EV Charging and Grid Integration Tool

User manual and technical note

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Abstract

As part of IEA's role in the GEF-funded Global Programme to Support Countries with the Shift to Electric Mobility, the IEA has developed an EV Charging and Grid Integration Tool accessible on the IEA website: http://www.iea.org/data-and-statistics/data-tools/ev-charging-and-grid-integration-tool.

This note is developed to serve as user manual and background note to the EV Charging and Grid Integration Tool. The note describes how users can provide inputs and interpret the results according to their own circumstances. The technical annex also describes the modelling assumptions and methodology.

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Introduction and overview of the tool

Electricity grids supply the power to charge electric vehicles (EVs). In 2021, the electricity consumption for charging the global EV fleet was 55 TWh, the equivalent of electricity demand of Switzerland, and accounted for 0.5% of global electricity consumption. By 2030, meeting the announced climate pledges will lead to electricity demand for road transport to be multiplied by 20, representing nearly 4% of power demand. A cross-sectoral approach is needed to align power sector expansion with mobility strategies. The previously published policy maker manual on grid integration of electric vehicles provides insights into how electric mobility impacts power grids and what solutions exist to mitigate these impacts and turn them into an opportunity for decarbonising electricity.

The EV Charging and Grid Integration Tool serves as a companion to the policy maker manual and delivers quantitative estimates through an interactive interface (http://www.iea.org/data-and-statistics/data-tools/ev-charging-and-grid-integration-tool). The tool enables to assess the impact of electric mobility strategies on power grids and the corresponding emission under a range of circumstances relevant for the countries under the GEF Global Electric Mobility Programme.

Objectives of the tool

Chapter 2 of the policy maker manual on grid integration of electric vehicles provides an overview of the impacts of electric mobility in electrical power systems. The tool is developed to present those impacts at different levels, at the (national) system level or the distribution level. The user defines the level of investigation by his inputs. For the national level, the focus is a general investigation to estimate the shape of the demand profile, order of magnitude of the demand, the potential of demand management and the emissions caused by EVs. For the distribution system the tool could help to investigate which additional demand the grid has to supply beside the non-EV demand and for example how managed charging could help decrease the peak demand of EVs or shift it away from the non-EV peak demand. It is very important that all inputs are related to the same level of investigation. The tool does not deliver detailed statements about the utilisation of distribution grids.

The tool allows extracting the EV charging demand curves (with or without managed charging). This enables the user to add them to any tool that represents the non-

EV demand curve with complete dispatch simulation modelling to determine the impact on power generation and the resulting emissions with high precision.

The three core modules of the tool

The tool contains three modules corresponding to its three purposes:

Module 1: Assessing the impact of EV charging on the power system

The module generates a **weekly electricity demand profile** corresponding to EV charging that will have to be supplied by the power system. The module simulates the driving and charging behaviour of a given fleet, by considering the energy characteristics of the EV fleet and the charging opportunities. This module assumes vehicles charge as fast as possible when they connect to a charger.

Module 2: Assessing the effects of managed charging

This module compares the demand profile when applying managed charging strategies to the unmanaged profile. These strategies can be as simple as peak-valley tariffs or more advanced approaches taking into account the system state. Managed charging can mitigate the impact of EV charging by making use of the opportunity to delay charging in time or modulate the charging power, when a vehicle is connected to a charger longer than needed to recharge the battery. Managed charging is a significant opportunity for the power sector since it can be used to increase system flexibility to accommodate more renewables, relieve the power system at the local and system level and avoid emissions.

Module 3: Estimating climate impacts of EV charging

The CO_2 emissions related to EV charging depend on the power mix supplying charging. This depends on the capacity mix in the power system but also on the time of charging and charger type. The tool estimates these emissions and offers comparison between the unmanaged and managed strategy.

User manual

The following sections explain the necessary user inputs and the tool outputs and their interpretation. The various functionalities are described, with examples to illustrate the use of the tool.

The interactive tool offers two user modes: basic and advanced. The **basic mode** gives access to the main functionalities of the tool. The **advanced mode** gives access to some additional functionalities, such as a temperature and managed charging.

An alternative way to use the tool is to access directly the Python code through an API. This allows accessing further functionalities that are not available in interactive mode: some managed charging strategies (time-of-use tariffs and V1G) or the upload of a custom electricity mix.

Module 1: Assessing the impact of EV charging on the power system

There are two tabs with user inputs. The first tab defines the fleet of EVs (number of vehicles in every segment, such as 2/3-wheelers, light-duty vehicles, etc.). The second tab defines the charging preferences of various EV drivers as well as the possible (private and public) charging opportunities.

Defining the EV fleet and driving patterns

On the first tab, the user defines the vehicle characteristics that they wish to model. Thirteen **vehicle segments** that are currently electrified in different markets are presented.

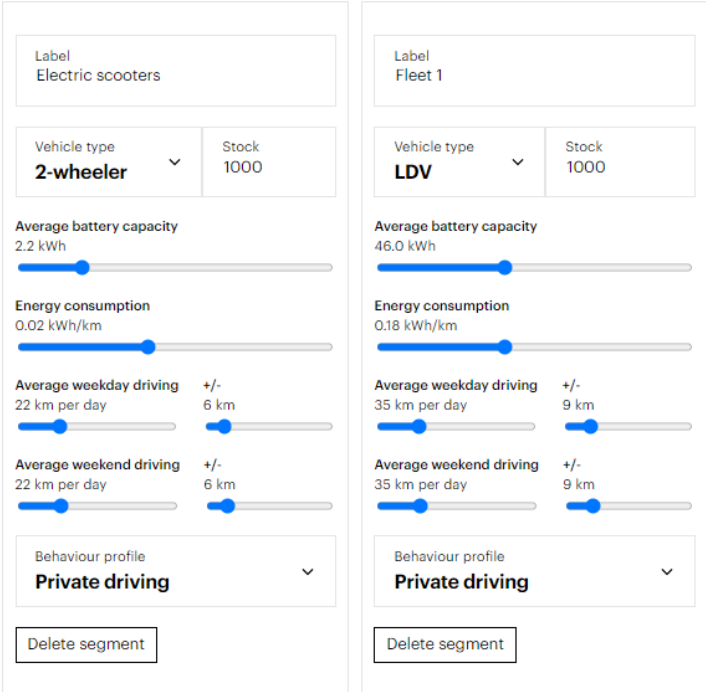
List of available vehicle segments

Two- and three-wheelers	Light-duty vehicles	Buses	Trucks
Two-wheeler private	LDV private		
	LDV car sharing		
Two-wheeler taxi	LDV taxi		
Three-wheeler taxi		School bus	
Three-wheeler last mile delivery	Last mile delivery van	Intra-city bus	Local distribution truck
		Regional bus	Regional long-haul delivery

Note: LDV = light-duty vehicle.

For every vehicle segment, the user's main input is the **vehicle stock**, but the user can also specify the charging profile (private or fleet). Default driving distances and battery capacities are provided based on literature but can be refined by the user.

Input window to specify fleet data



The **average daily driving distance** represents the typical distance that the vehicle drives in a day and informs the charging needs for the week. The user may also enter different driving intensities for weekdays and weekends. We advise users to consult their respective national travel surveys and transport statistics to adjust this input.

Default values on **battery capacity** and **battery average energy consumption per kilometre** are provided but can be modified by the user based on local market characteristics. The user can visit existing databases of vehicle models that compile this information. Alternatively, a factsheet is available on the IEA website with the battery capacity and range of the bestselling electric cars in selected countries in 2021.

The ambient temperature affects the charging and discharging efficiency. Therefore, the user can choose the **country** and calendar **month** and the tool determines an average ambient temperature. The selected country and month will also affect the renewables generation profiles (used by modules two and three).

In the current version of the tool, the user can choose between 12 countries, selected for their diversity: Argentina, South Africa, India, Ukraine, Chile, Columbia, Indonesia, Thailand, Uzbekistan, Ghana, Senegal, and Kenya. More countries may be added later to the tool.

Defining charging opportunities

The second tab contains the settings for the available charging infrastructure and charging preference of EV drivers. The user can create multiple charging profiles to associate with each of the vehicle segments. Default behaviours are provided based on literature but can be refined by the user.

The first parameter defines the **charging location types**, as defined in the table below.

Charging location types definitions and typical uses

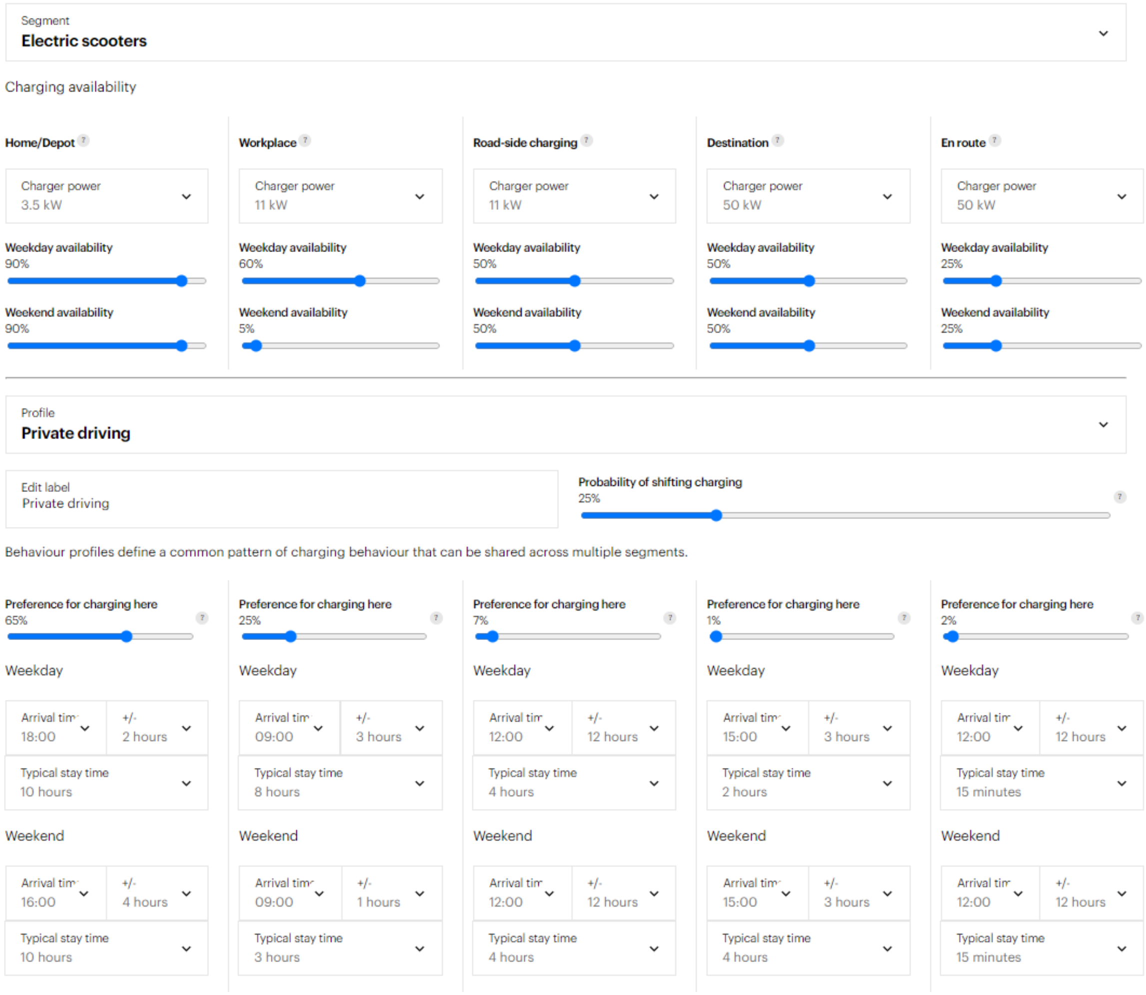
	Name	Definition	Use-cases
1	Home charging	Charging at the driver's residence	The default charging location for private vehicles
	Depot charging	Centralised charging of commercial fleets, buses or trucks in a building with restricted access fitted out with several charge points	The default charging location for fleet vehicles
2	Work charging	Charging at the driver's workplace	The first alternative to home charging for daily commuters to a workplace
3	Roadside charging	Charging at a public or private parking place next to the road, most often in a city or urban environment	The default charging for drivers without a dedicated parking place
4	Destination charging	Charging at a place of interest (shopping mall, restaurant, public institution…), the destination of a journey, outside of work and home	An additional option for charging, often for partial charging during stay time
5	Enroute charging	Charging at a charging station on the way to the destination, on a highway or travel corridor	Used during longer journeys or in absence of charging options during stay time
6	Opportunity charging	Strategy for partial charging outside of the base location (for a fleet, bus or trucks)	An additional option for charging, often for partial charging during stay time and *taking place several times per day*

Not every vehicle will have access to all the six location types. For all location types except opportunity charging, charging is assumed to take place once a day. Therefore, the user defines the **charging window** (arrival time, variance and stay time). The names of the charging locations are provided for the convenience of the user and in order to assign default values upon selection of a vehicle segment and driving profile. However, the user can refine the settings and flexibly assign charging locations to a segment. If, for example, a city bus has time to charge at the depot twice a day, the user can use the type “work charging” as the second daily charging window.

The behaviour profiles are generated based the following inputs, which are referred to the charging locations.

Availability of charging location types: This represents the share of vehicles that could charge at a certain location during the time window defined by the user. The input number needs to also take into account whether, although available, the chargers are accessible at these times. For example, since not all private car owners have a dedicated parking space, home charging availability may be 95% (in private house districts) to 25% (in dense cities). Workplace charging may not have a high availability during weekends since drivers do not go to the workplace on weekend and can be set below 10% during weekends.

Input window for charging availability and preference



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Charging power at charging locations: The user can select an available charging power for each charging location type. This power value corresponds to the maximum charging power at the location type and will be used (as constant value) for unmanaged charging.

Typical arrival times and stay (or dwell) times: The arrival time (hour of arrival) and dwell time (duration of stay) are key inputs and some variance is integrated into the model to account for natural variations. The tool assumes that the vehicles are connected to the grid during the entire dwell time. The window available for charging is calculated from these two variables. Users can refer to travel surveys to determine the typical arrival times in a day.

Typical time and number of events (for opportunity charging only): Opportunity charging is characterised by several short but intensive charging processes within a certain period of time. The related inputs are the start time and duration of the period of time, the number of charging events and the duration per charging event.

Probability of shifting charging to next day: EV users do not always recharge after each ride, especially if the consumption was low. This parameter defines the share of drivers who would shift a charging event to the following days if the state of charge of the battery is above 50 percent. This parameter is valid for all charging location types.

Defining charging preferences

The previous inputs define the energy consumption (fleet-related inputs) and thus the charging needs, and the charging opportunities. The matching between these two considerations requires another parameter, the charging preference of drivers, which emulates the decision-making process of a driver in relation to where and when to recharge.

Charging preference: The charging preference describes which of the charging location types are preferentially chosen by the EV drivers. The main aspects behind the preference are the costs (especially for private use) and the comfort. For each location type, the proportion of EV drivers who would prefer charging at that location type ranges from 0 to 100%. For a single driver profile, the sum of preferences of all location types must equal 100%.

For private vehicles, the preferences can be based on results from EV user surveys (examples in France or in the United States). For example, private LDVs typically charge in order of preference: at home, workplace, places with shopping and leisure opportunities (destination charging) and at the roadside near rest areas.

For fleet vehicles, charging patterns are strongly affected by fixed charging strategies. For example, bus charging is correlated to the bus service schedule and buses mainly charge at the depot overnight, although they would also need some opportunity to charge at bus stops after each trip (opportunity charging). The charging preference parameter decides on which of the two opportunities the buses first try to charge all their needs. The mentioned charging strategy would result in 100% preference for depot charging, because that is the preferred and main location type.

Defining the scope of study: bulk power system or distribution network

Thanks to the flexibility of the visualisation on the results tab, the tool user can define the scope of the study, or rather decide to consider only part of the fleet in the results. The tool is designed to ensure that the total electric demand for charging matches the needs of all the vehicle segments, but the user may decide to only visualise only a small part of the charging locations or of the fleet segments. For example, if one is interested in the charging profile in a residential network where there are only home chargers.

Studying a distribution network

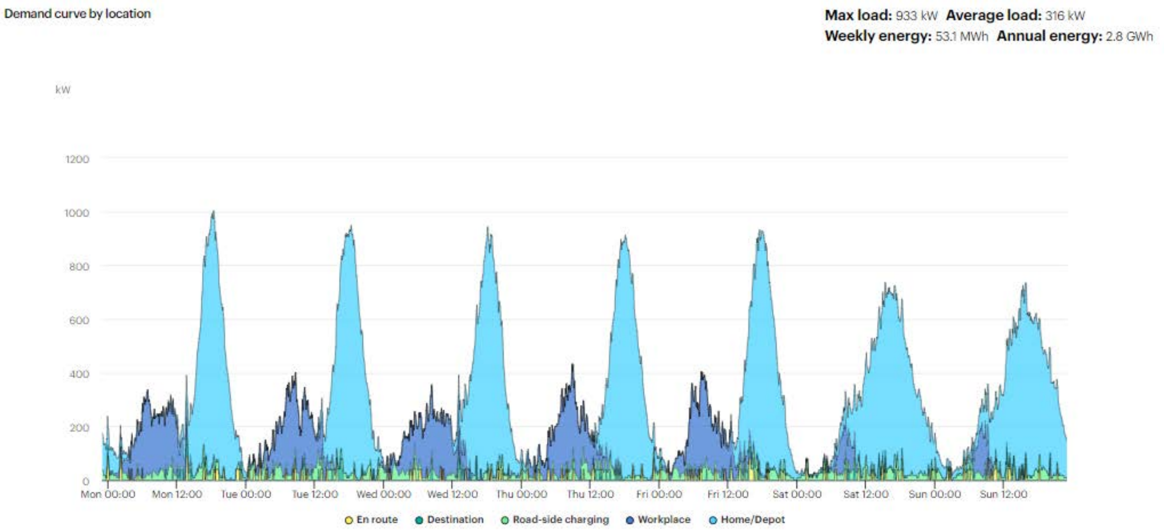
In this case, the charging location plays an important role, as the simultaneity in charging may overload transformers and lines and affect the voltage in weaker grids. The charging peaks can be compared to the **spare capacity of the relevant distribution transformer**. For example, the high intensity but short duration charging demand of public enroute charging is relevant for medium-voltage transformers since these chargers will be connected to that voltage level. For this, the user needs to ensure consistency between the fleet simulated and location types, and the distribution network under study.

Studying the bulk power system

In this case, the charging profile helps to assess the contribution to system peak demand and how that might affect the resources **dispatch and adequacy** (for example, whether a new peaking generator would be needed or if new flexibility sources are required to meet the power ramps).

The tool also provides information regarding unserved energy, i.e. the gap between the energy demand (as a consequence of the driving patterns) and the energy supplied by the charging infrastructure. A high gap means that the charging infrastructure solutions are insufficient to match the need of the mobility behaviours defined.

Tool output: charging profile



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Module 2: Assessing the effects of managed charging

Beside the determination of the unmanaged EV demand, the tool enables applying managed charging approaches. The principle is to shift energy within the charging window (the time frame during which charging is possible, that is, when the vehicle is connected to a charger), without changing the overall charged energy. Managed charging goals can be of different nature, such as reducing peak power or increasing the charged energy supplied by renewables.

Selecting a managed charging measure

Three managed charging strategies are available. In the **third tab** of the tool (advanced mode), the user can select:

Balanced charging (BC): The charging power is minimised according to the energy needs and the expected dwelling time in a certain location. This local optimisation only requires information from the EV and does not take into account the state of the grid.

When using the tool through the API, the user can select two other strategies:

Time-of-use tariffs (ToU): The charging cost is optimised according to a reference tariff schedule. Within a charging window, charging during lower tariff periods is prioritised. The user can provide as input the **hourly tariff schedule**.

Active control with unidirectional charging (V1G)[1]: The charging process is optimised to smooth the variations of the electricity demand. The user can provide as input a **reference electricity (non-EV) demand curve** which is continuously updated with every additional vehicle that charges, such that the collective charging behaviour is co-ordinated.

Through the API, the user also has the option to integrate variable renewable generation (VRE, wind and solar) in the reference electricity demand curve, such that deep valley periods caused by high VRE generation could be filled up by the charging EVs. We advise users to make sure the reference electricity demand curve corresponds to the distribution network analysed when investigating a distribution network.

The user can define the **participation rates in the managed charging strategy** for all locations and segments. The participation rate is affected by the capability of the charging infrastructure and by the willingness of drivers to participate. It is not possible to define several managed strategies at the same time.

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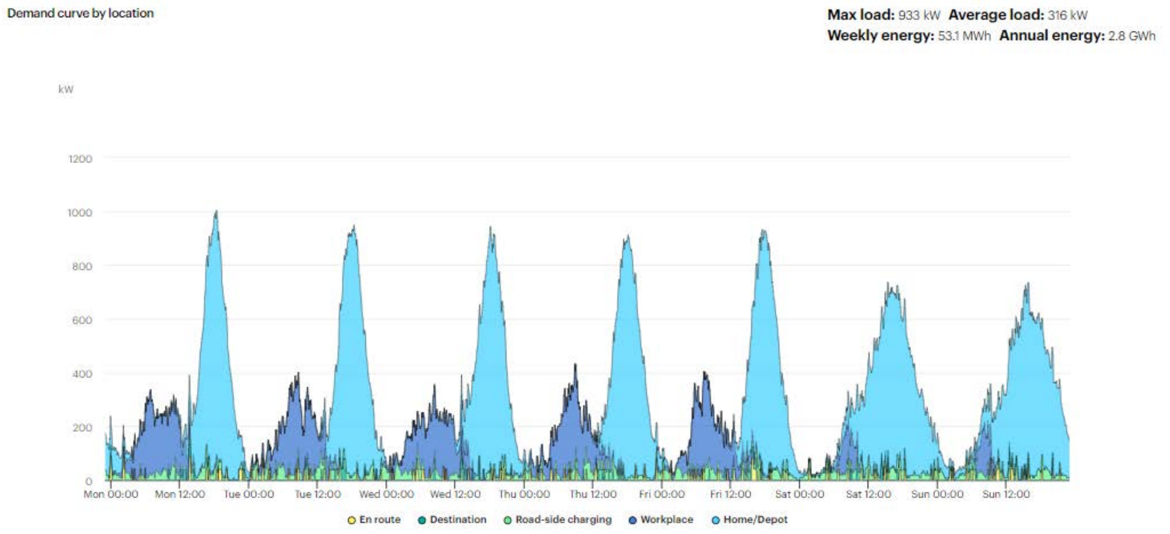
1 In the real world, V1G may be operated with different objectives such as frequency response or power quality regulation. These features are not included in this tool due to their specificity to local conditions.

Comparing impacts of unmanaged and managed charging

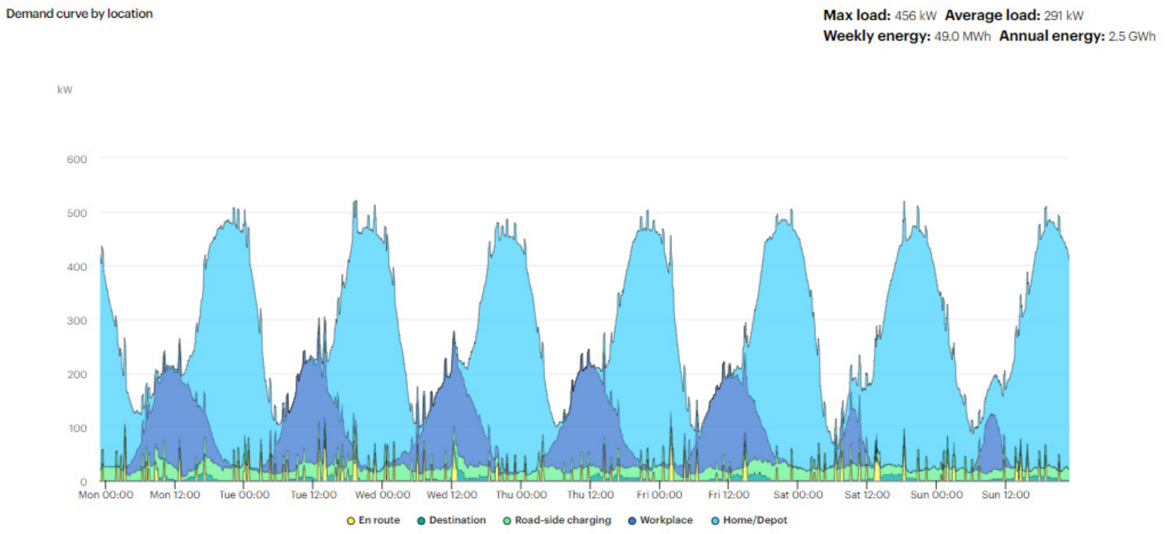
The results of this second module are a comparison of the EV charging profiles corresponding to the unmanaged and managed charging strategies.

Exemplary graphical comparison between the unmanaged and managed EV demand

Unmanaged charging:



Managed charging (balanced charging):



Module 3: Estimating climate impacts of EV charging

The tool offers a simplified[2] dispatch calculation assuming a merit-order dispatch based on typical costs and technology characteristics, based on default values for the countries available in the tool or, for advanced users, based on the user's input of the available capacity per type of generation source (hereafter, 'capacity mix').

Defining the capacity mix of the power system

Through the API, the user can modify the **capacity mix** with corresponding characteristics: **total installed capacity of solar photovoltaic, wind onshore and offshore** are used to calculate the renewable generation profile. The simplified dispatch and determination of CO_2 emissions also require the following information for all occurring conventional technologies: **total installed capacity, average installed capacity per power plant (and variance), marginal price for energy (and variance) and specific CO_2 emissions.**

Assessing the CO_2 emissions of EV charging

Each simulation will generate as result:

Yearly emissions caused by EV: The emissions over a week are scaled to a year, thereby it is possible to compare the emissions caused by EVs for different cases with this indicator.

The emissions module is suited for analyses at level of the **bulk power system** level given the use of capacity mixes and dispatch decisions. If the power system is wholly confined to its distribution area (e.g. small non-interconnected grids) then the emission analysis conducted can provide insights on the distribution level.

[2] Due to the limits of the web medium, this feature lacks more complex dynamics such as: minimum operating loads, ramp rates, contractual inflexibilities, outage probabilities, and other factors that may influence actual operational emissions.

Tool use: case studies

The three following examples correspond to contexts with different vehicle segments and charging approaches.

Case 1: Intra-city bus service in Chile

The first case study is an electric intra-city bus fleet in Chile. The fleet contains 25 buses with a passenger capacity of 87 passengers each. A bus has a battery capacity of 324 kWh and an energy consumption of 1.48 kWh/km. A pilot bus was run over 6 months, it completed 22 055 km and 1 173 trips during this time period. That corresponds to an average daily driving of 121 km and 6 to 7 trips per day. With this information, the inputs regarding the fleet can be entered in the tool. In absence of further detail, the average daily driving is assumed to be the same for weekdays and the weekend although bus frequency tends to be lower on weekends.

The charging strategy relies exclusively on depot charging for two and a half to three hours overnight. The available charging power at depot is 150 kW. The settings of “charging availability and preference” are entered as follows:

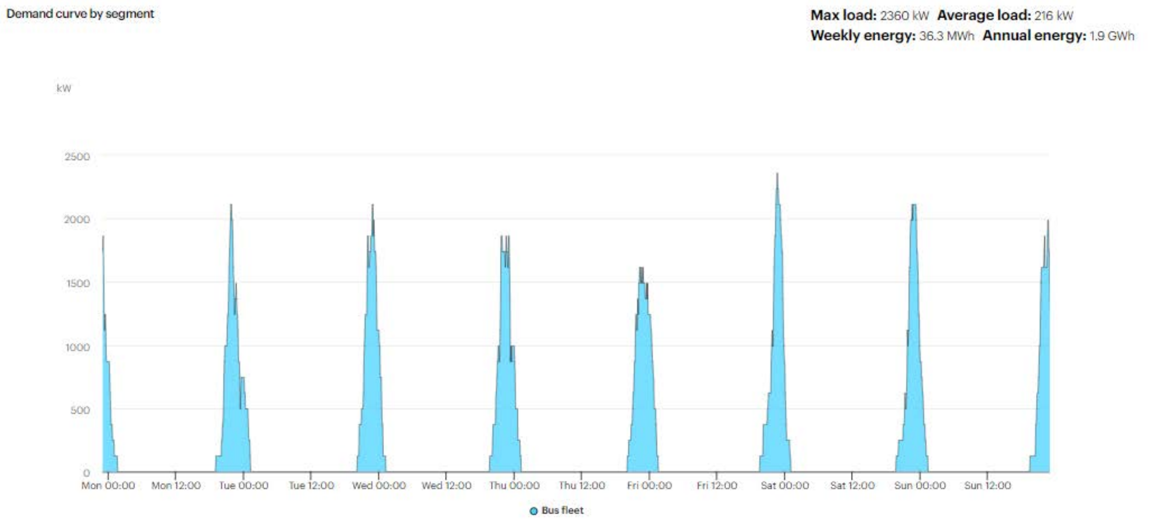
The share of depot charging is 100% because all buses can charge at the depot overnight. The availability of all other location types is zero, because the buses can only charge at the depot.

The arrival time depends on the time the buses finish the last trip and arrive at the depot. This can be based on the bus schedules. A bus starting the first trip at 6 am and finishing the last trip at 10 pm could be recorded as arriving around 11 pm with a variance (according to a normal distribution) of one hour and staying six hours if the depot is located near the bus terminus.

The probability of shifting charging to next day must be 0% if the buses should start the next day with a fully charged battery.

The resulting charging profile of the bus fleet with the aforementioned input parameters and settings looks as in the figure below.

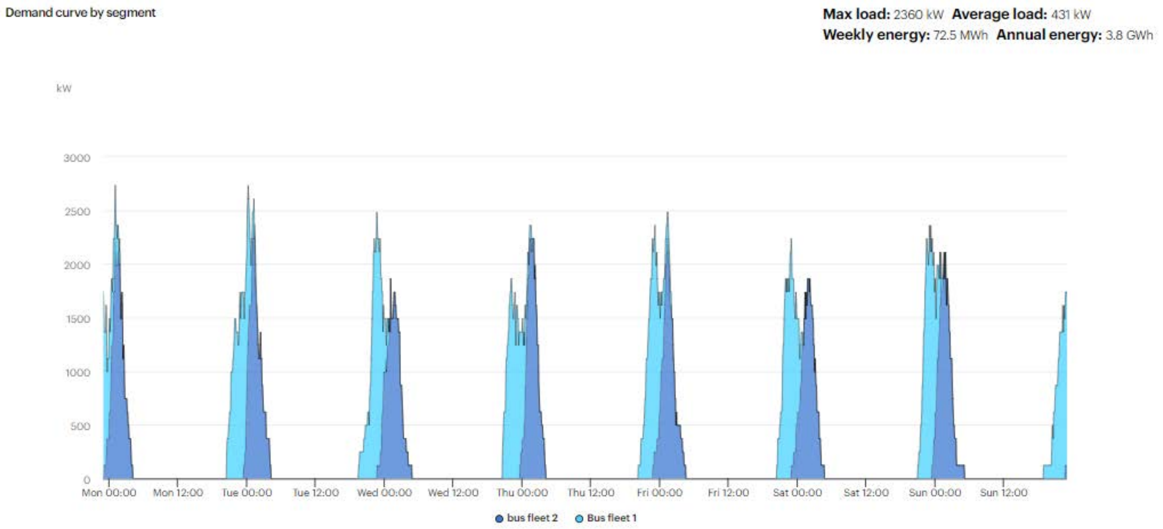
Charging profile for fleet of 25 buses



The figure above shows the overnight charging. The differences of the peaks are given by the variance when arriving at the depot. The peak power is barely 2.4 MW and is therefore very high.

Until now there were enough chargers for all buses staying overnight at the depot, all buses can charge at the same time during the complete charging window. The bus fleet shall be doubled to 50 buses. Now the chargers are only enough for a part of these buses (e.g. half of them), the user needs to create several fleets in the tool (e.g. with 25 buses each). The groups would then charge in succession and the charging durations is divided by the number of groups.

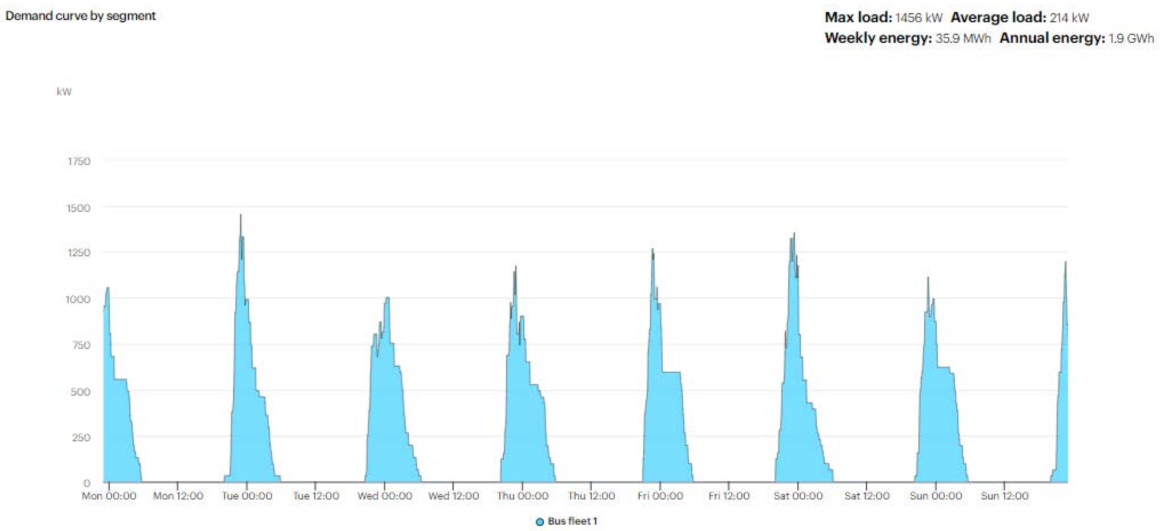
Charging profile for fleet of 50 buses



The figure visualises that the first fleet charges first, followed by the second fleet. In this way, the charging infrastructure can be better utilised.

Now back to the fleet with 25 buses. If the peak charging power is high and the number of chargers is high enough, the fleet operator can decide to apply balanced charging to reduce the cost and power of the transformer feeding the depot. If some chargers are older (for instance, 30% of them) and are not designed for managed charging, the participation rate of managed charging for the base location type can be set to 70%.

Balanced charging applied to the fleet of 25 buses



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Compared to the first charging profile, the peak power could be significantly reduced. The slightly changed total energy has probabilistic reasons.

The user can also assess the impact of some key parameters. For example, it could be that the bus fleet operator decides to reduce the battery capacity for the next fleet generation because it is one of the most expensive parts of the buses. The battery capacity is reduced from 324 kWh down to 150 kWh. Then the battery capacity would be too small to store the energy that is needed to complete the daily driving. To complement the overnight charging, buses can be given the opportunity to charge for 20 minutes after each trip if a charger is installed at the terminus. The charging power at the terminus is also 150 kW. The following inputs can be adjusted in the tool:

The location type “opportunity charging” is given a share of 100% as well, because all buses can charge after each trip. The start time is set to 6 am and the duration to 16 hours (operating hours). The number of charging events corresponds to the number of trips per day (seven) and the duration per event is 20 min (as assumed).

The charging preferences stay the same, because the strategy specifies that the main charging shall take place at the depot.

Case 2: Three-wheeler fleet for logistic use in India

This example is based on numbers and case studies of the Indian two and three-wheeler charging report. These three-wheelers are used for transport of food and groceries within urban areas. Each three-wheeler has a battery capacity of 7 kWh and drives 100 km per day. The stock of vehicles is set to 1000. The vehicles are used only during the weekdays (daily driving: 100 km on weekdays and 0 km on weekend days). The charging is centralised at the depot. The three-wheelers need one and a half charges per day: one full cycle overnight and a half cycle during the noon time.

In contrast to the previous example, there are two charging events over the day (overnight and at midday) at the same location. Here is how the tool user should set the right inputs to conduct this case study:

Charging location types can be defined flexibly. The tool user can enter the inputs for the overnight charging event in the first location type (depot) and for the midday event in a second location type of their choice (workplace, for example). The availability would be 100% for both charging types. The arrival times and dwelling time are adjusted by the characteristics of respective charging event.

By setting the preference to 100% charging at the first location type (overnight charging), it is attempted to have as much overnight charging as possible. The remaining half cycle is charged at the second location type (midday charging).

Case 3: Private cars in an advanced economy

This last example is fictive to illustrate various tool functionalities. It focuses on a fleet of 2000 private cars with a battery capacity of 50 kWh and an energy consumption of 18 kWh per 100 km. The daily driving is set to 30 km on weekdays and 25 km on weekend days.

All the inputs can be derived from driving and charging surveys. In absence of surveys, estimations can be made to use these values with a rough knowledge about the driving patterns.

Charging at home (base) is defined as follows:

From surveys, 90% of the drivers have the opportunity to charge at home, because they own a parking space and the required charging infrastructure. The share of availability of the charging opportunity does not change between days.

Surveys could also inform about the arriving and staying times. First, drivers may arrive later on weekdays than on weekends. The tool user would then enter different arrival times for the location type base (home), e.g. 7 pm for weekdays and 5 pm for weekends. The variance on arrival time could also be higher for the weekend (2 hours compared to one hour), because the driving pattern is more variable during weekends. The dwell times are established as the time difference between departure (on the next day) and arrival. That also tends to be longer for weekends (14 hours) compared to weekdays (12 hours).

The approach is similar for the other location types.

For workplace charging, the share of availability is significantly lower on weekends (5%) than on weekdays (50%). The arrival time is 8 am (variance one hour) and staying time is nine hours.

The arrival at public (roadside and destination charging) and enroute charging locations is typically more distributed over the day, that is why the variances could be several hours.

In contrast with home and workplace chargers, public and enroute chargers have a higher accessibility, greater variance in arrival, and the staying time is shorter. This results in a higher ratio between the number of charging stations and of charging opportunities, a factor that can be used to derive the "share of availability". A key finding of a study in the Netherlands was that the maximum number of public charging events per month is around 150, which corresponds to five charging events per day. The average is one to two charging events per day. For example, let us assume 100 public charging stations and 50 enroute charging stations. Based on the mentioned study and the main dependencies (accessibility, variance in arrival, staying/connection time) the ratio for public charging could be around three to four and the enroute charging five to six. The higher ratio for enroute charging is mainly because of the lower staying time and the higher variance in arrival. The ratios tend to be in the highest range of what the study mentions, because the maximum is related to what is possible. These assumptions would result in 30-40% (ratio times numbers of stations divided by vehicles) availability for public charging and 25-30% for enroute charging.

The tool user could be interested in analysing the impact of EVs in a residential area. In general, the tool would provide the charging demands of all location types, but the user can decide to visualise certain location types only (here only the home charging). The user wants to try to adapt the charging of the e-vehicles to the consumption of the non-EV demand and the renewable energy profile. Therefore, he decides to activate the measure V1G depending on the net load curve. For this, the user must upload the non-EV electricity demand profile and the installed capacities for the renewables. The charging would change for the applied managed charging measure as follows.

Tool limitations

The tool is designed with a focus on battery electric vehicles (BEV). For **plug-in hybrid vehicles** (PHEV), the distance driven will not match the energy needed to recharge the battery. If a user wishes to consider PHEV nevertheless, the user should create a separate profile for the considered vehicle segment where the distance driven is limited to the estimated distance driven on the electric drivetrain. The charging preferences can also be updated, for example excluding electric enroute charging.

The tool can be used for investigating **distribution grid impacts** to a limited extent. As illustrated throughout this note, the user can compare the distribution transformer capacity to the power demand including EV charging for a geographical area. However, more detailed investigations of distributions grids (power lines loading and voltage deviations) require more granularity in both the distribution grid topology and the vehicles (EV charging profile of single vehicles or charging stations). The individual charging profiles would need to be added to the demand profiles of individual households and other disaggregated electricity demands to calculate a power flow.

The tool includes three possible measures for managed charging, but other approaches exist. **Active control with bidirectional charging to the grid** (V2G or vehicle-to-grid), while promising for grid management and already at the trial phase in a few locations, is not included in the tool because the focus is on measures that could be implemented in the nearly future in GEF countries. In addition, the modelling approach of the current tool version does not allow a bidirectional power flow since the power system is not modelled in the tool.

The **CO_2 emissions** are determined with the help of a simplified dispatch model. In contrast to actual power system dispatch, advanced decisions are not considered, such as VRE curtailment, ramping rates, minimum operating loads of generators, effects of outages and grid congestions. The tool does not claim to calculate the emissions with high accuracy - the idea is to provide an order of magnitude and the focus is on the changes resulting from different situations (e.g. comparison between unmanaged and managed charging or comparison between effects of different charging preferences).

Annex

Modelling assumptions and methodology

This chapter contains the explanation of the modelling procedure, an overview of the default input data and the assumptions made. It describes how the input data mentioned in the first chapter is processed to obtain the desired results. First, the focus is on the three modules of the tool (charging behaviour, Demand Management and Emissions).

Module 1: Assessing the impact of EV charging on the power system

The first module simulates the charging behaviour based on availability of charging infrastructure and driver preferences.

General approach

Models to simulate EV charging can be classified according to two dimensions: the time resolution and the level of aggregation. Depending on the objective of the model, these dimensions need to be weighted.

The main output of this model is to deliver a demand profile corresponding to EV charging. In addition, the tool must show the effect of managed charging and calculate the CO_2 emissions caused by EV charging. All these aspects require a high **time resolution.** Therefore, a time step of five minutes was chosen. This also allows modulation of short, high power charging events. The simulation duration is one week to consider different activities and behaviours during different days.

The tool user must be able to provide input data based on travel surveys. Therefore, inputs are at the level of fleets. The same applies to results, thereby a **fleet approach** (aggregation) is acceptable for the user interface. Although convenient for users, this does not allow modelling of managed charging, which requires simulation at the vehicle level because the flexibility -the overlap between the possible charging window and the required energy- is unique for each vehicle and each charging event. Vehicle-level simulation is also necessary to determine the unserved energy and charging events shifted to the next day (more detailed explanations follow in the next sub-chapter). Therefore, the simulation takes place at the level of individual vehicle and charging station. In order to keep a fleet approach for the user, the input data is disaggregated and aggregation takes place for the results.

Modelling procedure

The modelling of the charging behaviour includes four main sub-processes in sequence. First, there is the determination of the available charging windows followed by the calculation of the daily consumed energy and energy to be charged (at the vehicle level). Afterwards the energy to be charged is allocated to the possible charging windows. In the final step, the energy allocated to the charging windows is converted into power values at the correct time steps to generate the desired charging profile.

These four sub-processes, which are detailed below, are applied on a daily basis. They are thus repeated for every day of a week. The input data could be different for weekdays and the weekend. A charging event is assigned to a day by the start time but can also span across two days. During the simulation, the vehicle segments are treated one after the other.

Determination of available charging windows

An EV driver can have many charging opportunities over a day. Each opportunity is characterised by the time the driver arrives at the potential charging station, the duration of the vehicle's stay there (dwell time), and the available charging power on the spot. The vehicle is assumed to be connected to the charger during the whole dwell time. A charging window is therefore defined as this time- and power-based charging opportunity.

First, the model estimates how many charging windows there are for each charging location type. The number of charging windows are equal to the product of input setting “availability of charging location” for each location type and the vehicle stock.

Then, the model characterises each charging window by the charging power, the specific arrival time and dwell time. The available charging power is fixed per location type by the input “charging power at charging locations”, i.e. the charging power of the charging windows within a location type is the same. The approach distinguishes between the location types.

The procedure for the location types one to five (home/depot, work, roadside, destination and enroute) is as follows. For each of these location types, the arrival time of EV drivers can be roughly assumed, and it happens only once per day. For example, the drivers arrive at the base charging location in the early evening. Dwell times are also similar for each location type. Therefore, the arrival times and dwell times of the charging windows are determined by normal distributions functions for each location type. The required inputs for the normal distribution functions correspond to the “typical arrival times and dwell times (location type 1-5)” including their variances. After this step, there are arrival times, dwell times and the fixed charging power for the calculated number of charging windows for each charging location type.

For the last location type, opportunity charging, it is different: it is characterised by several charging events over a certain period of time. The charging windows of the opportunity charging are thus composed of several short sub-charging windows each day. The sub-charging windows are defined by the inputs “typical time period and number and duration of the charging events (locations type 6)”.

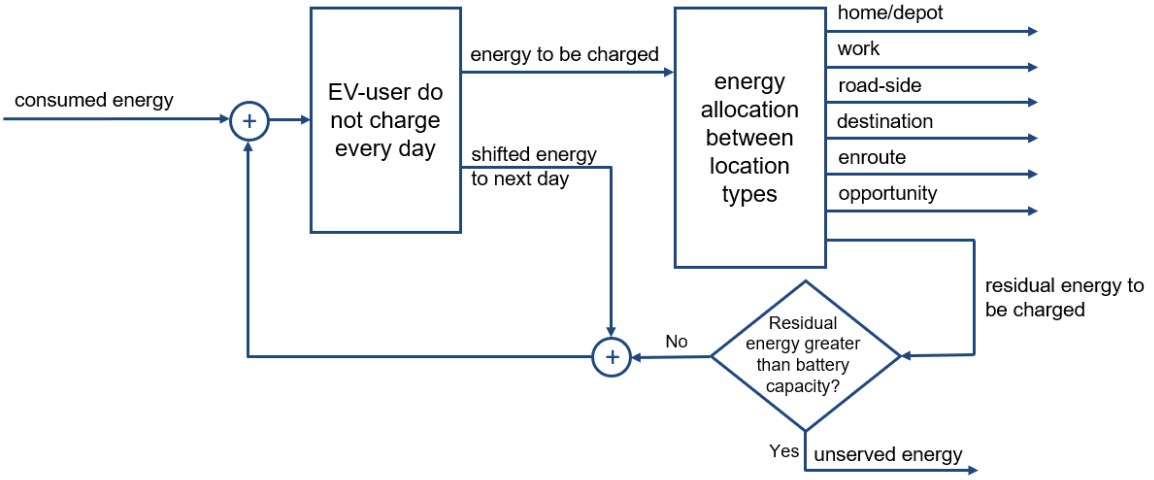
For all location types, the available energy of the charging windows is calculated by multiplication of the dwell time and the charging power. For the energy allocation, it is considered that a vehicle never charges more than 90 percent of the battery capacity of the vehicle (with the assumption that the state of charge (SOC) is never below 10%).

Calculation of energy to be charged

The distance driven by every EV is the base for the energy consumed by the vehicle over a day and needs to be recharged. In the tool, the distance driven by each vehicle depends on the entered **average daily range**. A normalised **lognormal distribution** function weighted by the average daily range allows an imitation of usual **private-use driving patterns**. The lognormal distribution function was selected because it is assumed that there are many drivers with only a small daily range and very few drivers with a very high range. In the case of other segments used for other purposes than private use, the range is calculated by a **normal distribution** function. After this step, each vehicle in the fleet is assigned a daily driven distance. This driven distance can be transformed to the consumed energy with the consumption per distance travelled indicator. Hereby, the influence of temperature on the discharge efficiency of batteries is considered.

Not all EV drivers decide to charge immediately after a trip respectively on the day the energy was consumed. The tool models this decision-making process by using the input “probability of shifting charging”. This defines the share of vehicles that postpone charging until the next day if the state of charge is higher than 50 percent. As shown in the flow chart below, the consumed energy is divided into two parts, the energy to be charged on the current day and the shifted energy to the next day. If an EV driver decides to charge the consumed energy immediately, the next choice is regarding the charging location (type) and time. This process is called energy allocation and is explained in the next paragraph.

Energy balance



As shown in the figure above, the energy to be charged is allocated to the possible charging location types, but there could be also shifted energy in case the available charging infrastructure is insufficient. The sum of the total shifted energy (due to both shifting of charging and insufficient charging infrastructure) is compared with the reference state of charge of 90 percent of the battery capacity for each vehicle, because normally around 10 percent stays in the battery and the net capacity is 90 percent. Of course, the shift of energy could not be higher than the net capacity – it would become unserved energy in that case. The energy which is shiftable is added to the consumed energy of the next day and the process starts again as shown the figure above.

Allocation of energy to charging windows

The energy allocation answers two questions: 'which charging locations are available for which vehicle?' and 'at which locations do the vehicles charge which amount of energy?'. The first question corresponds to which charging windows (determined in the first step) are available for which vehicles in the modelling process. Typically, EV drivers have a preference at which location type they prefer to charge and there is a dependency between the preferred location type and the number of available charging locations. That does not exclude that the preferred location type of an EV driver may not be available. These relationships form the basis for the following modelling process.

The allocation begins with the assignment of charging preferences. Each vehicle is assigned a preferred charging location. The input parameter "charging preference" provides the shares of preference for the fleet. Each vehicle is assigned a certain number and types of charging locations. The matching process between vehicles including the preferred charging location type and the charging windows is illustrated by the following example with a stock of 1000 vehicles. 700 vehicles prefer to charge at home, 200 at work, 70 roadside and 30 enroute. In every case, the total sum of the preferred charging location types must be equal to vehicle stock, because each vehicle gets exactly one preferred charging location type. The availability is as follows: 800 charging windows at home, 100 at work, 150 roadside and 50 enroute are available. The maximum total number of charging windows is five times the stock, because each vehicle could theoretically have a charging window at each location type.

The first objective is to ensure that each vehicle has at least one charging window per day, preferably at the preferred location type. The algorithm tries to find a charging window of the preferred location type. This is possible here for the EV drivers who prefer charging at home because there are 700 of them and 800 charging windows at the location type home. On the other hand, it is not possible for EV drivers who prefer charging at work. Some of these EV drivers are thus assigned a leftover charging window of the other location types (e. g. 100 charging windows from location type home). If there are more charging windows than vehicles like in the example, after this step each vehicle has exactly one charging window. Last, the remaining charging windows are randomly assigned to the vehicles under consideration that a vehicle can only get one charging window of each location type.

In case there are fewer charging windows than vehicles, some vehicles do not have the opportunity to charge (on this day). This would lead to **unserved energy**.

All vehicles are now associated with the energy which should be charged, the preferred charging location type and their potential charging windows including arrival time, dwell time, charging power and chargeable energy. This is how, the second question (‘at which locations do the vehicles charge which amount of energy?’) can be answered.

Each vehicle has a set of charging windows. If a charging window at the preferred location type is included in this set, that is the first charging window. The following order is defined by the assumption that the order of preference is ‘home/depot’, followed by ‘work’, then ‘roadside’, ‘destination’, then ‘enroute’ and finally ‘opportunity’. An attempt is made to charge the total amount of energy to be charged during the first charging window. If there is still energy to be charged, an attempt is made to charge it in the next window. This process is repeated until there is no energy to be charged left or no charging window available anymore. In this last case, the remaining energy to charge is shifted to the next day, if possible, as shown in the figure energy balance. Energy can be shifted to the next day if it is lower than 90 percent (with the assumption that 10 percent always stays in the battery) of the battery capacity, otherwise the vehicle would not be able to finish the ride.

Calculation of power values

Until now, the tool has estimated the amount of energy to be charged, the charging window and charging location. The final step for generating the charging profile is the calculation of the appropriate charging power values, for each vehicle and each time step of the week.

The maximum charging power is known for all charging windows; therefore, it is possible to calculate the duration of charging for each charging window where a charging process takes place. The charging efficiency and the influence of the temperature during charging processes is considered at this calculation. The duration of charging is converted into time steps where the power value corresponds to the charging power of the charging window. This sequence of time steps begins with the time step of the arrival. Because of this discrete approach, the charging power of the last time step is adjusted to exactly charge the energy which should be charged in the charging window. Afterwards, each location and time step are fitted with a power value. Adding all power values of the same time step enables the generation of locations type related profiles or a total charging profile. Hereby, the input “exclusion of demand from some charging locations” decides the charging profiles of which location types will be considered and have impact to the overall charging profile.

Module 2: Assessing the effects of managed charging

The second module applies managed charging to benefit from the flexibility of charging and mitigate the impact of charging on the power system.

The modelling of managed charging requires three steps: determining which charging events participate, checking if flexibility is available, and application of one out of the three available managed charging strategy.

Decision whether a charging event participates in managed charging is made based on the tool’s input participation rates corresponding to the charging location type and vehicle segment. A random draw determines in which events managed charging is enabled. For these charging events, it is next verified if there is flexibility for shifting energy within a charging window by comparing the available energy within a charging window and the energy demand. If flexibility is available, one of the three managed charging measures is applied.

The modelling approaches for the three measures are as follows:

Balanced charging aims for a low and constant charging power output during the possible charging window, using the entire dwell time. The adjusted charging power is calculated by dividing the energy which should be charged within the charging window by the dwell time that results in the lowest possible constant charging power. Here, the assumption is a perfect knowledge of the dwelling time beforehand, and the ability of the charger to adjust the power output.

The assumption behind **Time-of-Use tariffs (ToU)** is a perfect knowledge of the tariff block ahead of the charging session and an automatic or semi-automatic response facilitated by the smart charging service provider or the utility itself. Modelling of ToU starts from the unmanaged charging behaviour. The procedure is that every charging event is considered on its own, that means only the prices of the tariff during the charging windows are looked at. From the unmanaged charging behaviour, part of the charging is moved to the time steps with the cheapest prices. This effectively concentrates charging over the cheapest periods, which are typically correlated with the typical system stress levels. The effect of the (managed) charging on emissions is investigated in the third module.

The assumption behind **V1G** is available forecasts for demand and renewables generation and real-time availability of data about additional EVs connecting to the grid, such that the charging schedule can adapt accordingly. This entails the availability of high levels of communication in the whole ecosystem, that is, among EV, EVSE (Electric vehicle supply equipment), smart charging service provider, and power system. The modelling process of the V1G is very similar to that of ToU, the difference is here that the charging power values are ranked according to the demand curve of the system instead of prices. Furthermore, the adjusted charging profiles are added to the demand curve because. For the case of V1G with charging depending on the net demand curve (demand curve minus VRE generation profile), the renewable generation profile is subtracted from the demand curve beforehand.

Module 3: Estimating climate impacts of EV charging

CO_2 emissions related to EV charging are calculated for both the unmanaged and (if applied) the managed charging profile. Beside the EV charging demand, the non-EV demand curve (input) is needed to completely describe the electricity demand of the system. The calculation of emissions requires defining what power plants are supplying the demand, as described below.

The tool user can select 12 countries and the calendar month to yield a predefined normalised generation profile (wind onshore/offshore and solar PV). The normalised profiles are scaled by the installed capacities entered by the user. Alternatively, the user can enter their own time series of renewable generation. There are three electricity demand curves: the non-EV demand curve, the total electricity demand curve with unmanaged EV charging and the total electricity demand curve with the managed EV charging. The emissions caused by EV charging are calculated by comparing the emissions of the total demand curve (unmanaged and managed) and the emissions of the non-EV demand curve.

The fleet of centralised generation supplies the *net demand*, which is calculated by subtracting the renewable generation[3] profile from the demand curves. First, the power plant fleet is generated from the inputs. This process sets an installed capacity, marginal price per energy unit and emissions per energy unit for each power plant. The following process is run for every existing energy carrier (fuels and technologies). The total installed capacity of the energy carrier and the average installed power of a power plant form the basis for the determination of capacity per power plant. Dividing the total installed capacity by the average installed capacity for a power plant delivers an estimated number of power plants. A normal distribution calculates an installed capacity for each of these power plants by using the average capacity and the related variance. The total installed capacity and the sum of capacities of the power plants are subsequently equalised, whereby a number of power plants is determined and each of them has an installed capacity. The specific emissions per power plant depend mainly on the energy carrier, so all power plants of the same energy carrier are assumed to have identical specific emissions. Finally, a normal distribution based on the inputs price per unit of energy and the related variance determine the energy price for each power plant. After running through these steps for all energy carriers, each power plant is assigned an installed capacity, emissions and price per energy.

The following simplified dispatch determines which of the power plants run at which time to supply the demand of the net demand curve (based on the non-EV demand, based on the total demand including the unmanaged and managed EV charging). The power plants are sorted by price. The last power plant which is needed to match the demand is consequently the most expensive one and runs at the power level required to fulfil the net demand curve. All the other plans operate at maximum capacity. By repeating this procedure for all time steps the overall timetable of conventional generation is made. The power values can transform into energy values by multiplying the duration of the time step. Because of the existing specific emissions per power plant, the emissions per power plant and time step can be calculated by the product of energy and specific emissions per energy. The EV-related emissions can be determined by the difference of total emissions (based on total demand curve inclusive the unmanaged/managed EV charging) and the emissions of the non-EV demand curve. Furthermore, it is possible to compare the emissions of the unmanaged and managed charging.

Beside the emissions, the tool is also able to calculate the share of energy which is consumed by EVs and generated by renewables energies. This calculation requires the determination of the energy which is provided by renewables for the different demand curve types (total demand curve including the unmanaged/managed and the non-EV demand curve). The difference between the energy (provided by VRE) of the total demand and the non-EV demand corresponds to the energy provided

[3] This assumes that renewables are not curtailed.

by VRE and consumed by EVs. The share of energy which is consumed by EVs and generated by renewables is given by setting this energy difference in relation to the total energy consumed by EV charging. The shares of the unmanaged and managed situation can be compared to investigate the time-based conformity between EV demand and renewables generation.

Existing tools to assess grid impacts of EV charging

Classification of existing tools according to their scope

Name	Developer	Geographic scope	Vehicle	EVSE	EVSE	EVSE	Power grid	Power grid	Power grid
			Stock projection	Stock projection	Location	Techno-economic, financial	Hosting capacity	Charging load simulation	Network simulation
Behavior, Energy, Autonomy, and Mobility (BEAM)	LBNL	United States	x		x			x	
CarbonCounter	MIT	United States	x						
ConnectMore Interactive Map	SP Energy Networks	United Kingdom					x	x	
E-amrit	NITI Aayog	India				x		x	
eMob Calculator	UNEP	Generic / Global	x	x					
emobpy	DIW Berlin	Germany			x			x	
EV Capacity Map	Western Power Distribution	United Kingdom					x		
EV Charging financial analysis Tool	ATLAS Public Policy	Generic / Global				x			
Evaluation & Development of Regional Infrastructure for Vehicle Electrification (E-DRIVE)	ERM / MJ Bradley & Associates	United States			x				
EVI-Ensite	NREL	United States							
EVI-Pro	NREL	United States	x	x				x	
Future Mobility Calculator	Coalition for Urban Transitions, Siemens, WRI	Generic / Global	x			x			
Grid Integrated Electric Mobility (GEM)	LBNL	United States	x					x	
Homer Grid & Pro	UL	Generic / Global							x
Infrastructure Location Identification Toolkit (ILIT)	ERM / MJ Bradley & Associates	United States			x				
Jump Start	Field Dynamics	United Kingdom			x				
MiPower	PRDC	Generic / Global							x
Network Assessment Tool	EA Technology	United Kingdom	x	x				x	x
Power Factory	DIgSILENT	Generic / Global							x
PSCAD	Manitoba Hydro	Global							x
Standort Tool	BMWi	Germany		x	x				
Transportation Energy Evolution Modelling (TEEM)	Oak Ridge National Laboratory	United States							
UC Davis GIS EV Planning	UC Davis	California			x				
WRI EV simulator	WRI	United States						x	

Abbreviations and acronyms

BEV	battery electric vehicle
EV	electric vehicle
HDV	heavy-duty vehicle
LDV	light-duty vehicle
PHEV	plug-in hybrid electric vehicle
SOC	state of charge
VRE	variable renewable energy

Glossary

GW	gigawatt
GWh	gigawatt hour
kW	kilowatt
kWh	kilowatt hour
MW	megawatt
MWh	megawatt hour

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