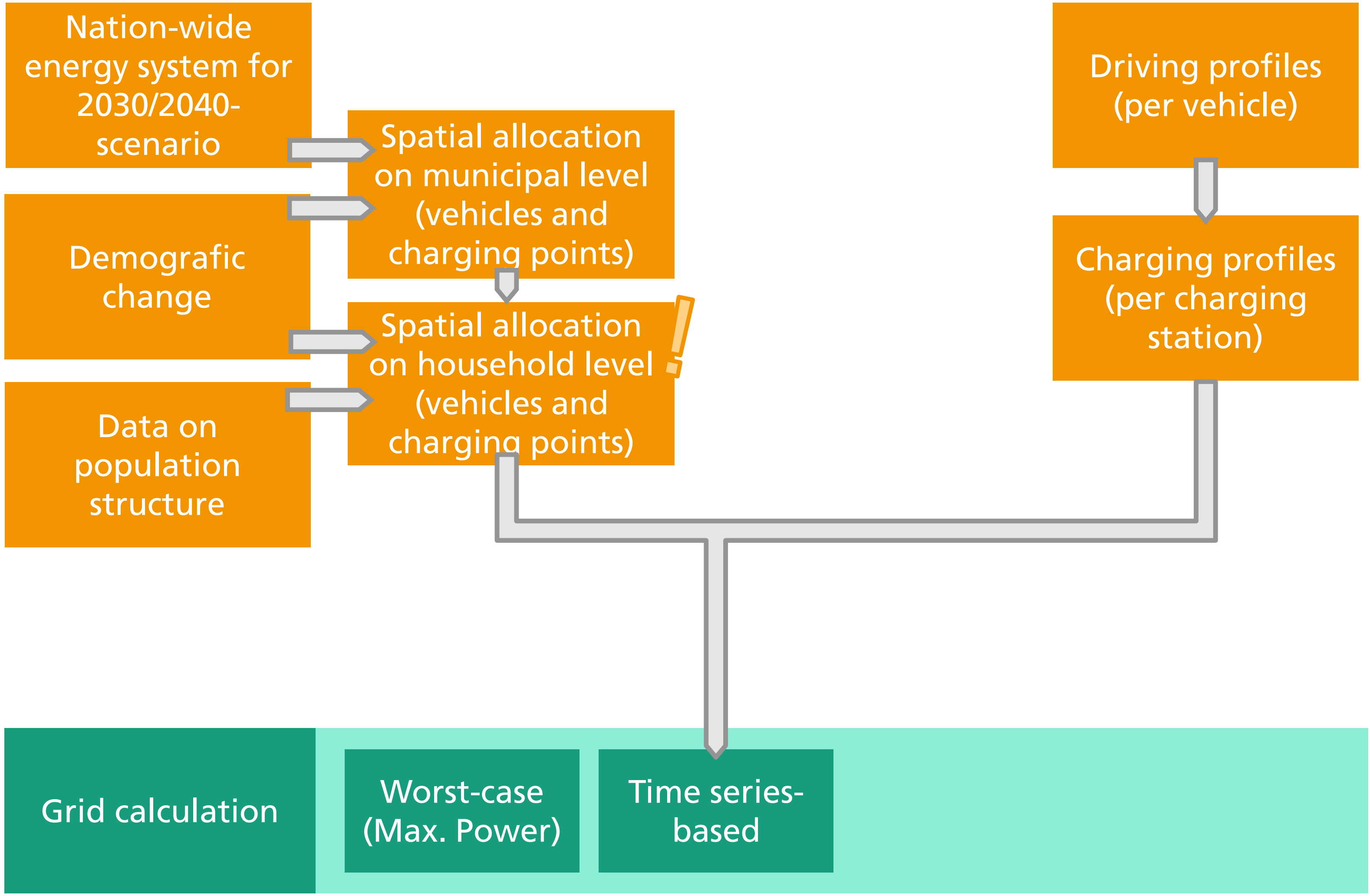

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In combination with charging profiles this data set enables time series bases grid analyses. The charging profiles can be provided in different variants:

- Charging without market or grid contraints

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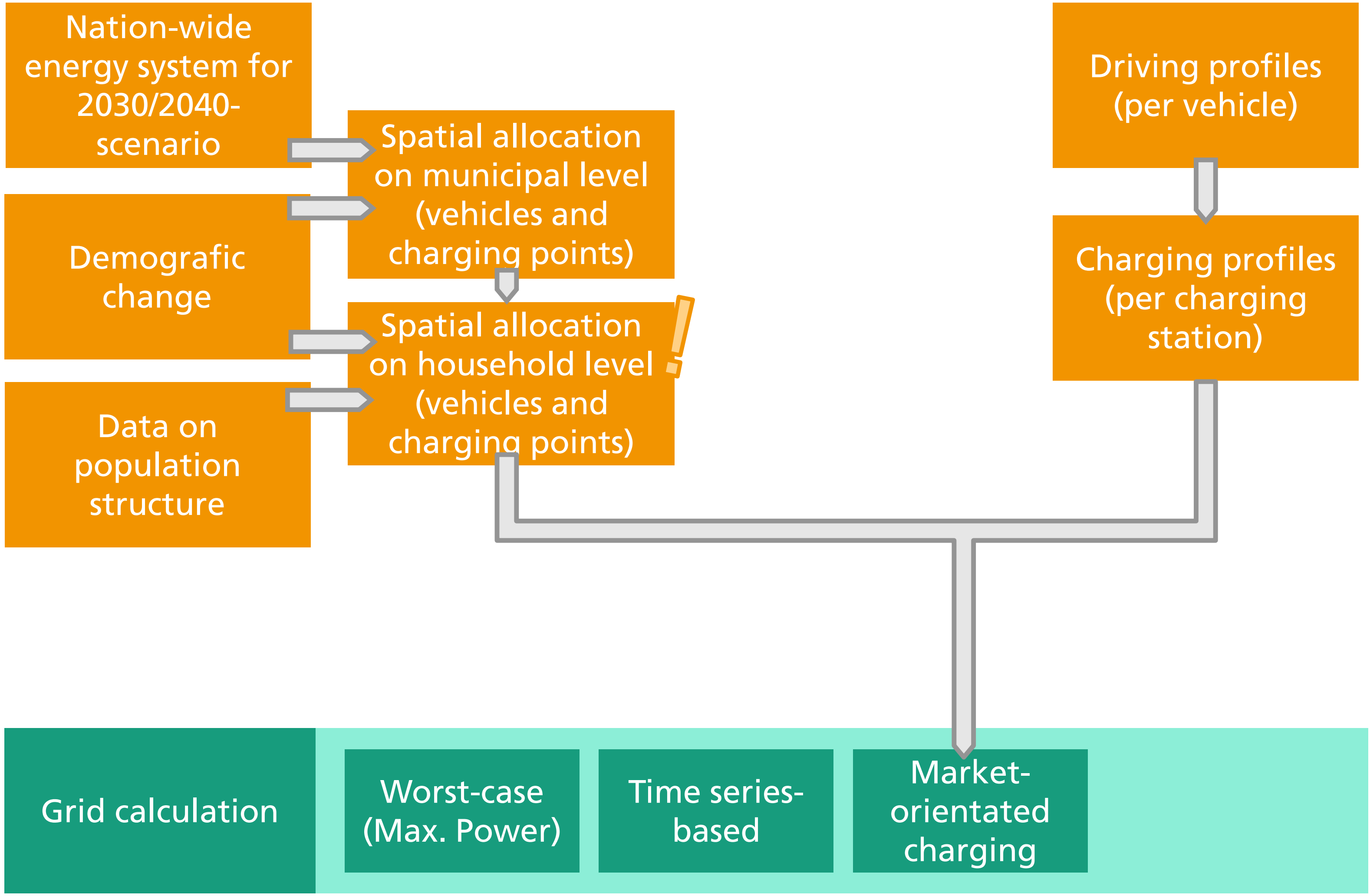

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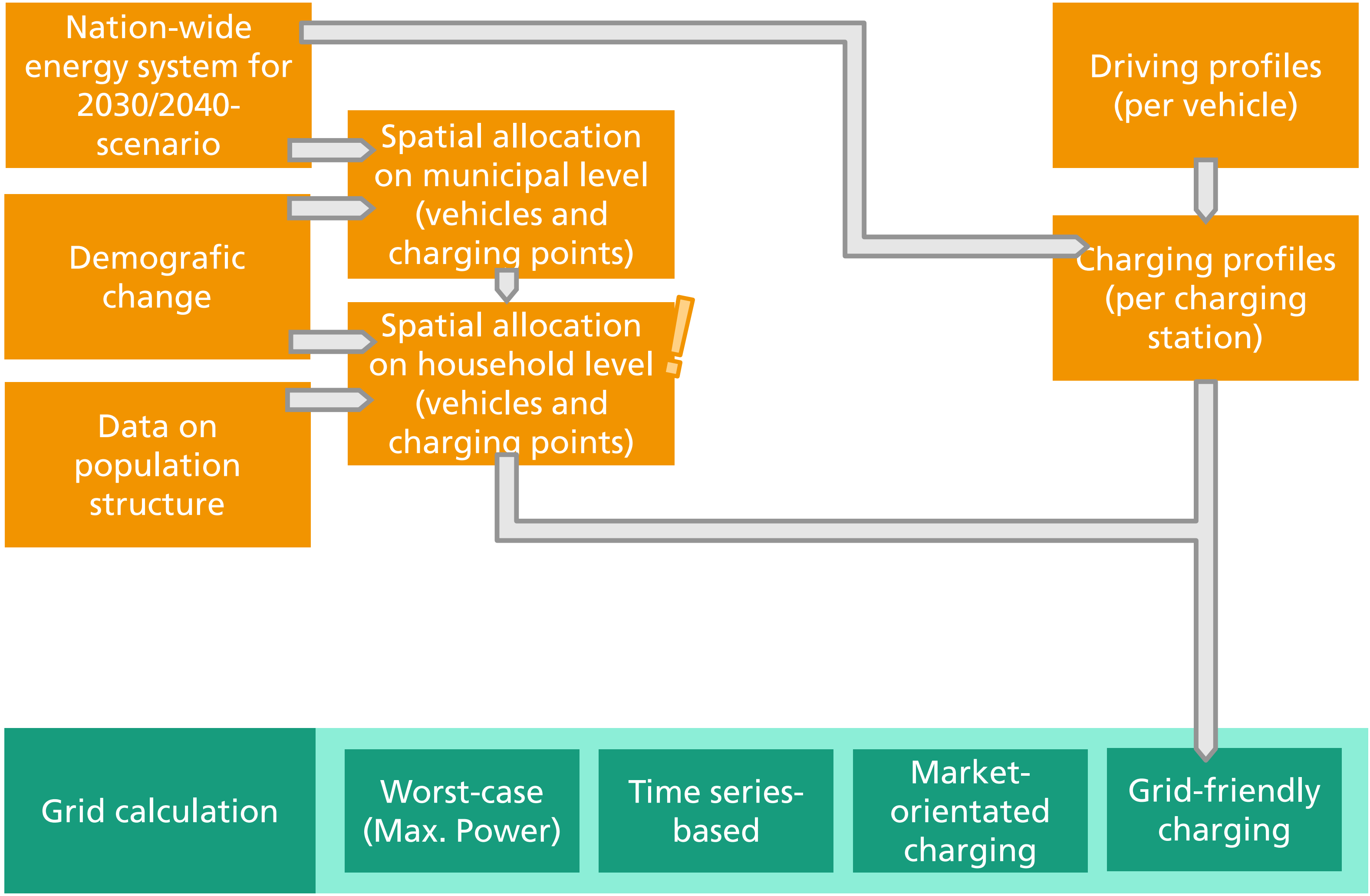

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This spatial allocation is used for worst-case grid analyses and provides a high added value compared to less detailed approaches.

In combination with charging profiles this data set enables time series-based grid analyses. The charging profiles can be provided in different variants:

- Charging without market or grid contraints
- Market-oriented charging, depending on electricity prices
- Grid-friendly charging, controlled by the grid operator

Data on Population Structure

- Data set for each road section with information on households:
  - Number of households per type, income group, age of the head of household etc.
  - Number of inhabitants
  - Number of buildings per building type
- Requirement for model: Generating the combination of household-characteristics (each household, not only per margin)

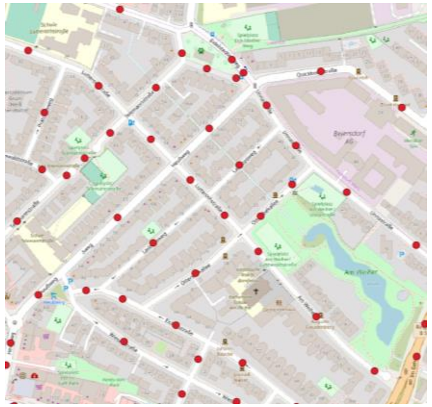


Table 1: Example of household distribution by household type and income

Income / Type	< 2000 €	2000 € - 4000 €	> 4000 €	Σ
Single	?	?	?	7
Multiperson w.o. children	?	?	?	5
Multiperson with children	?	?	?	3
Σ	5	6	4	15

The basis for the spatial distribution of charging points is data on the population structure.

The authors have developed a model for creating representative individual households.

It is based on a data set from the provider GfK Geomarketing, which contains households aggregated on street sections and a wide range of socio-economic characteristics.

However, a scenario for a point-precise distribution of charging points requires the individual combinations to be assigned to the marginal sums (and later to addresses, not to street sections). This so-called synthetic population is created using the Iterative Proportional Fitting Algorithm, initially developed by Beckmann et. al 1996 [1], for the characteristics income and household type. Age and gender are assigned using a random weighted distribution based on statistical data of the German federal statistical office.

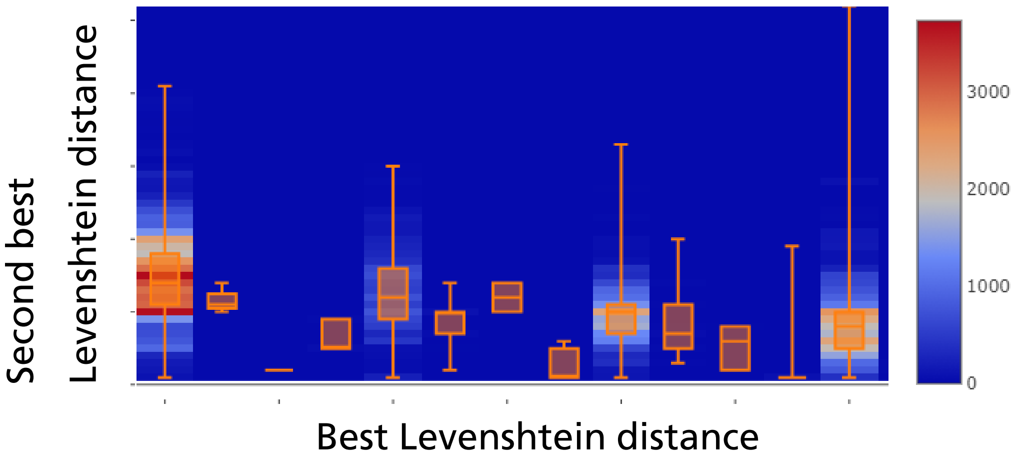
After this calculation step, these are available as a data set for distribution to specific addresses and living spaces.

It should be emphasized, that it is not assumed that the household data match the actual household distribution, but that this data set adequately reflects the population for our research question (distribution of charging points).

[1] Richard J. Beckmann, Keith A. Baggerly and Michael D. McKay: Creating Synthetic Baseline Polulations, Los Alamos, 1996

Fuzzy-String-Match for Geo-Coding in PGSQL

- Objective: Allocation of residential buildings to street sections
- Challenge: Implementing a computationally efficient method
- Solution presented here: Levenshtein distance for comparison of the adresses strings



The buildings are assigned to street sections via postal addresses. The advantage is that a string-based approach allows an efficient calculation.

A Levenshtein distance of the addresses strings is used (pre-filtered by municipalities), which yields very good (low) distance values.

Demographic Change

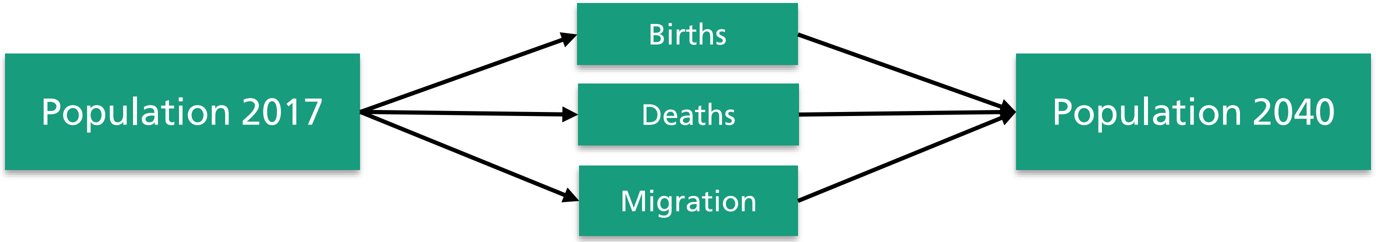


Table 2: Inhabitants and households in 2017 and projections to 2040

Age group	Inhabitants 2017	Households 2017	Households to inhabitants	Inhabitants 2040	Households 2040
f 18-29	20,548	6,790	0.33	23,357	7,718
m 18-29	19,423	9,930	0.51	20,331	10,394
f 30-39	20,160	7,592	0.38	19,481	7,336
m 30-39	18,012	16,635	0.92	18,089	16,706
…	…	…	…	…	…

Table 3: Projections of household characteristics by age groups in 2040

Age group	Type	Income	Share in age group	Difference 2017 to 2040
f 18-29	Single	< 2,000 €	51 %	-52
	Single	2,000 – 4,000 €	13.6 %	125
	Single	> 4,000 €	2.2 %	16
	Multiperson without children	< 2,000 €	0.44 %	-38
	…	…	…	…

Regarding the demographic change, there are three main influcencing factors: births, deaths and migration. For each municipality in Germany, the German federal statistical office publishes data sets on the past development of those factors. The base data set provides a population prognosis for the year 2030 for each municpality with over 5000 inhabitants. Based on this two data sources a forward projection of the population to the scenario year 2040 is realised.

To build the future set of households two assumptions are made:

1. The ratio of households to inhabitants within age groups remains the same (see Table 1).
2. The share of household characteristics within age groups remains the same (see Table 2).

In general, households of each age group can increase or decrease in the future. Households that decrease are randomly chosen and removed from the dataset. In case, other households of other age groups increase, the removed households are replaced. Additional households are randomly placed in the existing road sections, whereby road sections that currently have a high number of inhabitants are more likely to get additional households.

Geographic placement of households

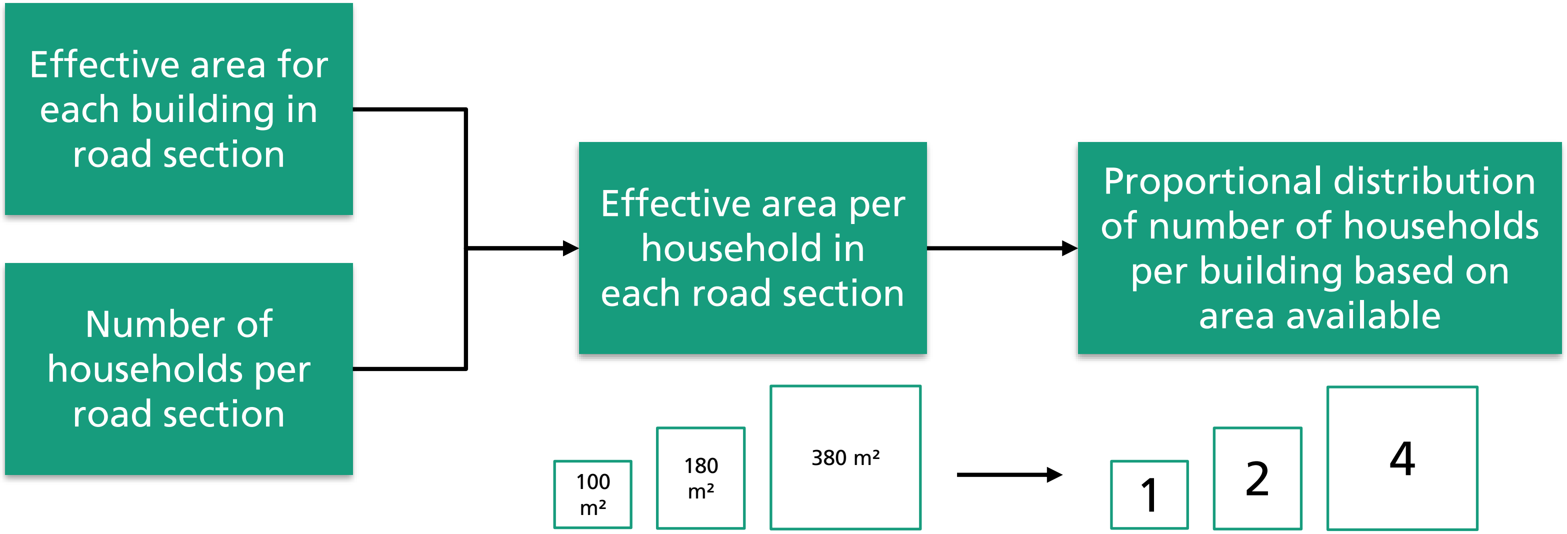
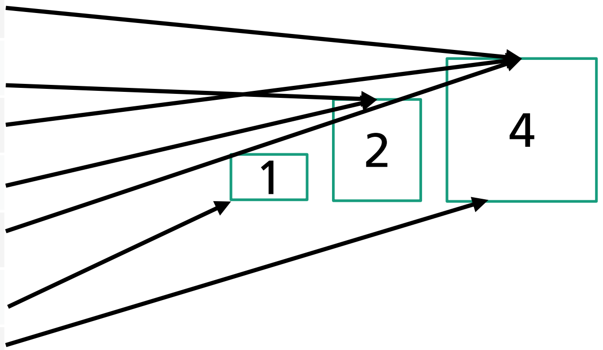


Table 4: Example for allocation

Age group	Type	Income
f 18-29	Single	< 2,000 €
f 18-29	MP[1] without children	2,000 – 4,000 €
m 30-39	Single	2,000 – 4,000 €
m 40-49	MP with children	> 4,000 €
f 60+	Single	< 2,000 €
f 50-59	MP with children	> 4,000 €
f 60+	Single	< 2,000 €



After having created the household data set for the scenario year 2040, the households are placed at exact geografic loactions.

In a first step, by using the known height and area the effective area for each building is calculated and summed up for the road section. Divided by the total number of household the potential area per household is determined.

The number of households per building is then distributed proportionally based on the building size.

To determine which household is placed in which building a random weigthed distribution is applied based on data of the German federal statistical office concerning household types and buildings.

[1] MP: Multiperson

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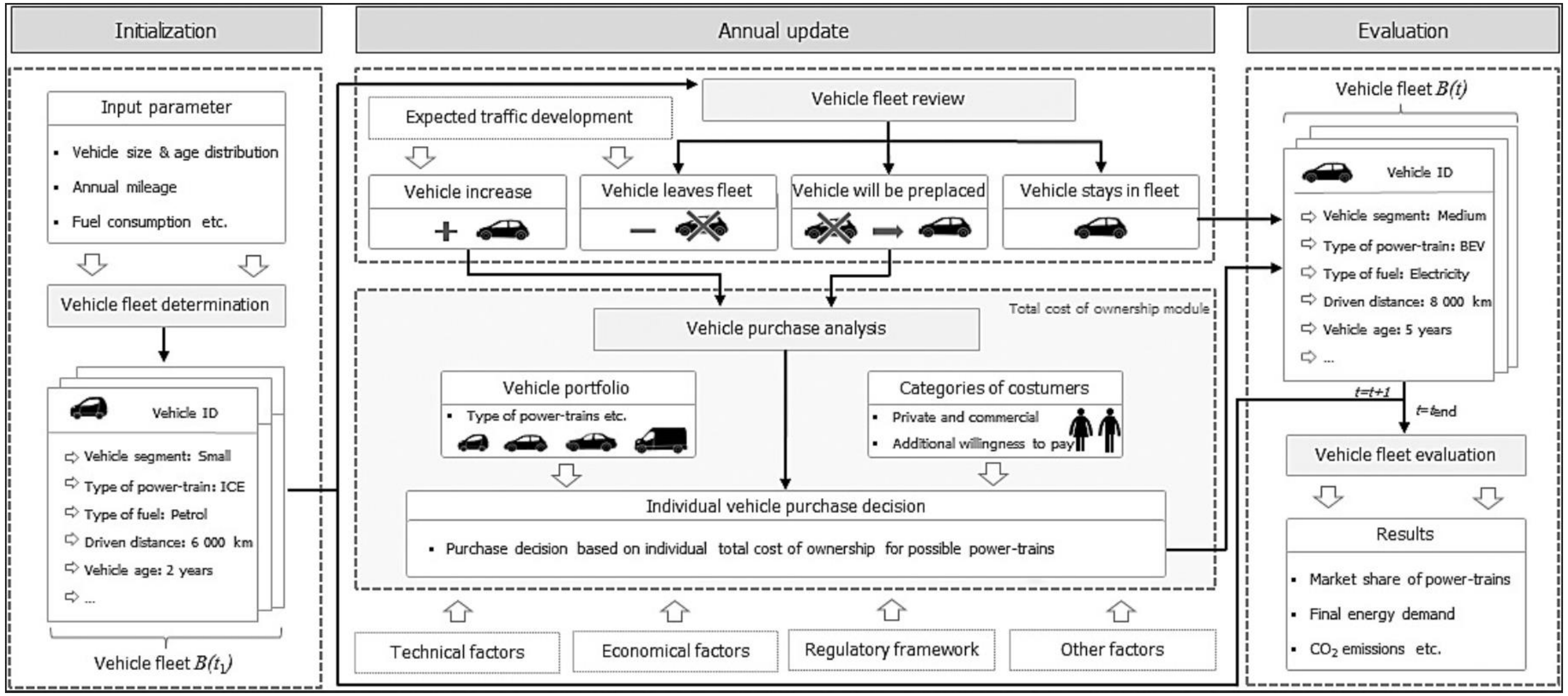
Vehicle Fleet Model for Germany (TCO)

- Objective: Quantitative determination of future vehicle fleets for Germany.
- Modeling approach: Bottom-up consumer demand model combined with a dynamic stock-flow approach.
- As a central element, the individual purchase decision is based on the different total cost of ownership (TCO) for different power-trains and fuel types.
- Considering: Market development under regulatory conditions.

Schematic model construction and procedure



Trost et al. (2017): Impact of electric vehicles and synthetic gaseous fuels on final energy consumption and carbon dioxide emissions in Germany based on long-term vehicle fleet modelling. In Energy 141, pp. 1215-1225 http://publica.fraunhofer.de/documents/N-473725.html

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For the quantitative determination of future vehicle fleets, a model was developed that requires a variety of technical, ecological, and economical input parameters and allows a detailed simulation of the market penetration for different power-trains.

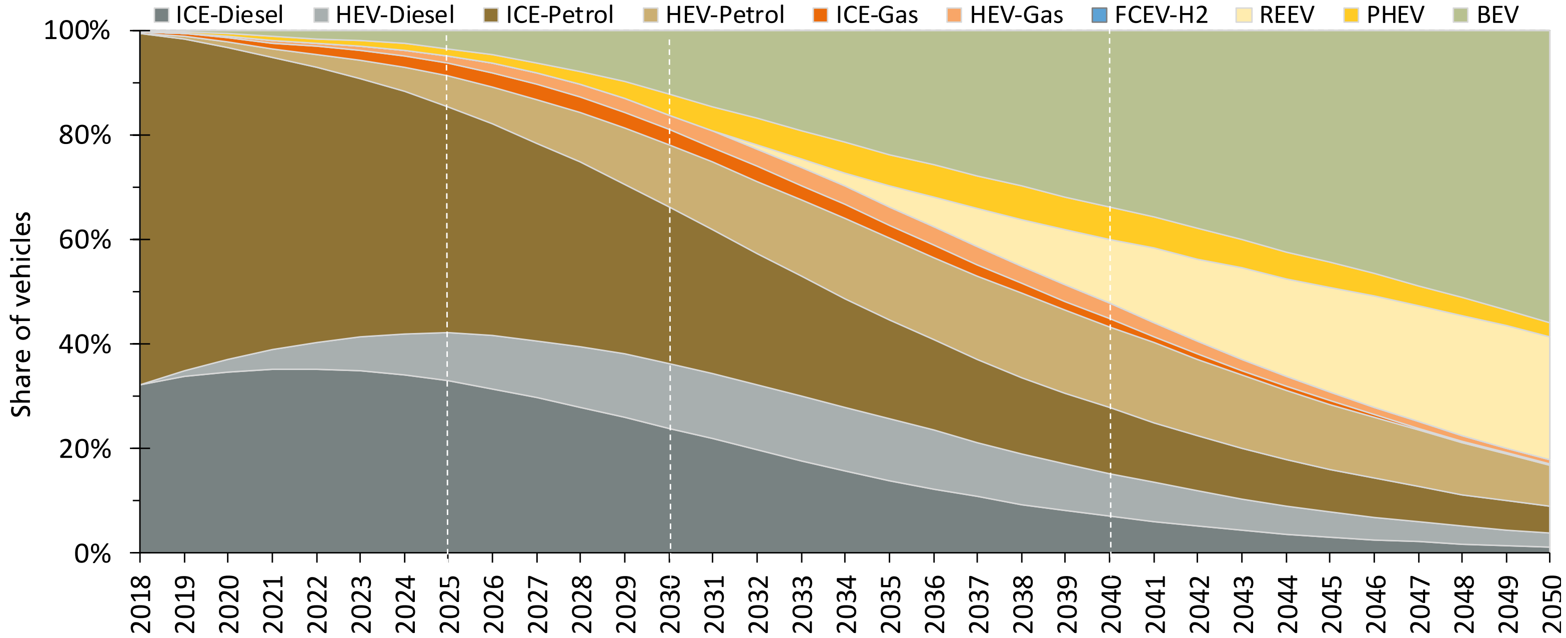
The modeling approach is based on a bottom-up consumer demand model combined with a dynamic stock-flow approach. As a central element, the individual purchase decision is based on the different total cost of ownership (TCO) of the considered vehicle types. For this purpose, all foreseeable costs for the vehicle use are calculated for a specific holding period or vehicle lifetime. Besides the vehicle purchase costs, and if necessary residual value, all variable and fixed operating costs are considered in order to calculate the net present value. To estimate the specific costs per kilometer the net present value is then divided by the total mileage. When modelling the purchase decision, a distinction between private and commercial customers is made in order to get a realistic forecast.

In general, the vehicle fleet is subject to a continuous change over time. On the one hand, vehicles leave the fleet because of damage or vehicle age, and on the other hand, new vehicles are purchased. In annual steps, the vehicle fleet B(t) in the year t results from the vehicle fleet of the previous year B(t-1) including all vehicle disposals and purchases in the last time step. The vehicle fleet is the sum of the individual vehicles with different techno economic and ecological parameters.

Results of the Vehicle Fleet Model (Base Case)

- Simulation of the market uptake of potential drive train technologies and fuel combinations for passenger cars (PC)/LCV in Germany.
- Base Case Scenario, not that ambitious suppositions with focuses on BEV.

Development vehicle fleet 2018-2050[1]



[1] ICE: internal combustion engine HEV: hybrid electric vehicle REEV: range extended electric vehicle PHEV: plugin hybrid electric vehicle BEV: battery electric vehicle

2018	2025	2030	2040	2050
~ 0.3 % Electric Vehicles	~ 4.7 % Electric Vehicles	~ 16.2 % Electric Vehicles	~ 52.2 % Electric Vehicles	~ 82.2 % Electric Vehicles
~94,000 BEV	~ 1.62 Mio. BEV	~ 5.87 Mio. BEV	~ 15.58 Mio. BEV	~ 24.75 Mio. BEV

Electric Vehicles includes BEV, PHEV and REEV

Trost et al. (2017): Impact of electric vehicles and synthetic gaseous fuels on final energy consumption and carbon dioxide emissions in Germany based on long-term vehicle fleet modelling. In Energy 141, pp. 1215-1225 http://publica.fraunhofer.de/documents/N-473725.html

In this case study, four different vehicle sizes (small, medium, large and light commercial vehicles) are taken into account. For the categorization of the vehicle sizes the different vehicle segments according to the Federal Motor Transport Authority are used. As a starting point for the simulations, the year 2018 was chosen since all necessary data was available.

The existing vehicle fleet today (2019) is dominated by internal combustion engines and fossil fuels (mainly petrol and diesel) with a total share of over 98 %. In this context, innovative power-trains and alternative fuels are almost irrelevant today. In addition to the technical vehicle specifications, different empirical data surveys on the mobility behavior in Germany are used (see section "Mobility and Charging Profiles") in order to derive representative driving profiles and annual mileages for the private and commercial transport.

Base case (see figure): The results of the simulation showed a market ramp-up of electric vehicles. The share of electric vehicles will increase from today's 0.3% of the total German vehicle fleet up to 16.2 % in 2030, to more than 52 % in 2040 and to more than 80% in the long term perspective.

More progressive assumptions resulted in a much faster market uptake of electric vehicles, so that electric vehicles accounted for 24% of the total German vehicle market in 2030 and a penetration rate of over 90 % in the long term perspective.

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Spatial Distribution of Charging Points for Home Charging

- 2-step procedure for assigning charging points to households and thus to spatial points:
  - Step 1: Assignment of electric vehicles (analogous to a utility value analysis)
  - Step 2: Spatial allocation of charging points to electric vehicle owners
- Criteria for weighting:
  - Household income
  - Household type (single, household with children etc.)
  - Type of building (single family house, two family house, apartment building)
  - Gender of head of household
  - Planned: Existence of a photovoltaic system

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In the final model all categories of charging points should be represented, including charging points at employers and in public spaces. However, this presentation will initially focus on home charging points.

We use a 2-step procedure for assigning charging points to households and thus to spatial points:

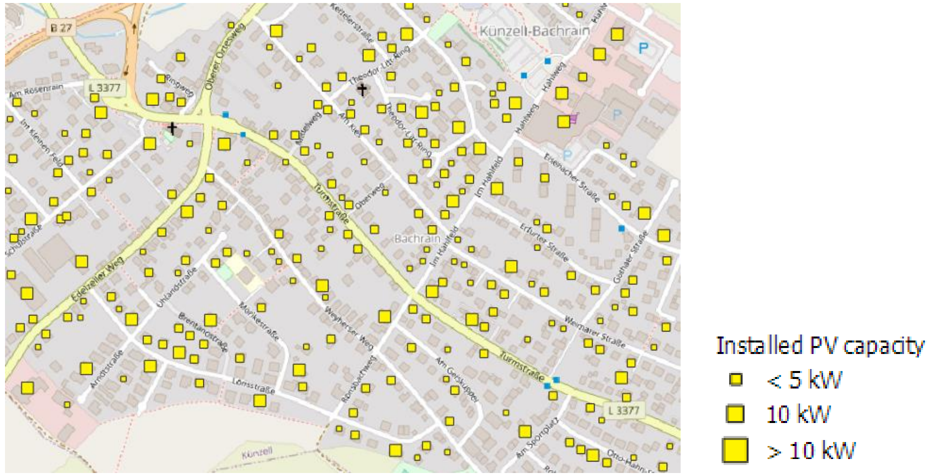
- Step 1: Assignment of electric vehicles from the spatial distribution on municipal level: Household criteria are used for a scoring analogous to a utility value analysis. The points are used for a weighted random distribution.
- Step 2: Partial allocation of charging points to electric vehicle owners. (the vehicles without charging points are used for later model steps such as the distribution of public charging points.) In order to reflect the fact that there are sometimes no parking spaces in apartment buildings, apartment buildings are first removed from the allocation pool. This is currently done randomly, but data on underground car parks or parking spaces – if available – can be added.

Spatial allocation has the following characteristics:

- Characteristics of the household are mapped
- a multiple weighted random drawing allows a stable modelling of the network calculations (in the current case: 50 distribution variants for the same boundary conditions)
- Sensitivities-capable
- Exact spatial distribution, which enables a precise allocation to house connections

Other Spatial Distributions

- Other charging points
  - Charging points at employers
  - Charging points in public space
- Renewable energies & electrification of other sectors
  - Photovoltaic systems
  - Heat pumps (for different size categories and applications)



To display the influence of electromobility on the energy network, additional spatial distributions are needed and included in the model.

Regarding the charging points for electric vehicles, charging possibilities at employers and in public space will be modeled. The planned methodology is based on potential areas (e.g. parking spaces) and needs (e.g. when home loading is not possible or at points of interest).

Renewable energy distribution is included in the form of photovoltaic systems. Thereby, rooftop PV systems as well as large open space photovoltaic systems are included. To calculate the allocation of PV, the plant size will be determined depending on the roof and the generation of time series based on satellite data.

The installation of heat pumps is applied by considering different size classes and applications. For this purpose, the distribution between residential and commercial buildings is regarded, taking into account average mixes of plausible size classes. It is planned to also include building age classes.

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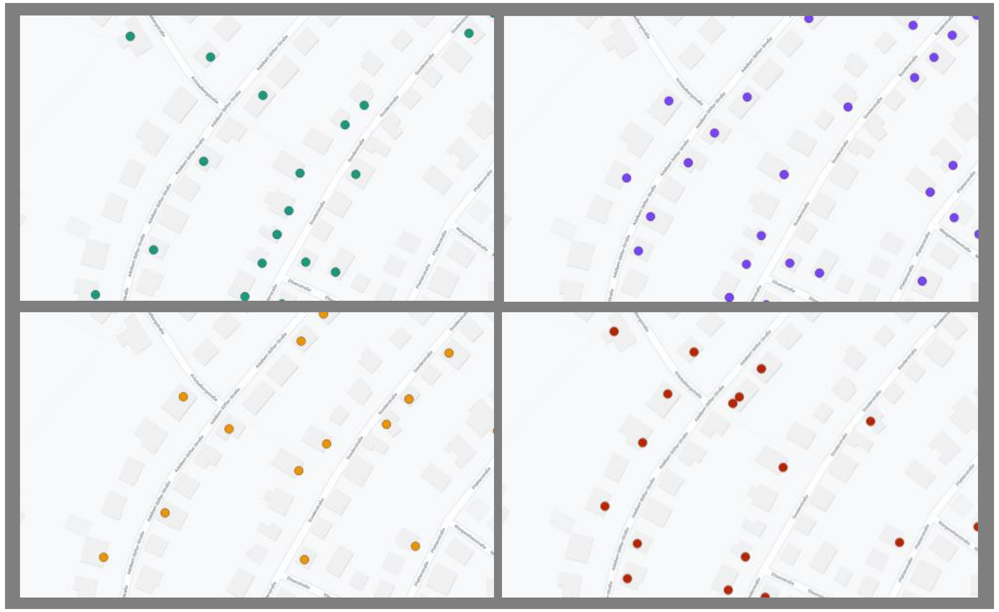
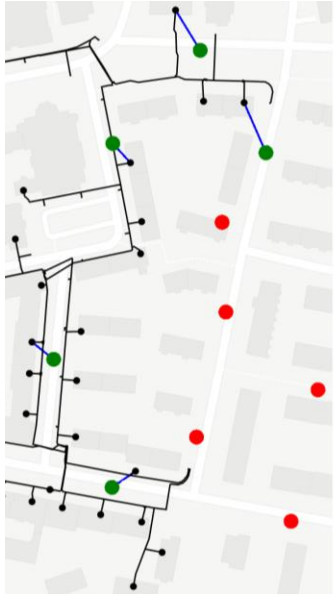
Probabilistic Scenario Variations and Grid Integration

- Since the exact spatial distribution of future charging points, heat pumps and photovoltaic systems is unknown, 50 probabilistic scenario variations are investigated.
- Charging points are then allocated to the closest grid connection point within a maximum distance of 30 meters.



4 (of 50) different distributions of charging points



Charging point allocation. green – allocated charging points; red – non-allocated charging points; black – available LV grid connections

From a grid planning perspective, the total amount of EV charging points, PV systems or heat pumps that will have to be integrated into the grid is not the only important aspect. For assessing worst-case voltages and line loadings it makes a big difference, where in the grid these additional loads and generators will be connected.

Since it is very unlikely to predict their exact spatial distribution, we investigate 50 independent probabilistically generated distributions of new loads/generators, that are added to the grid. This allows us to simulate a broad range of possible future grid situations.

On the left-hand side, four exemplary distributions of EV charging points are shown. At this point, there is no connection to the LV grid. The charging points are distributed solely based on demographic information.

The charging points are combined with geographic power grid data. All charging points are allocated to the closest low-voltage connection point, with a maximal distance of 30 meters. On the right-hand side an example of that process can be seen. The green dots are allocated charging points, that are connected to a low-voltage connection point. The red dots are charging points, that are too far away from the grid. They will be allocated to a different low-voltage grid.

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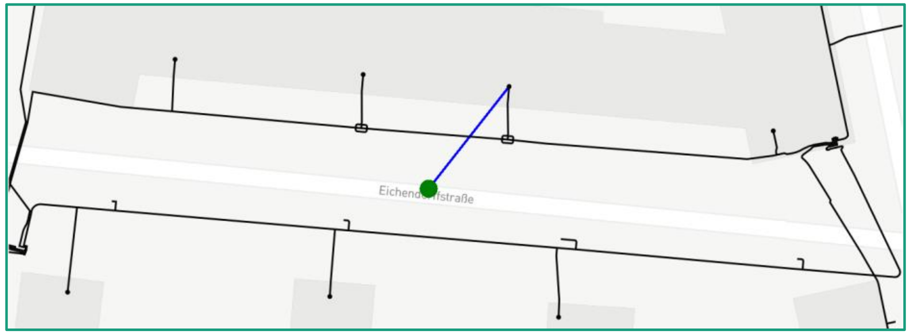
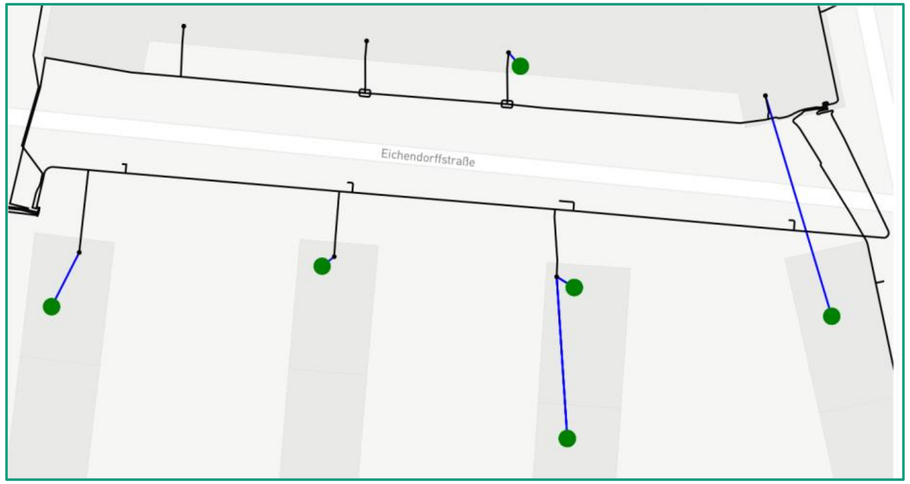
Worst-Case Assessment in Distribution Grids

Influence of the Level of Detail in Spatial Scenario Resolution



street-level resolution

All charging points in a street are placed at the same coordinates.



building-level resolution

Charging points are placed at individual buildings.

In reality the usage of simplified grid models with aggregated consumers and generators for grid planning purposes due to a lack of more detailed information is very common.

The upper image shows an example of that. In this case all charging points are aggregated at the center of a street. This could be done, if no additional information is available, where low-voltage connection points are located or in order to simplify the planning process.

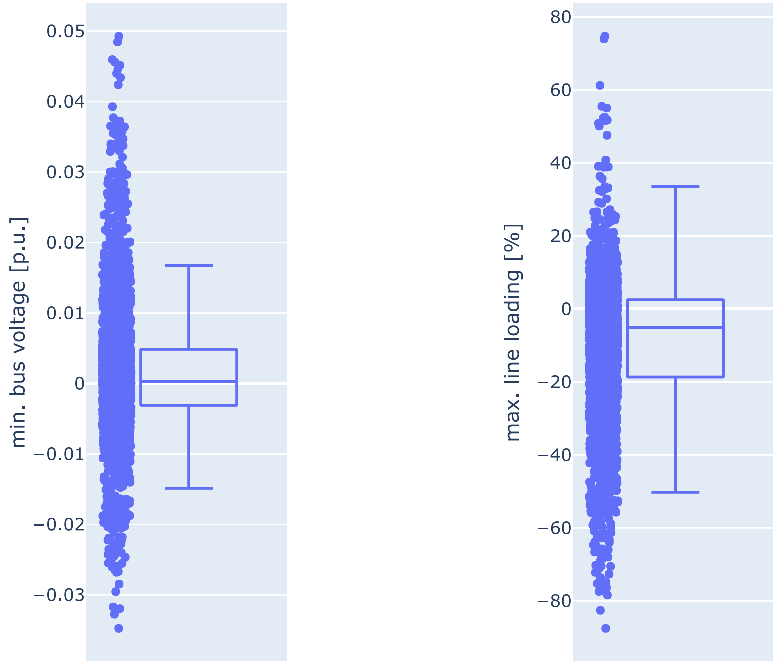
In the lower image all charging points were distributed to actual buildings. Therefore each charging point can be connected to a different low-voltage connection point, which is much more realistic.

As a consequence,
a more detailled scenario disaggregation allows for more precise assessments, where in the grid violatio ns might occure.

Worst-Case Assessment in Distribution Grids

Influence of the Level of Detail in Spatial Scenario Resolution

Absolute deviation between street-level and building-level resolution



- Case study: difference in minimum bus voltages and maximum line loadings in 50 real low-voltage grids.
- 50 probabilistic variations of charging point distributions per grid (=comparison of 2500 grid situations).
- Positive deviations mean building-level resolution results in higher bus voltages/line loadings.

On this slide a case study in 50 real low-voltage grids is presented, in order to demonstrate the influence between street-level and building-level resolution for grid planning purposes. For this comparison, charging points were spatially distributed with both approaches in the same 50 low-voltage grids. For each grid, 50 probabilistic distribution variations were investigated.

The two graphs show the absolute deviation regarding minimum bus voltages and max. line loadings per grid calculation. A positive deviation means, that the distribution of charging points with building-level resolution lead to higher voltages/loadings. The scatter plots show all values, including outliers. For easier interpretation of these distributions, boxplots are additionally provided.

It can be seen, that a distribution at building level resolution can lead to severy over- or underestimation of worst-case grid situations, with deviations in minimum voltages up to 0.05 p.u. and line loading deviations up to 90 percent.

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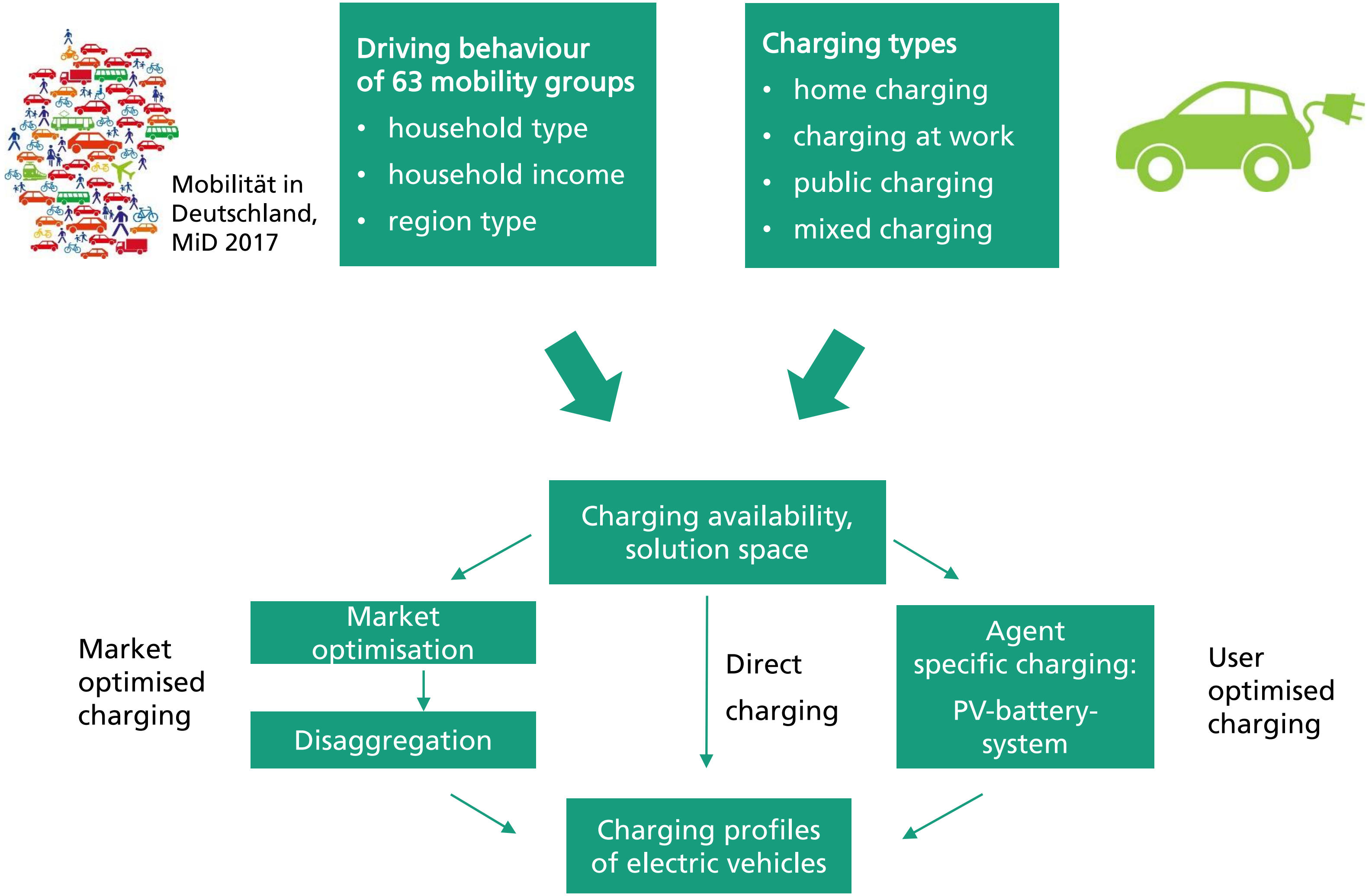
Outlook: Integration of Mobility and Charging Profiles



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At this point we demonstrated a comprehensive approach for the spatial modelling of EV charging points and an application for worst-case grid planning.

The next step will be to include the time-variant behaviour of charging points, for application in time series based grid analyses. Therefore data from the empirical study "Mobility in Germany 2017" is used to model mobility needs. The study includes detailed data on the mobility behaviour of 300.000 people. Groups of different income, region type and houshold type are differentiated for allocations of charging stations. Furthermore, yearly driving profiles are generated based on the survey data. From these driving profiles charging profiles are derived.

Charging can be direct or optimised.

- Direct charging: Charging profiles only depend on mobility behaviour and charging point availability.
- Optimised charging: Charging profiles are influenced by market contraints or user preferences.

Summary

- Detailed assessments of future charging infrastructures for electric vehicles are required for a number of use-cases such as grid planning.

- A comprehensive model, using a variety of different sources for the past and future development of demographic, geographic and energy sector related data allows predictions of possible charging point locations with a high spatial resolution.

- This high level of detail in spatial resolution has a big influence on grid integration studies and analyses of worst-case grid situations.

- The integration of charging profiles would additionally enable time series based investigations for the dimensioning of future infrastructures.