Super Smart Charging Hubs | Interreg North Sea | Co-funded by the European Union

D1.7: Usage of storage batteries in combination with smart charging and peak demand

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Summary sheet

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Project partners

Organisation	Abbreviation	Country
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Gate 21	Gate 21	Denmark
ASTER cv	Aster	Belgium
GreenFlux Assets B.V.	GFX	Netherlands
VUB-MOBI Electromobility Research Centre	VUB-MOBI	Belgium
Flux50	Flux50	Belgium
AgriSnellaad	ASL	Netherlands
Autodelen.net – carshare Belgium	Autodelen	Belgium
Hub Park AB	HUB	Sweden
Free Hanseatic City of Bremen	BRE	Germany
Partenord Habitat	PH	France
Sustain	SUS	Denmark
Dutch Association of Electric Drivers	VER	Netherlands

Document history

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0.1	2024-12-17	VUB	Chapter 2 and 3	
0.2	2025-01-28	VUB internal supervisor review		
1.0	2025-03-03	VUB internal reviewed version		
2.0	2025-04-15	Partner review and adaptations of VUB accordingly		
2.1	2025-04-25	VUB	Language & readibility	
2.2	2025-05-14	VUB		Final check

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Acronyms	
SSCH	Super Smart Charging Hub
MILP	Mixed Integer Linear Program
SOC	State Of Charge
V2G	Vehicle To Grid
(B)EV	(Battery) Electric Vehicle
ROI	Return On Investment

1. Introduction

This report summarises the work conducted, and results achieved in T1.7. The task consists of investigation how the installation of storage batteries helps the smart use of renewables and charging of BEV, e-trucks, e-busses, and e-ferries.

Section 2 discusses the simulation methodology, and the data input used for the calculations.

Section 3 discusses the set-up and results of 5 different specific use cases relevant to the project.

Section 4 holds the conclusions and general insights

2. Simulation methodology and input data

Section 2 discusses the simulation methodology and the input data used. The core of the SSCH design model is a Mixed Integer Linear Program (MILP) and is discussed in detail in paragraph 2.1. The simulations all use the year 2023 as a reference for weather data, electricity prices and grid tariffs and consumer behaviour. Paragraph 2.2 discusses the input data in detail.

2.1. Methodology

For the simulations, a hierarchical asset-based model (Felice, 2024) is used to define the behaviour of each SSCH set-up. The model is a Mixed Integer Linear Program (MILP) that optimizes the size of different assets, and their operation based on external data input. Technical characteristics are implemented as linear constraints (e.g. minimal SOC, maximal SOC of a battery, battery charging power limitations, grid connection limitations, …). The method strives to minimize total cost, including energy costs, grid costs, investment costs of new technologies (battery & solar) and operational costs.

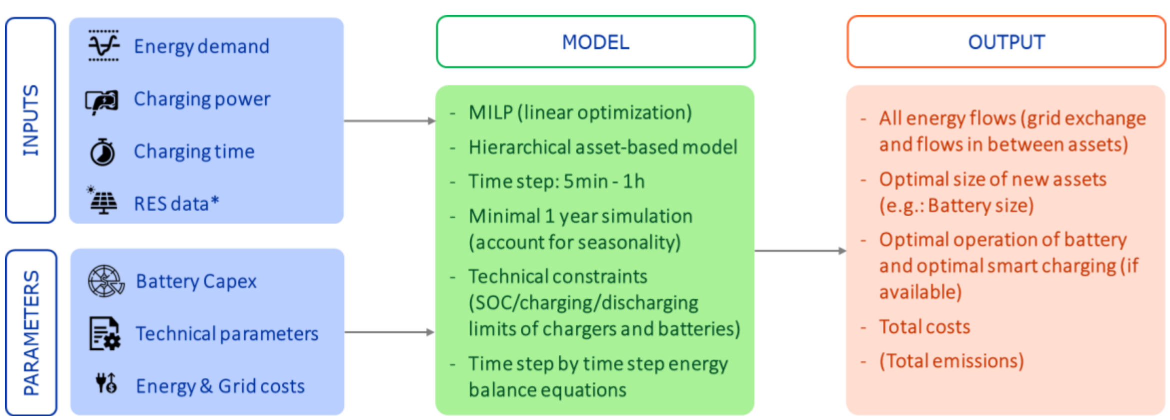

Figure 1: conceptual overview of the simulation model

Figure 1 shows the typical built up of the design and optimization model. The model is restructured specifically for the set-up of different SSCH simulations.

The full SSCH simulation process can be separated in 3 layers, illustrated in Figure 2:

- External behaviour modelling which generates the input time series data for the simulation model for each specific simulation or consumer behaviour.

- Configuration and physical properties of assets.
- Interface with the electrical grid and energy markets.

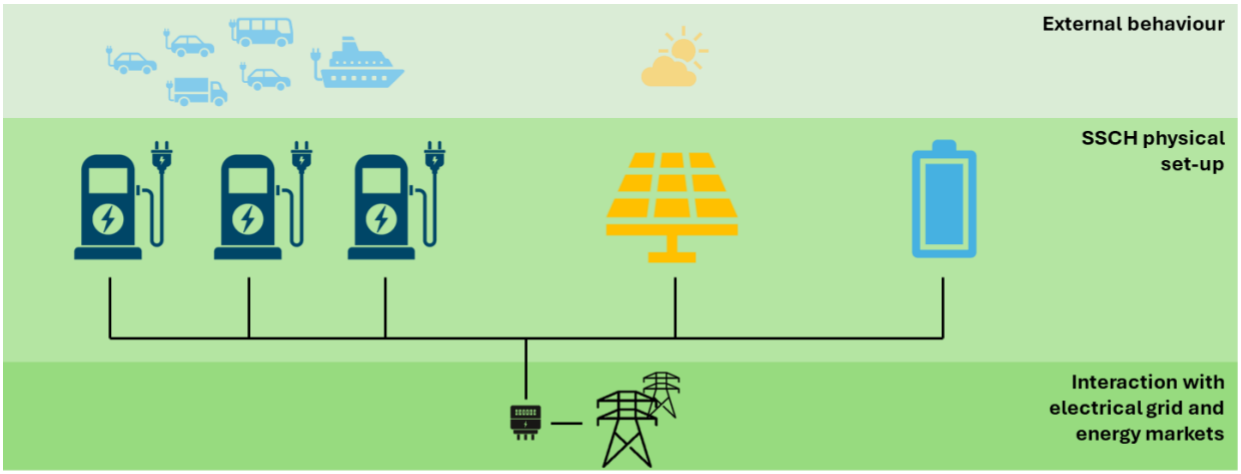

Figure 2: schematic overview of modelling building blocks

External behaviour
The user behaviour is generated based on real life data of comparable situations. For most of the modelled cases, the user behaviour is generated in a stochastic manner for typical consumer profiles with different values for the relevant parameters (arrival time, detention time, energy needs and charging profile) to create a realistic but varying charging behaviour over the simulation period. For very specific cases, deterministic charging behaviour is implemented (e.g. the ferry charging behaviour based on known examples of sailing schedules, charging power and energy needs). The model uses historical weather data for the simulated reference period.

SSCH physical set-up
A selection of assets, technical parameters and degrees of freedom in size and operation are determined to configure the SSCH. Each individual asset in the SSCH (e.g. one charge point, stationary battery…) is represented by a modelling block ('the asset model') which is the lowest layer of abstraction in the hierarchical simulation model. This asset specific modelling block describes the behaviour of the asset which is determined by a list of technological parameters.
On top of these asset models, an overarching modelling block ensures the energy balance behind the meter of the grid connections and optimizes the exchange of energy with the electricity grid.

Interaction with electrical grid and energy markets
Once the behaviour of the consumers and the configuration of the SSCH is determined, an optimal size and/or operation for the different assets can be calculated. The result of the optimal set-up depends fully on how the behaviour is valorised in the interaction with the outside world (electricity prices or grid costs). The model can be configured towards different energy contracts and different grid tariffs (grid tariffs are based both on energy use and capacity use, for both off-take and injection).

2.2. Input data

Justification of the use of location and time specific data

The simulation uses input (time series) data like weather data, grid tariffs and electricity prices. These data are typically dependent on the specific geographical location of the SSCH. For the simulations in this report, the region Flanders is chosen as a reference location. It has a well distributed mix of different energy production plants (nuclear, gas, wind, solar) and an abundant cross-border transmission capacity and a lot of energy market coupling with neighbouring bidding zones like the Netherlands and Germany. This means the energy prices in Belgium are considered as representative for the wider region (North-Sea Region). But when the location of the SSCH is known, using the local prices (and by extension local weather data and local grid tariffs) is always preferred in combination with a sensitivity analysis on this data. Especially for countries with a very specific energy mix (for example France with a lot of nuclear power plants or Denmark with a lot of offshore wind), it will make sense to perform a dedicated analysis with input data specific to the case to have to most accurate results.

The simulation model uses historical time series data of the reference year 2023 as an input. Energy prices are correlated both with weather data and consumer behaviour (for example weekday or weekend day). For this reason, when using historical data and simulating consumer behaviour, the data should originate from the same year. The year 2023 is chosen because this is the most recent year with all data available at the time of the simulations.

In the next paragraphs each data type that is used in the simulations is discussed in more detail.

Weather data

Historical weather data is extracted from the EU-funded open data platform of Climate Data Store making use of the services of Copernicus (https://cds.climate.copernicus.eu/). Weather data from the ERA5 dataset (https://cds.climate.copernicus.eu/datasets/reanalysis-era5-land?tab=overview) is used to simulate the production of renewable energy plants in the reference year. The coordinates of the used weather data are 52.6, 4.7 [latitude, longitude].

- Temperature
  - 2m temperature: temperature of air at 2m above the surface of land
- Wind Speed
  - 10m u-component of wind: eastward component of the wind at 10m above surface
  - 10m v-component of wind: northward component of the wind at 10m above surface
  - 100m u-component of wind: eastward component of the wind at 100m above surface
  - 100m v-component of wind: northward component of the wind at 100m above surface
- Sollar radiation

- Surface solar radiation downwards: amount of solar radiation (also known as shortwave radiation) reaching the surface of the Earth

Energy price data

All the simulations assume a dynamic energy off-take and injection contract. This means that the cost (off-take) or revenue (injection) is equal to the day-ahead price for the time of use. Figure 3 and Figure 4 show the day-ahead prices from the Belgium power exchange market (Belpex: https://my.elexys.be/MarketInformation/SpotBelpex.aspx) for the year 2023 for the whole year and an example month respectively. The average electricity price with an equal weighting factor for every hour over the whole year is 97 €/MWh.

Figure 3: Belpex price for the year 2023

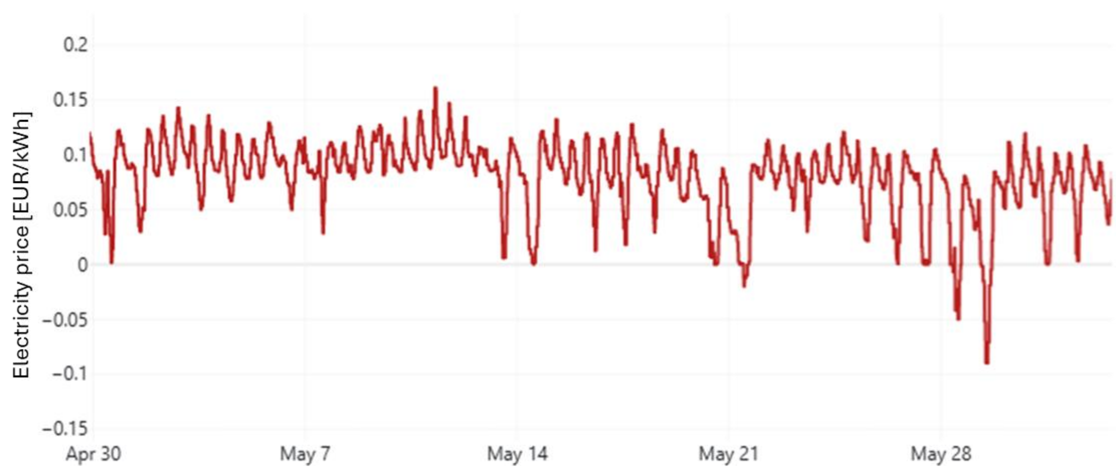

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Figure 4: Belpex price for the month may in the year 2023

Grid tariffs

The grid tariffs used in the reference simulations are based on the average prices of the Flemish distribution grid operator Fluvius. Especially for larger installations, the grid costs are mainly calculated based on the maximal power offtake. Total energy offtake has only a very limited impact. Fluvius has reported all his prices for the year 2025 for different voltage levels and power limits. An average but realistic combination of costs is taken along in the further simulations:

- Grid costs for energy offtake: 0.01 EUR/kWh
- Grid costs for energy injection: 0.002 EUR/kWh
- Grid capacity cost for the maximal power off take: 5-7 EUR/kW/month
- Grid capacity cost ratio yearly to monthly: 0.35-0.65

Grid costs for the use of capacity are partially calculated based on the monthly peak and partially calculated based on the reserved yearly capacity. Both the yearly and the monthly grid capacity costs together are hereafter together referred to as 'capacity tariff'. The cost breakdown of the capacity tariff in between cost for monthly peak and cost for yearly peak is a weighing factor 0.65 for the monthly peak and 0.35 for the yearly peak.

Calculation example

For an average peak cost of 6 EUR/kW/month and a year peak of 100 kW:

- *A yearly fee of 6 EUR * 0.35 * 12 * 100 has to be paid to the grid operator for the reserved capacity of 2520 EUR even if this peak only happens once a year.*
- *For every month a fee must be paid based on the peak off take of that month. Assuming that all monthly peaks are between 50 and 100 kW and in average 75 kW, a total monthly peak cost will result in a fee of 6 EUR * 0.65 *12 *75 = 3510 EUR*

Because the capacity tariff has a very high impact on the revenue of batteries or smart charging, and the capacity tariff is location dependent, this tariff is formatted as a sensitivity parameter in the simulations ranging from typically 0 EUR/kW/month to 9 EUR/kW/month which can be considered as a lower limit and an upper limit for the average EU countries (https://www.gridx.ai/knowledge/capacity-tariffs). In the next chapters we will use often the terms 'low capacity tariff' and 'high capacity tariff', those mean respectively a grid capacity cost of 0-3 €/kW/month and a grid capacity cost of 7-9 €/kW/month.

Battery technology

The battery in the model is parametrised as a stationary Li-ion battery:

Table 1 Li-ion parameters used for the simulations

Parameter	unit	Value
Round trip efficiency	[%]	90.25
C-factor	[kW/kWh]	1
Minimal SOC	[%]	10
Maximal SOC	[%]	100
lifetime	[year]	10
Lifetime cycles	[efc]	4000

Specific battery investment cost	[Euro/kWh]	100-700

The specific battery investment cost, next to the capacity tariff, is an important parameter for the optimal design calculations. Therefore, it is selected as a sensitivity parameter in the simulations. The specific investment cost is simulated in a range in between 100 to 700 EUR/kWh. One should note that a battery has a lifetime in years and in cycles. In our model the battery lifetime is set to 10 years and the maximum number of cycles over its lifetime to 4000 cycles. The model cannot consider early replacement but will instead size the battery such that the 4000 cycles are never exceeded over the 10-year period.

Solar technology

The solar output is simulated based on the hourly weather data (solar irradiance, temperature, clouds), the position of the sun and the direction and the tilt of the solar panels. The output is generated by using the pvlib toolbox which is an open-source python software package (https://pvlib-python.readthedocs.io/en/stable/).

The PV solar installations are parameterised with the following parameters:

Table 2 Solar model parameters for the simulations

Parameter	Value
Direction	south
Tilt	30°
Module technology	Monocrystalline Silicon
Specific investment cost	850 €/kWp

3. Use cases

This chapter discusses 5 different use cases. Use cases are defined based on the vehicle types for which the SSCH is designed and the specific charging behaviour.

Three different vehicle types are considered:

- Passenger cars
- Heavy duty road transport (buses and/or trucks)
- Ferry ships (short distance)

We distinct the use cases based on the whether charging happens with a known schedule and whether it is flexible (coordinated) charging. Figure 5 illustrates how use case 1-4 are distinct by their combination of these two charging characteristics.

Use cases 1-4 (further discussed in paragraphs 3.1 to 3.4 respectively) are single vehicle use cases with a predefined charging behaviour. The results will then be tailored to the specific use case configuration.

UC1: Ferry charging with up front determined sailing schedule

UC2: Depot charging of buses with a known number of buses with a known battery capacity and a good understanding of arrival and departure times and energy need

UC3: Fast charging of cars with an uncertain arrival time, uncertain energy need and uncertain charging behaviour

UC4: Over day employee parking with an uncertain number of daily charges, range of potential arrival times and a rather limited energy need in comparison with the detention time.

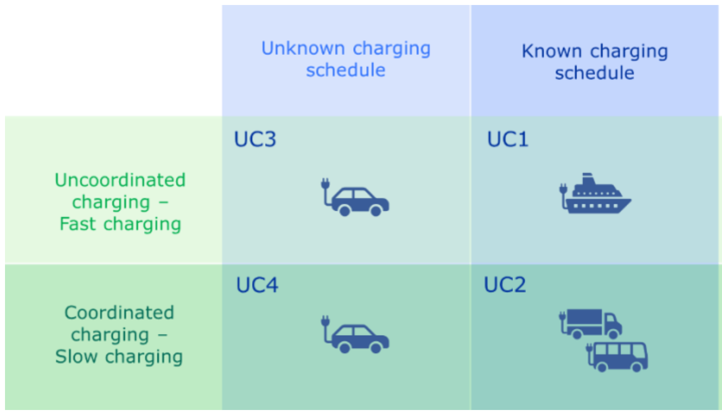

Figure 5 Use case distinction based on charging schedule and charging mode

Use case 5 (further discussed in paragraph 3.5) is a combination of vehicles and charging behaviour of use cases 1 and 4. The goal of this use case is to gain insights in the complementarity of use cases and the impact on the business cases and the optimal size of batteries. In this use case a small ferry is combined with a parking lot for the slow charging of passenger cars.

In the next paragraphs, an in-depth calculation is done for each of the use cases to optimize operational strategies and battery sizes. The optimization takes into account the exploitation cost of the charging hub (focussing on energy and grid costs). Investments in batteries and solar are part of the analysis because both are considered as a mean to reduce the total exploitation cost of the charging hub. Initial investment costs that are originated in the set-up of the grid connection, construction works of the parking lot or the initial purchase and installation of the chargers are out of scope of the optimization as these are very case specific. Similarly, the revenue of selling charging sessions is not part of the optimization (as the latter is considered as a constant - as no consumer behaviour change is simulated in this analysis – and should not have an impact on the optimization). In this way, the analysis in this report is contained and can generate very concrete insights in the usefulness of batteries in reducing operational costs for different types of charging hub configurations. However, the results are reported in a way that it is also possible to understand what the peak reduction potential of different sizes of batteries are, which then indirectly can deliver insights in what costs can be saved by opting for a smaller (and cheaper) grid connection by installing a specific size of a battery when different offers from the grid operator are available.

3.1 Ferry charging on fixed daily schedules

Description of SSCH use case 1

Use case 1 is a high-power ferry charging station. The ferry has a 1-hour sailing round trip with a stable charging need of 417 kWh every round trip. The ferry sails the whole year from 6 a.m. to 21 p.m. which results in 15 charging sessions a day every day of the year.

The detention time (time plugged-in to the charger) varies from 5 minutes to 15 minutes depending on the simulated scenario. The energy need remains the same in the different simulated scenarios. The charging power, however, changes inversely proportional to the detention time (to be able to charge the same energy in a smaller time window).

Three different solar scenarios are included in the simulation:

- No solar
- Small solar installation of 500 kW (covers approximately the energy need during the day in summer
- Big solar installation of 3000 kW (covers approximately the peak demand during the charging of the ferry)

This results in 9 different scenarios of the SSCH

Table 3: Overview of the scenarios investigated for use case 1 based on solar installation size and ferry detention time.

	5 min charge	10 min charge	15 min charge
No solar	1A	1D	1G
500 kW	1B	1E	1H
3000 kW	1C	1F	1I

Results of SSCH use case 1

For each of the scenarios (1A to 1I), the optimal battery size, the highest yearly peak and the corresponding annualised costs for the SSCH are calculated. Each output is calculated for a range in capacity grid costs (1-9 EUR/kW/month) and a range in battery costs (100-600 EUR/kWh) and presented in Figure 6 to Figure 14 for scenario 1A to 1I respectively. The results are presented in sensitivity graphs to generate generic figures that can be used during a pre-design phase. Based on the effective capacity cost and an estimated specific battery investment cost, the estimated optimal battery size for the specific new SSCH case can be found. This optimal size is furthermore influenced by the other parameters like energy costs, levies on energy, consumption profile, interest rates, grid expansion costs etc., which were fixed in our simulation. For this reason, the results of the simulations should mainly provide insights into whether the installation of a battery makes sense in typical use cases and the expected order of magnitude of the operational and investment costs and battery size. Yet for an exact business case and sizing, a specific analysis should be made using more precise data specific to the case.

Scenario 1A: 417 kWh charging in 5 minutes, no solar

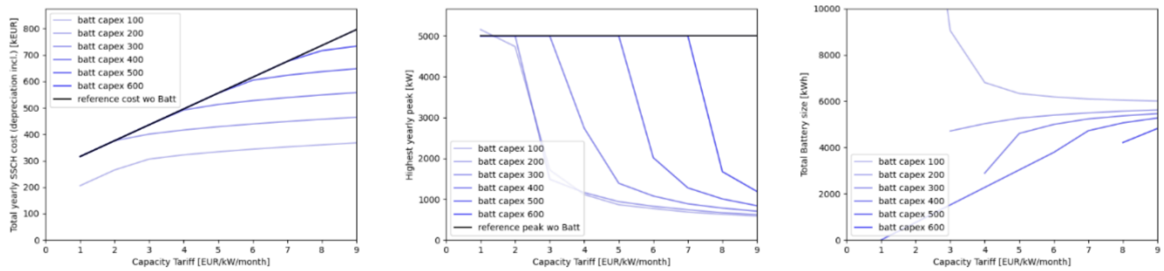

Figure 6 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 1A

Scenario 1B: 417 kWh charging in 5 minutes, 500 kW solar

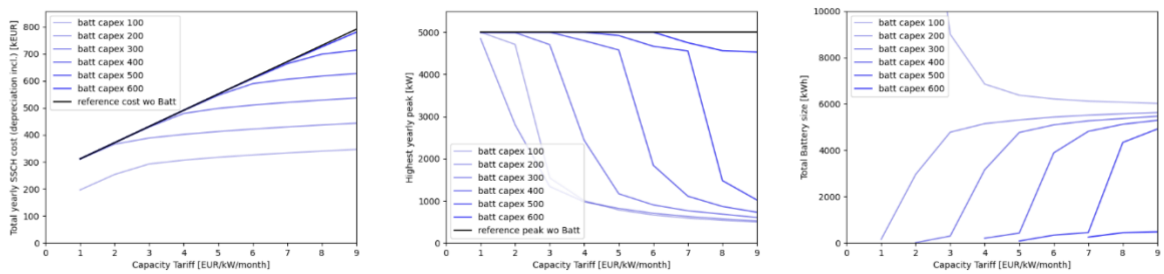

Figure 7 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 1B

Scenario 1C: 417 kWh charging in 5 minutes, 3000 kW solar

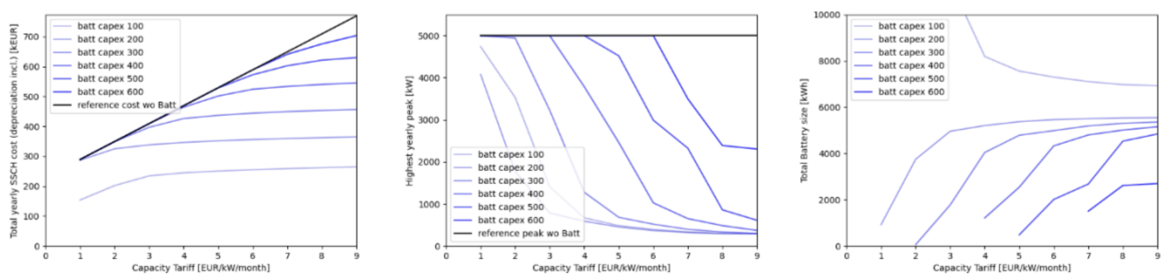

Figure 8: Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 1C

Scenario 1D: 417 kWh charging in 10 minutes, no solar

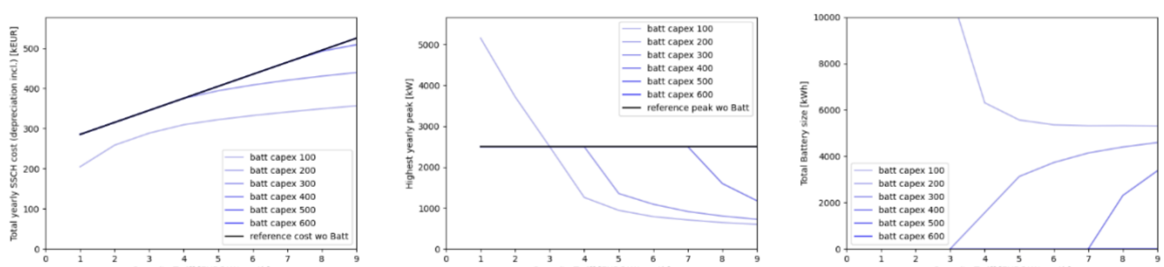

Figure 9 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 1D

Scenario 1E: 417 kWh charging in 10 minutes, 500 kW solar

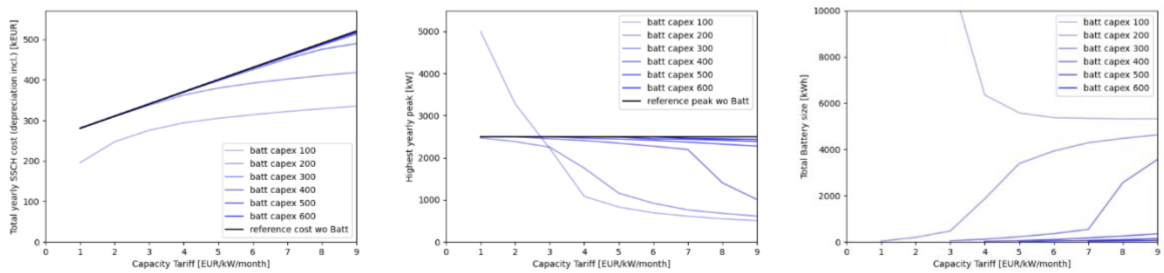

Figure 10 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 1E

Scenario 1F: 417 kWh charging in 10 minutes, 3000 kW solar

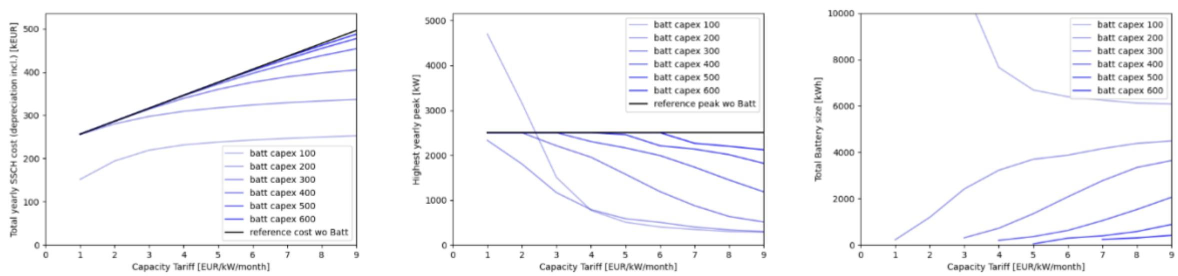

Figure 11: Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 1F

Scenario 1G: 417 kWh charging in 15 minutes, no solar

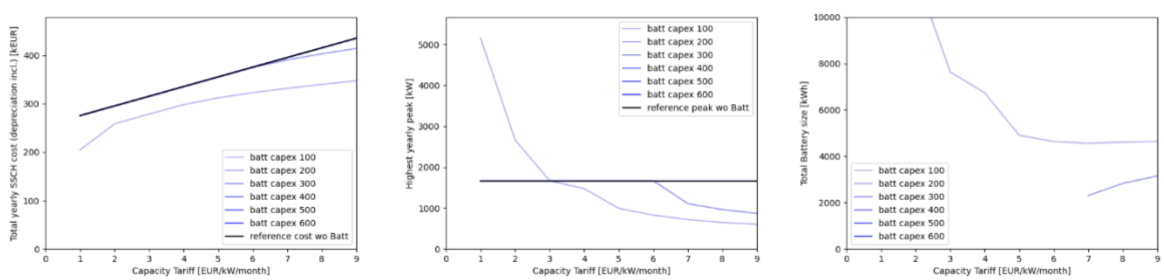

Figure 12 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 1G

Scenario 1H: 417 kWh charging in 15 minutes, 500 kW solar

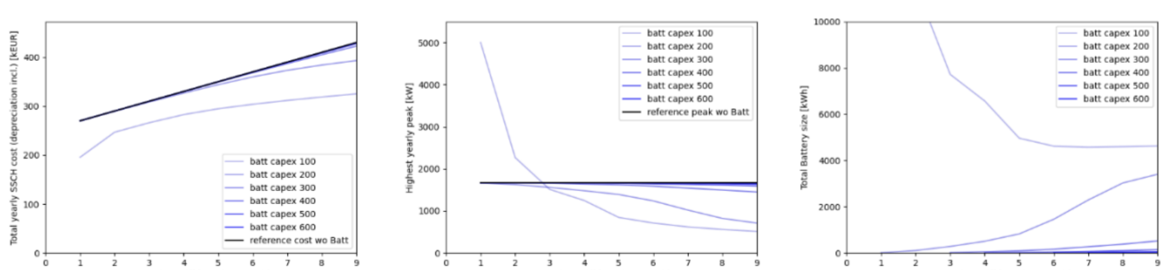

Figure 13 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 1H

Scenario 1I: 417 kWh charging in 15 minutes, 3000 kW solar

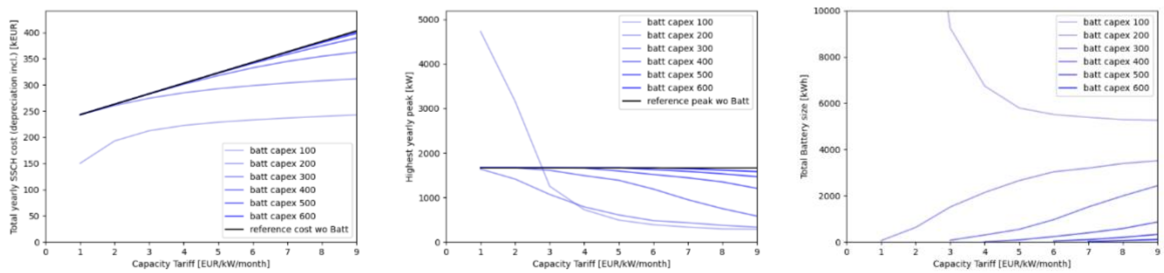

Figure 14 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 1I

Figure 6 to Figure 14 show some clear trends:

- A higher capacity tariff results in a linear increase of total yearly SSCH cost, but with the installation of batteries, an inflection point appears where the cost curve saturates. With decreasing specific battery investment cost the capacity tariff at which this inflection point occurs lowers.
- A higher capacity tariff results in a smaller off-take peak.
- A higher capacity tariff results in a bigger optimal battery size. With the exception of extremely low battery prices, where a low-capacity tariff increases the profitability of a battery by charging and discharging at high power rates to exploit volatile electricity prices while inducing limited capacity cost.
- With increasing solar size, the optimal battery size increases as well.

Summary analysis for a battery capex of 300 €/kWh

As it is not easy to compare the results across the different scenarios based on Figure 6 to Figure 14, all the results of the different scenarios are combined in Figure 15, Figure 16, Figure 17 for a for a fixed specific battery cost of 300kW/kWh. The figures show respectively the optimal battery size, the annualised cost, the yearly grid off-take peak and the ROI. The cost of 300 €/kWh is a rather low specific battery investment cost, however not unrealistic for big battery sizes in the range of 1 to 6 MWh. At this battery cost, the dynamics of the optimal battery size are clearly visible for use case 1. For completeness, the same graphs are also created for a specific battery investment cost of 500 €/kWh and are added to Appendix I.

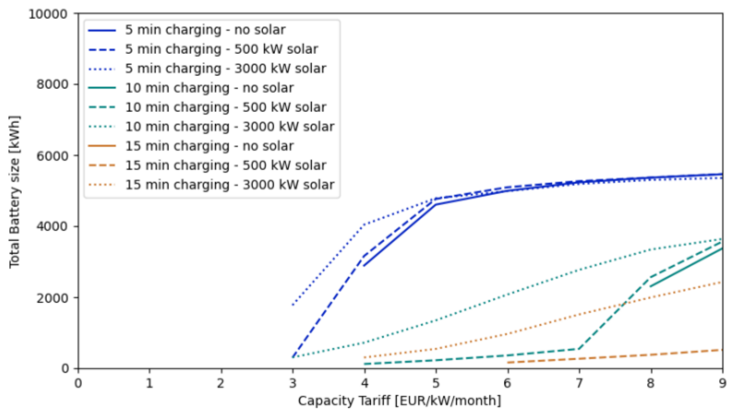

Figure 15: Optimal battery size for scenario 1A-1I with a fixed specific battery capex of 300 EUR/kWh

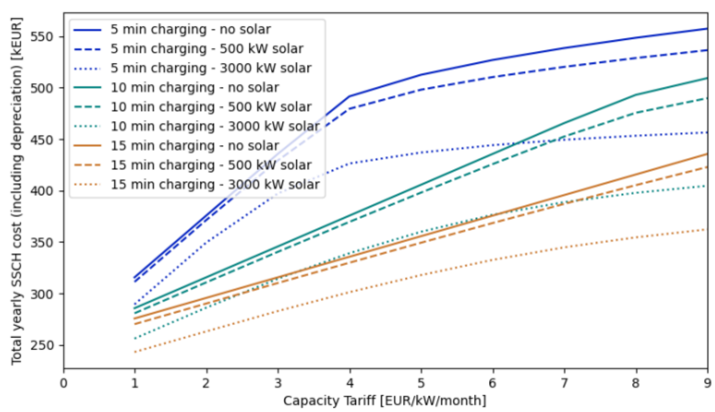

Figure 16:Annualised cost for scenario 1A-1I with a fixed specific battery capex of 300 EUR/kWh

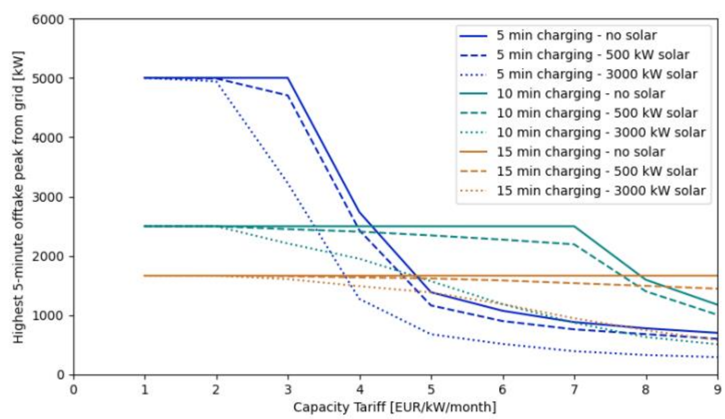

Figure 17: Max yearly 5-min peak for scenario 1A-1I with a fixed specific battery capex of 300 EUR/kWh

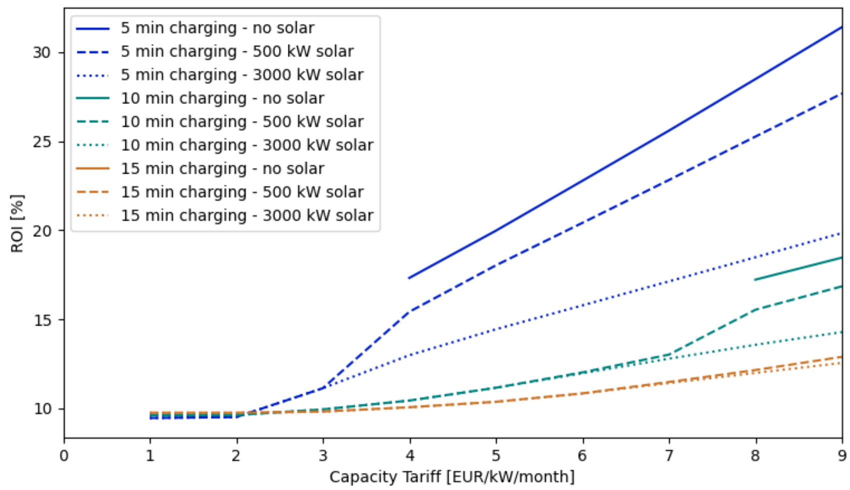

Figure 18: ROI for scenario 1A-1I with a fixed specific battery capex of 300 EUR/kW

Figure 15 to Figure 18 show some clear dynamics for use case 1:

- A short detention time always results in higher peaks (Figure 17), higher costs (Figure 16) and thus a thus bigger incentive for battery investments (Figure 15). The bigger incentive for battery investments is shown in the ROI (Figure 18) and bigger size of the battery (Figure 15).
- Optimal battery size increases with capacity tariff but tends to saturate from a certain medium-to-high-capacity tariff.
- Introducing PV into the system shifts the optimal battery size curve upwards but curves converge with high-capacity tariff.
- Investments in PV installations have, in all cases, a positive impact on the yearly SSCH cost. However, the ROI decreases with higher PV investment.
- In the scenario with the longest detention time (15 minutes) and without a PV installation, a battery is not an interesting investment even for high-capacity tariffs.
- In all scenarios where a battery is profitable, a clear grid offtake peak reduction is visible. Peak shaving is the primary business case. Secondary the battery can also be used to increase self-consumption of solar production or to make use of lower electricity prices.
- At low capacity tariffs (1-2 EUR/kW/month), which is shown on the outer left side of Figure 18, a battery is not profitable (and not present) for all scenarios and thus the ROI of the solar installation is visible. The ROI for these cases is always in between 5-10%. This means that independent of the consumer scenario, the investment in solar PV has a positive business case on the medium to long term.

Figure 19 shows boxplots of the monthly offtake peak for the optimal sized case at 300 Euro/kWh specific battery cost in function of the capacity tariff. As Figure 19 shows only the yearly peak (which has a cost impact for the reserved grid capacity) but gives no indication of the monthly peaks (which is the main driver for the capacity tariff), also a box-plot of the peak distribution across the year is added with Figure 19. Figure 19 shows the monthly peak distribution for a full year of simulation for scenarios 1A-1C (5-min charging case). The figure shows that an abundance of renewable energy production on site (3000 kW PV scenario), will result in a highly reduced monthly peak during the summer months for a high-capacity tariff. In all other cases, the monthly peaks are coinciding with the yearly peak.

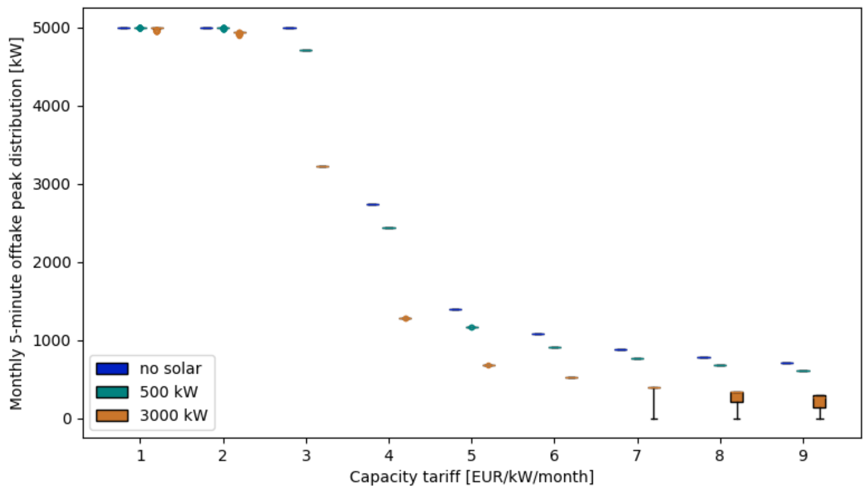

Figure 19: boxplot showing the monthly peaks for scenario 1A-1C with a fixed specific battery capex of 300 EUR/kW

Figure 20 shows for the same subset of scenarios (1A-1C) how the annualised cost breakdown looks like. The annualised capex is calculated as a yearly depreciation cost based on the lifetime and the initial capex. In the scenarios with an oversized PV installation, the net supplier energy cost can be negative. This means that the total revenues for injecting energy into the grid are bigger than the total costs for taking energy from the grid.

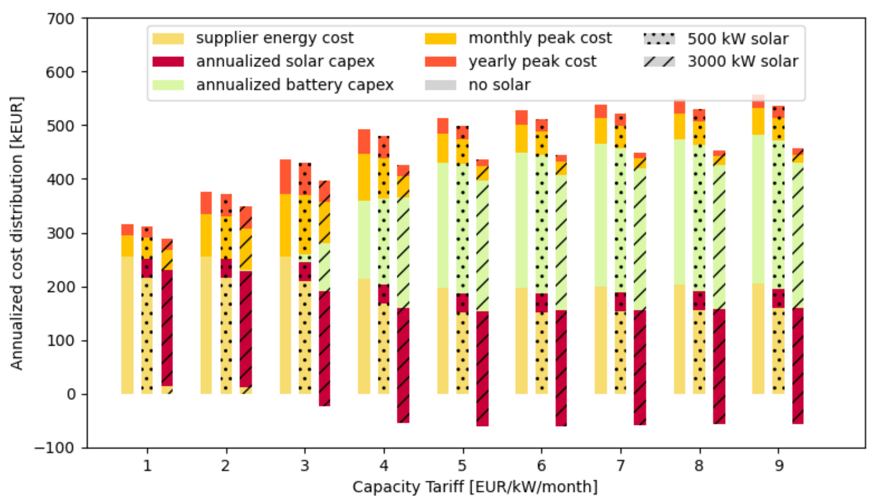

Figure 20: Annualized cost breakdown for scenario 1A -1C with a fixed specific battery capex of 300 EUR/kW

Conclusions of SSCH use case 1

- Scenarios with big solar (and battery) installations have a high upfront cost relative to the yearly energy and grid costs. But as a result, the grid dependence and the risk towards energy markets is reduced strongly. (see Figure 20)
- For a low-capacity tariff, the battery will also enable load shifting to generate revenues on the day-ahead tariffs. For a high-capacity tariff, the benefit of installing a bigger battery is purely originated in reducing the off-take peaks.
- The presence of a big solar installation has a clear impact on the monthly peak costs (monthly peak can be pushed to zero in summer months) but also results in a lower yearly peak. The optimal yearly peak is a balance in between flexibility towards load shifting (revenues on the energy market) to maximal peak reduction (see Figure 19). All simulations are executed under the assumption of a dynamic energy contract. Would the SSCH have a flat tariff for energy off-take, the same size of battery would be operated in a way that the peaks would be even more reduced because load shifting over the day would not make sense economically.

3.2 Heavy duty road transport: overnight charging

Description of SSCH use case 2

Use case 2 is a bus depot where it is assumed buses arrive in the evening (between 19h and 23h) and have a standstill time of 9 to 11 hours. The battery capacity of all buses is set to 440 kWh. Buses are required to be fully charged by the time they leave the depot. Buses come in with a varying state of charge in between 20% and 40 %. In total, 8 electric buses come in every night. They are connected to the chargers during their full depot stand-still time and each of the chargers has a max charging capacity of 55 kW. The charging power of 55kW is not arbitrary but considered as a logical choice in the sense that it is the relevant charging power for overnight charging of batteries with a capacity of 440 kWh to make sure they are fully charged while still having some flexibility to modulate the charging power. Higher charging capacity leads to a higher charging flexibility but requires a bigger electrical installation and grid connection. The grid connection is sized such that all 8 chargers can charge at full capacity simultaneously.

Three different operational strategies are simulated:

- Uncoordinated: the vehicle starts charging at maximum power at the moment of arrival and keeps on charging at maximal charging power until the battery is full.
- Smart: the charging power is optimized, considering the economic reality (typically making use of low energy prices and keeping the grid off-take peak as low as possible). The charging power is unidirectional from grid/battery to vehicle.
- V2G: similar as the smart charging case, but bidirectional. This means that the vehicle can also be discharged, and the power flow can also go from vehicle to grid/battery.

For each operational strategy a case is simulated with and without a solar installation. The size of the solar installation is chosen such that the total yearly PV yields match the total yearly consumption.

Table 4: Overview of the scenarios investigated for use case 2 based on solar installation size and charging operation.

	Uncoordinated	Smart	V2G
No solar	2A	2B	2C
900 kW	2D	2E	2F

Results of SSCH use case 2

For each of the scenarios (2A to 2F), the optimal battery size, the highest yearly peak and the corresponding annualised costs for the SSCH are calculated. Each output is calculated for a range in capacity grid costs (0-9 EUR/kW/month) and a range in battery costs (200-600 EUR/kWh) and presented in Figure 21 to Figure 26 for scenario 2A to 2F respectively. The results are presented in sensitivity graphs to generate generic figures that can be used during a pre-design phase. Based on the effective capacity cost and an estimated specific battery investment cost, the estimated optimal battery size of the SSCH is calculated. This optimal size is furthermore influenced by the other parameters like energy costs, levies on energy, consumption profile, interest rates, grid expansion costs etc., which were fixed in our simulation. For this reason, the results of the simulations should mainly provide insights into whether the installation of a battery makes sense in typical use cases and the expected order of magnitude of the operational and investment costs and battery size. Yet for an exact business case and sizing, a specific analysis should be made using more precise data specific to the case.

Scenario 2A: 8 buses overnight, no solar, uncoordinated charging

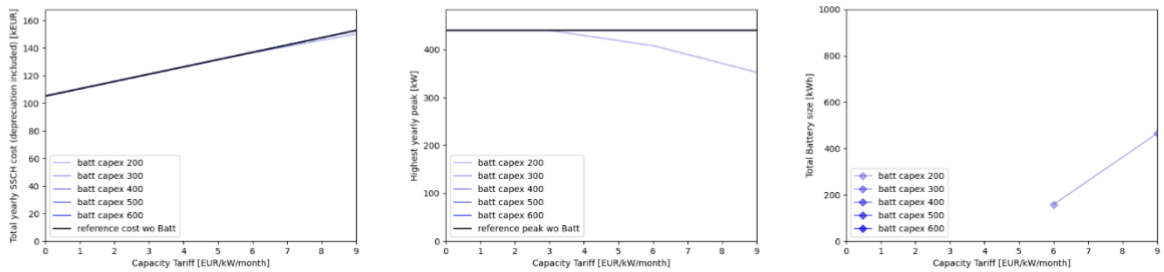

Figure 21 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 2A

Scenario 2B: 8 buses overnight, no solar, unidirectional smart charging

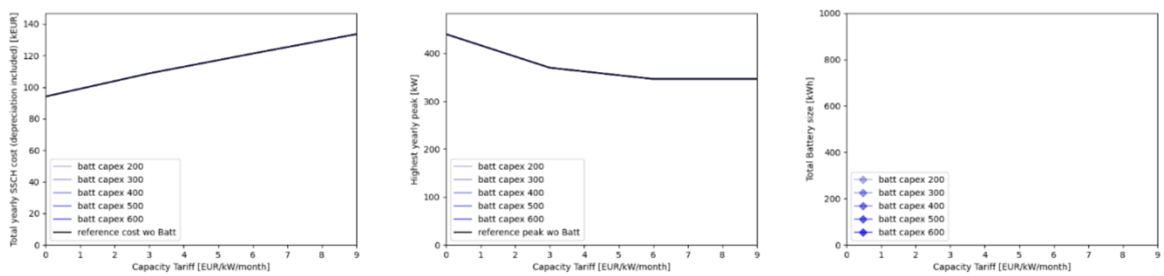

Figure 22 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 2B

Scenario 2C: 8 buses overnight, no solar, bidirectional (v2g) smart charging

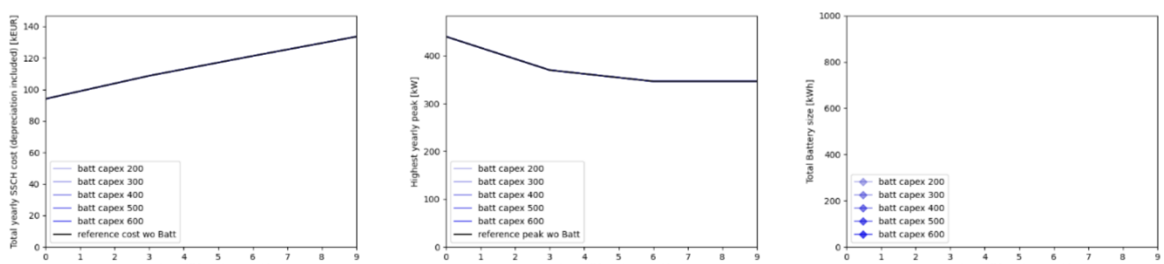

Figure 23 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 2C

Scenario 2D: 8 buses overnight, 900 kW solar, uncoordinated charging

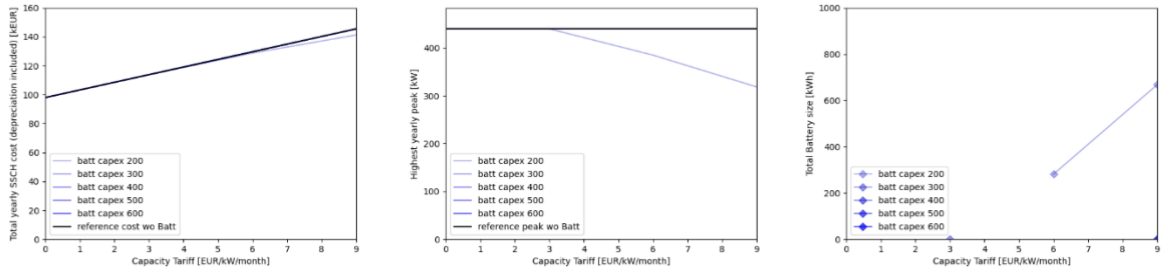

Figure 24 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 2D

Scenario 2E: 8 buses overnight, 900 kW solar, unidirectional smart charging

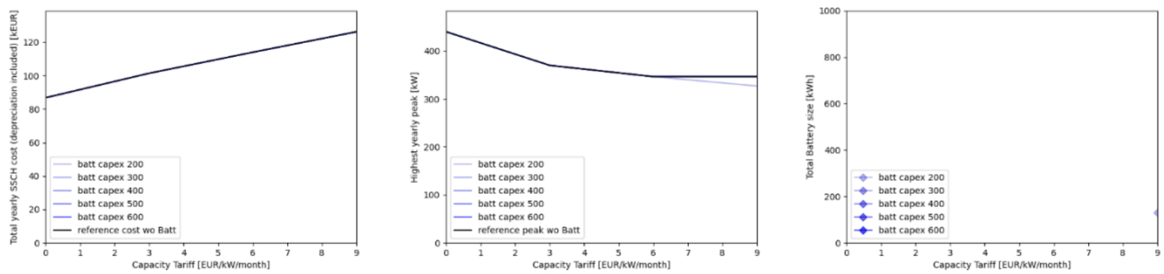

Figure 25 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 2E

Scenario 2F: 8 buses overnight, 900 kW, bidirectional (v2g) smart charging

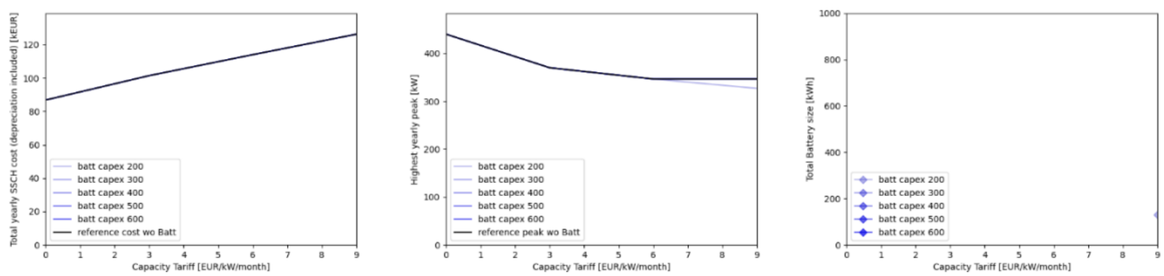

Figure 26 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 2F

Figure 21 to Figure 26 show some clear trends:

- A higher capacity tariff always results in a higher yearly costs
- Batteries are typically not an interesting investment case for this use case of overnight bus charging
  - Only when there is no possibility of smart charging (uncoordinated charging), and battery costs are very low, it appears useful to invest in a battery system
  - The presence of a local solar PV installation has a small positive impact on the profitability of a battery
  - Batteries are typically completely irrelevant when unidirectional or bidirectional smart charging is implemented
- A higher capacity tariff results in a smaller off-take peak.

- Even without a capacity tariff (0-point on the x-axes of Figure 21 to Figure 26), smart charging leads to lower costs. This means that due to the dynamic electricity off-take contract, load balancing is always an interesting operational strategy.

Summary analysis for a specific battery investment cost of 200 €/kWh

Figure 27, Figure 28, Figure 29 and Figure 30 show respectively optimal battery size, annualised cost, yearly grid off-take peak and return on investment for a set of different scenarios when keeping a fixed specific battery cost of 200 €/kWh . Despite 200 €/kWh currently being low as a specific battery cost, increasing this specific investment cost does not yield a positive business case for installing a battery. Hence, to be able to show the dynamics of the optimal battery sizing, this low battery investment cost is chosen. As a reference, all graphs are also created for a specific battery investment cost of 400 €/kWh and are added to Appendix II.

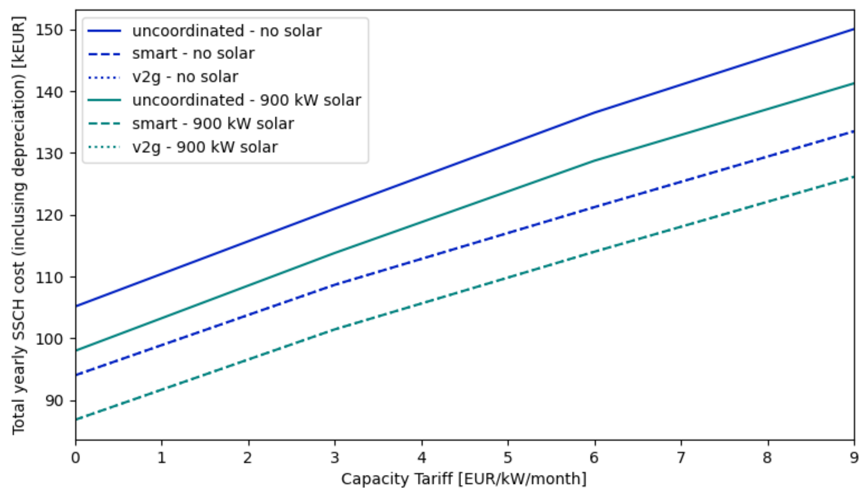

Figure 27: Total yearly costs for UC2 (overnight bus charging) for a specific battery cost of 200 EUR/kWh

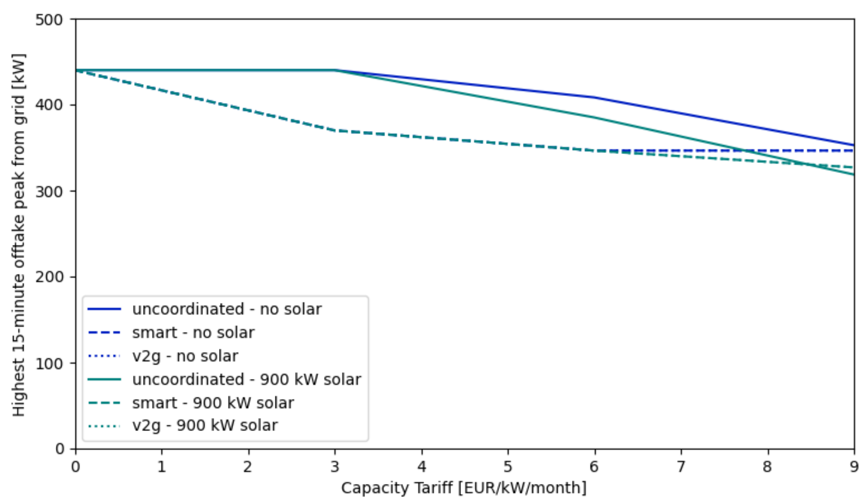

Figure 28: Highest 15-minute peak for UC2 (overnight bus charging) for a specific battery cost of 200 EUR/kWh

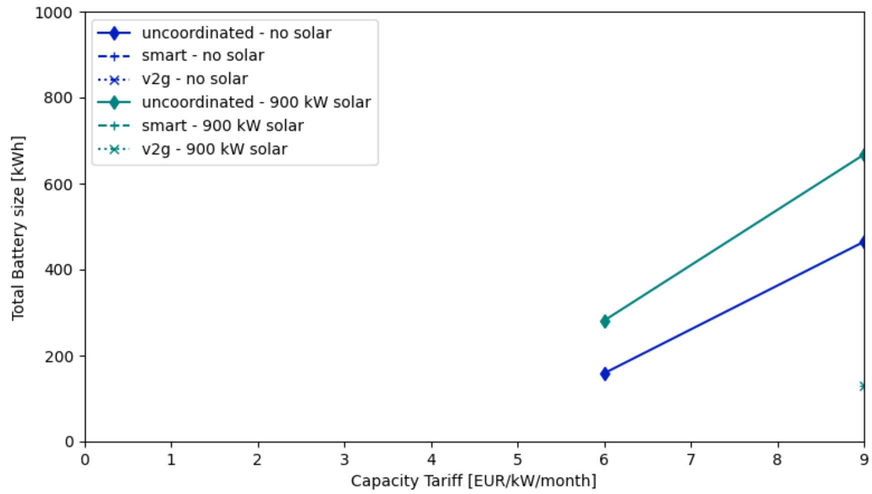

Figure 29: Optimal battery size for UC2 (overnight bus charging) for a specific battery cost of 200 EUR/kWh

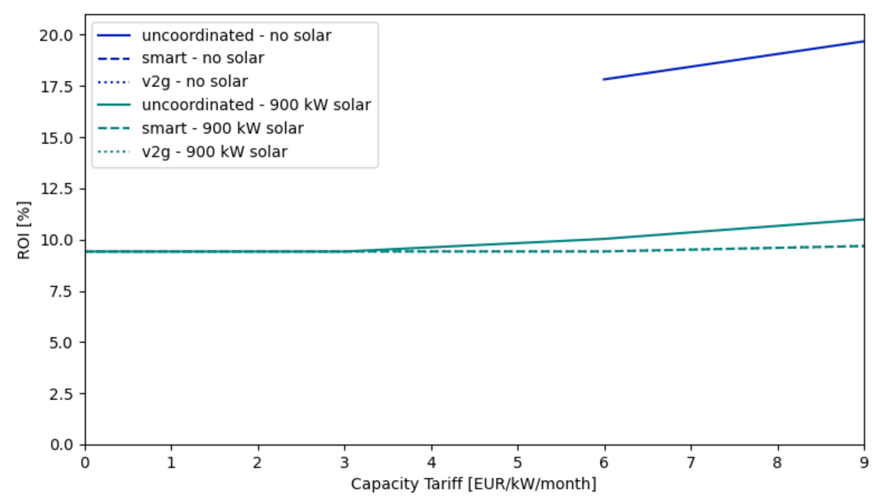

Figure 30: ROI for UC2 (overnight bus charging) for a specific battery cost of 200 EUR/kWh

In above figures (Figure 27 to Figure 30), the ‘v2g’-curves are not visible. They coincide almost completely with the ‘smart’-curves, which means that no clear benefit or change for bidirectional smart charging in comparison to unidirectional smart charging is detected for this specific use case of overnight bus charging.

Some other conclusions are:

- The presence of a solar installation has a positive impact on the yearly cost of the charging hub;
- The presence of a solar installation has a positive impact on the optimal size of the battery. However, batteries will still only be interesting at high-capacity tariffs.

- At high-capacity tariffs and using uncoordinated charging, a battery becomes economically interesting. The peak reduction achieved by the battery in this scenario is similar to the peak reduction of smart charging, as can be seen in Figure 28.

Figure 30 shows the monthly peak distribution over the year for the uncoordinated charging case and the v2g charging case, with and without a solar installation. The presence of a solar installation in the system decreases the optimal set point for peak shaving (even in winter). The impact on the peak costs is shown in Figure 32, which also shows the full cost breakdown for the different cost components for the different scenarios.

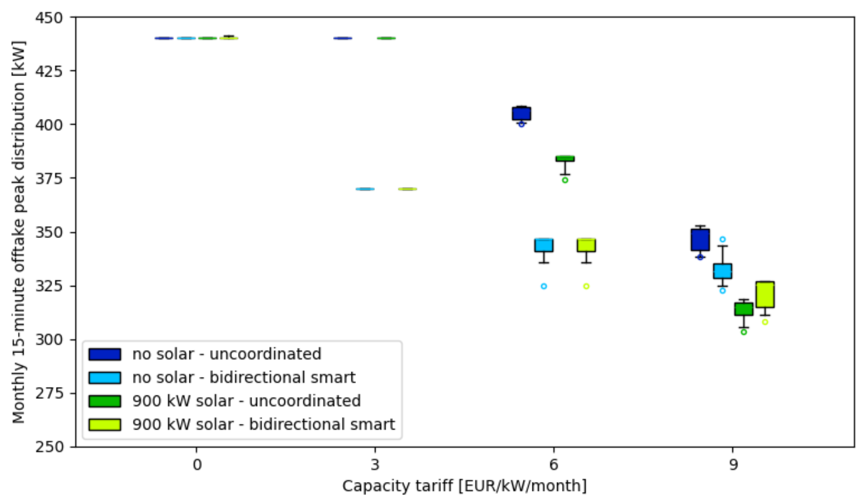

Figure 31: Boxplot 15-minute off-take peak for UC2 (overnight bus charging) for a specific battery cost of 200 EUR/kWh

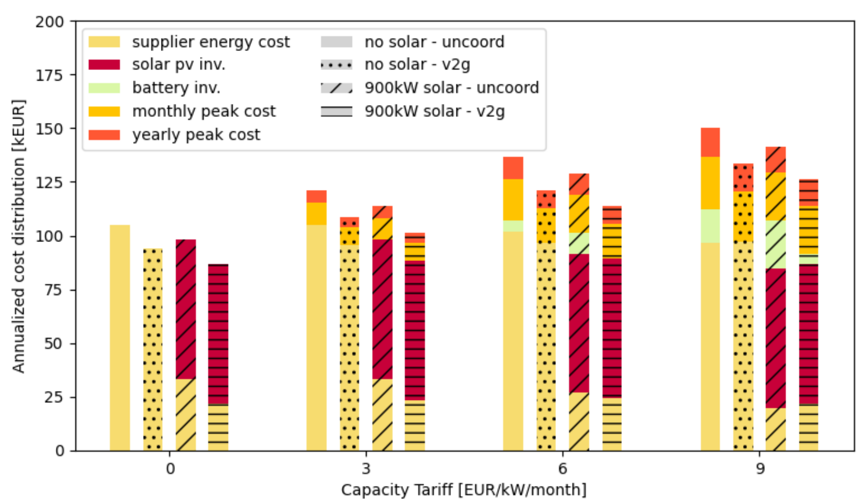

Figure 32: Annualised cost breakdown for UC2 (overnight bus charging) for a specific battery cost of 200 EUR/kWh

Conclusions of SSCH use case 2

- The investment in a battery is only profitable in cases with a medium-to-high-capacity cost in combination with very low battery prices (< 300 EUR/kWh)
- The presence of solar on site is a clear incentive for increasing the battery size. In those scenarios, the battery can be used for both storing cheap solar energy over day and reducing the offtake peak during the night.
- The presence of solar on its own, without a cost for grid capacity use, is not sufficient to justify the investment in batteries, even for a very low battery cost (of 200 EUR/kWh).
- When smart charging (with and without v2g) is implemented, a battery is never necessary unless the following conditions are fulfilled:
    - Abundant solar production on site
    - Very high-capacity costs are in place.
    - Very low battery costs (<= 200 EUR/kWh)
    - And even in this very specific case, the battery is sized rather small in comparison to the size of the solar installation and the capacity of the chargers.
- When smart charging is not implemented, a battery can be economically interesting at medium-to-high-capacity tariffs. It will then be used to reduce the offtake peak from the grid. A battery can thus be profitable, even without solar present on site, but only for a very low specific battery investment cost.

3.3 Passenger cars: fast charging

Description of SSCH use case 3

The use case is a fast-charging hub for passenger cars. Different types of cars with different maximal charging capacities and charging behaviour are considered. The charging sessions depend on the daily needs and no flexibility in charging is considered. Connected cars will always be charged at their maximal capacity for the duration of the detention time. Three utilisation rates of the fast-charging hub are considered: low arrival frequency, medium arrival frequency and high arrival frequency. Depending on the type of day and the utilization rate, the amount of charging sessions a day varies in between 1 and 18.

The simulated case represents a fast-charging station with 4 chargers. Each of the chargers has a charging capacity 150 kW. The common charging power is the sum of the separate chargers and even in the cases with the highest rate of simultaneous charging, a charging demand of 500 kW is never exceeded. The combined charging profile is simulated based on real life measured fast charging profiles.

Three different solar scenarios are included in the use case:

- No solar
- Small solar installation of 30, 60 or 90 kWp. The solar installation is sized based on the yearly consumption for respectively the low, medium and high utilization rate scenarios.

- Big solar installation of 300 kW (which is sized based on the yearly peak demand of the fast-charging hub)

This results in 9 different scenarios for use case 3, presented in Table 5.

Table 5: Overview of the scenarios investigated for use case 3 based on solar installation size and utilisation rate.

	Low freq.	Med freq.	High freq.
No solar	3A	3D	3G
30-60-90 kW	3B	3E	3H
300 kW solar	3C	3F	3I

Results of SSCH use case 3

For each of the scenarios (3A to 3I), the optimal battery size, the highest yearly peak and the corresponding annualised costs for the SSCH are calculated. Each output is calculated for a range in capacity grid costs (0-9 EUR/kW/month) and a range in battery costs (300-700 EUR/kWh) and presented in Figure 33to Figure 41 for scenario 3A to 3I respectively. The results are presented in sensitivity graphs to generate generic figures that can be used during a pre-design phase. Based on the capacity tariff and the specific battery investment cost, the estimated optimal battery size of the SSCH is calculated. This optimal size is furthermore influenced by the other parameters like energy costs, levies on energy, consumption profile, interest rates, grid expansion costs etc., which were fixed in our simulation. For this reason, the results of the simulations should mainly provide insights into whether the installation of a battery makes sense in typical use cases and the expected order of magnitude of operational and investment costs and battery size. Yet for an exact business case and sizing, a specific analysis should be made using more precise data specific to the case.

Scenario 3A: 4 fast chargers, no solar, low arrival frequency

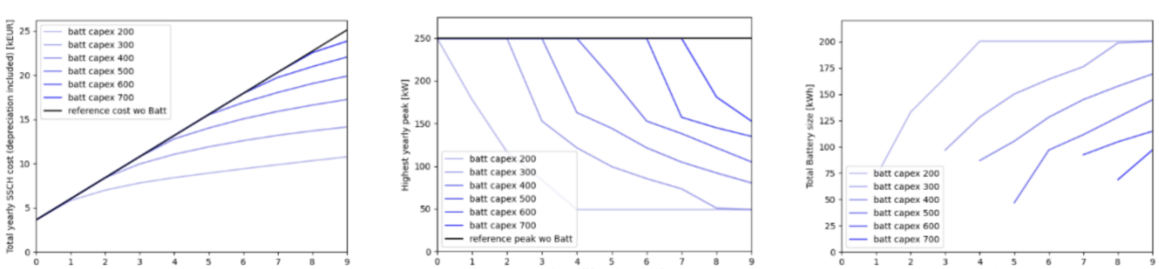

Figure 33 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 3A

Scenario 3B: 4 fast chargers, 30 kWp solar, low arrival frequency

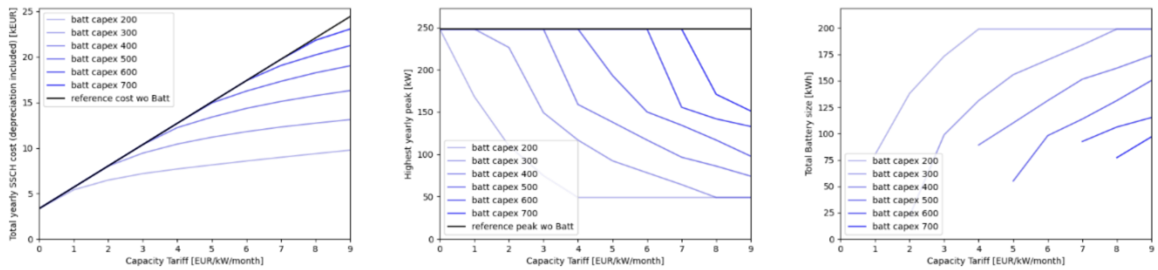

Figure 34 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 3B

Scenario 3C: 4 fast chargers, 300 kWp solar, low arrival frequency

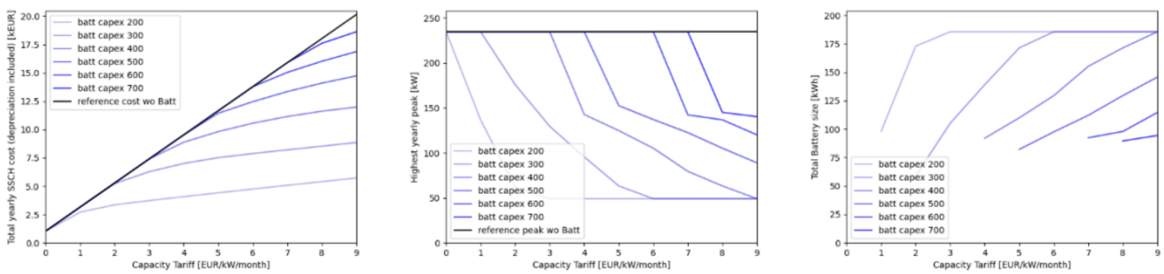

Figure 35 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 3C

Scenario 3D: 4 fast chargers, no solar, medium arrival frequency

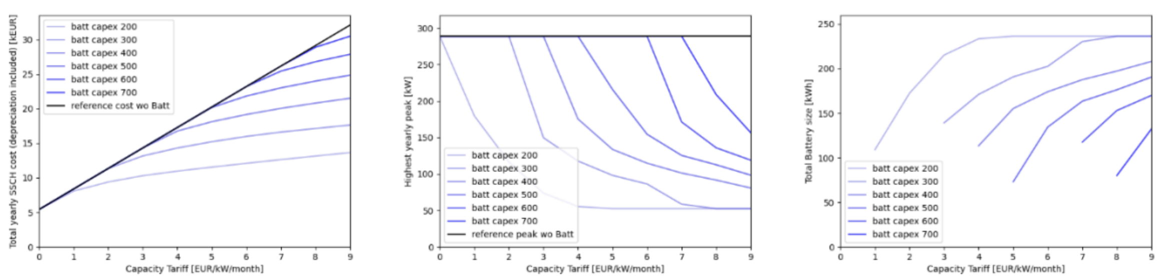

Figure 36 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 3D

Scenario 3E: 4 fast chargers, 60 kWp solar, medium arrival frequency

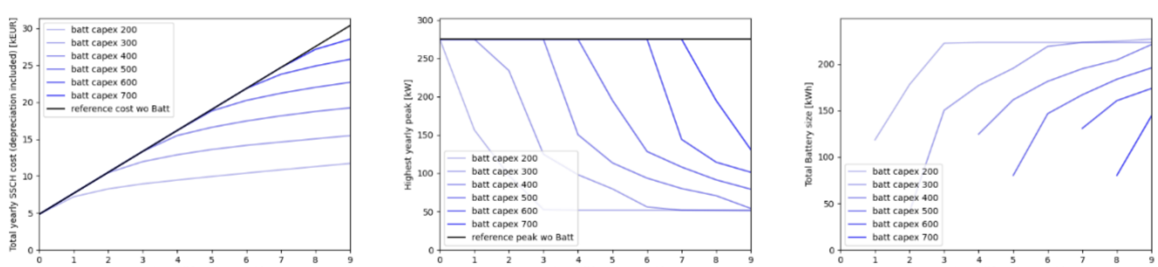

Figure 37 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 3E

Scenario 3F: 4 fast chargers, 300 kWp solar, medium arrival frequency

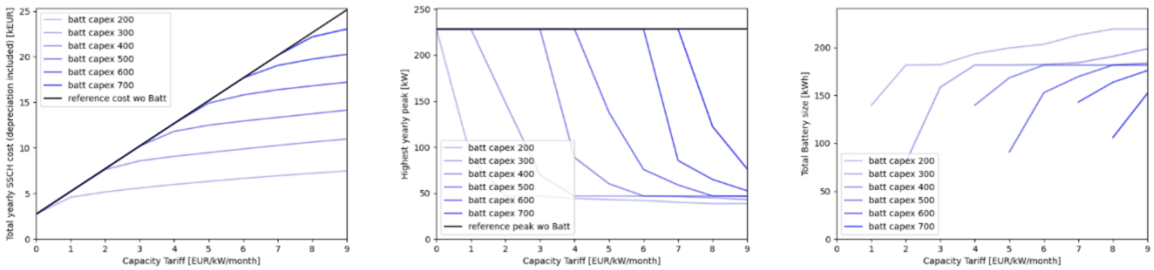

Figure 38 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 3F

Scenario 3G: 4 fast chargers, no solar, high arrival frequency

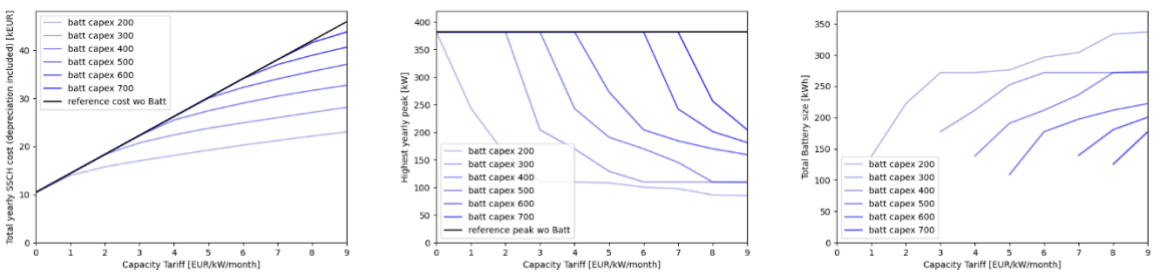

Figure 39 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 3G

Scenario 3H: 4 fast chargers, 90 kWp solar, high arrival frequency

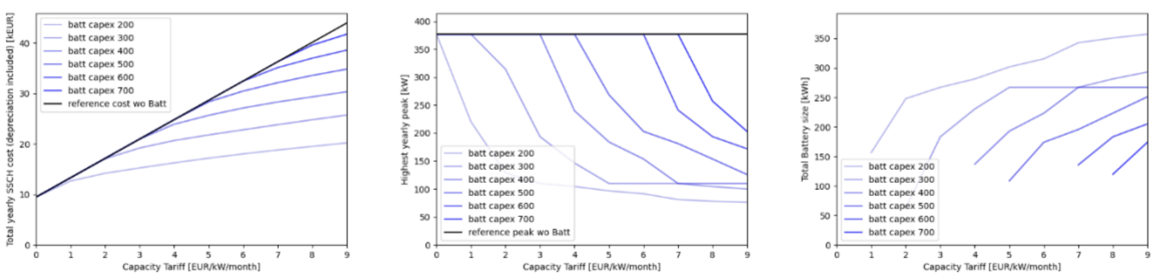

Figure 40 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 3H

Scenario 3I:. 4 fast chargers, 300 kWp solar, high arrival frequency

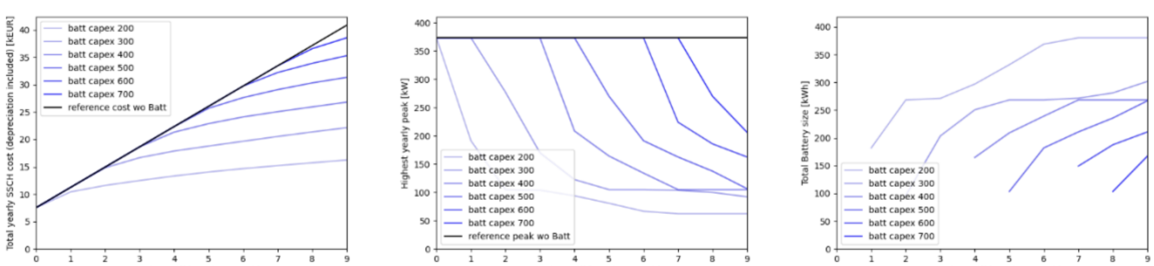

Figure 41 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 3I

Figure 33 to Figure 41 some clear trends:

- A higher capacity tariff results in a linear increase of total yearly SSCH cost, but with the installation of batteries, an inflection point appears where the cost curve saturates. With decreasing specific battery investment cost the capacity tariff at which this inflection point occurs lowers.
- A higher capacity tariff results in a smaller off-take peak. However, this happens only at the point where the installation of batteries becomes an interesting investment. This threshold changes according to the specific battery investment cost and the capacity tariff.
- A higher capacity tariff results in a bigger optimal battery size. The optimal battery size curve tends to flatten with increasing capacity tariffs.

Summary for a specific battery investment cost of 400 €/kWh

Figure 42, Figure 43, Figure 44 and Figure 47 show a comparison in between different scenarios for a fixed specific battery cost of 400 €/kWh for respectively annualised cost, yearly grid off-take peak, optimal battery size and return on investment. 400 €/kWh is chosen for illustration purposes as at this battery price, the dynamics of the battery optimization most clearly visible. However, the dynamics remain similar for a specific investment cost of batteries going up to 700 €/kWh. At higher specific battery costs, the battery will be sized smaller, the off-take peak will be reduced less and the total cost will increase slightly.

It should be noted that in this use case, the different scenarios (low-med-high) are based on different consumer needs and a different yearly energy consumption. Comparison in between scenarios (especially when evaluating total cost) should be made with real care.

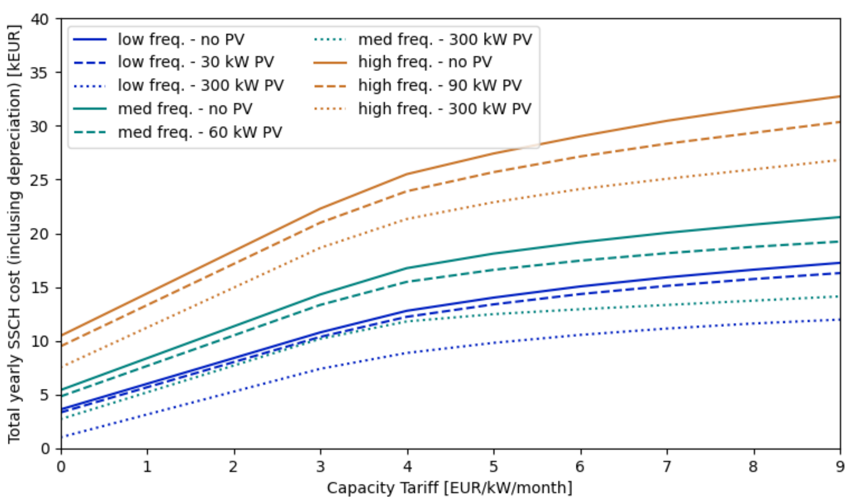

Figure 42: Total yearly costs for UC3 (fast charging passenger cars) for a specific battery cost of 400 EUR/kWh

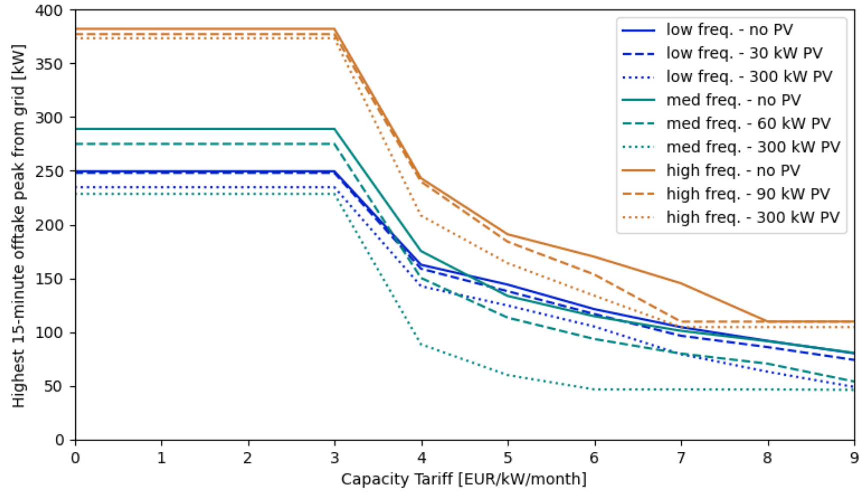

Figure 43: Highest 15-minute peak for UC3 (fast charging passenger cars) for a specific battery cost of 400 EUR/kWh

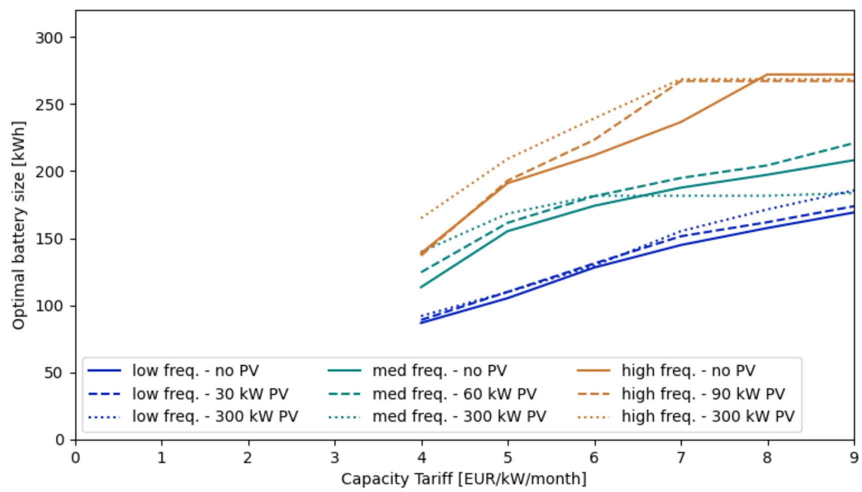

Figure 44: Optimal battery size for UC3 (fast charging passenger cars) for a specific battery cost of 400 EUR/kWh

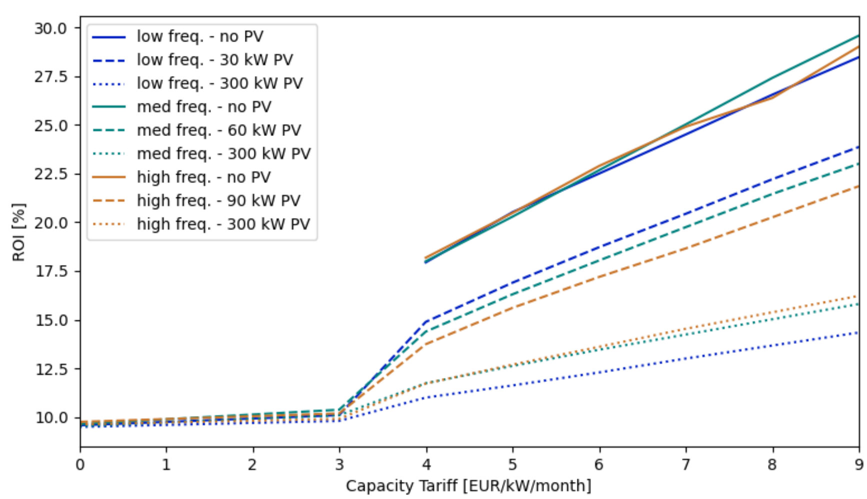

Figure 45: Return on investment (ROI) for UC3 (fast charging passenger cars) for a specific battery cost of 400 EUR/kWh

Figure 42 to Figure 45 show some clear dynamics for use case 3:

- The occupation (and total yearly electricity consumption) of the charging infrastructure increases linearly throughout the scenarios from low, medium, to high frequencies of arrivals. The optimal battery size and the yearly off-take peak do increase as well, however with a slower pace.
- Introducing a solar installation into the system reduces overall exploitation costs, but has a limited impact on the optimal battery size.
- Investments in solar installations have in all cases a positive impact on the yearly SSCH cost.
- In all scenarios where a battery is profitable, a clear grid offtake peak reduction is visible. Peak shaving is the primary business case. Secondary the battery can also be used to increase self-consumption of solar production or to make use of lower electricity prices.
- At low capacity tariffs (0-3 EUR/kW/month), which is shown on the left side of Figure 18, a battery is not profitable (and not present) for all scenarios and thus the ROI of the solar installation is visible. The ROI for these cases is always around 10%. This means that independent of the utilization rate, the investment in solar PV has a positive business case on the medium to long term.

Figure 46 shows the monthly maximal peak distribution for the scenarios from Table 5 with the solar installation size and utilisation rate equal to its upper bound (300kW, High arrival frequency) or lower bound (No Solar, Low arrival frequency) value (3A, 3C, 3G, 3I). This distribution determines the total grid cost of the scenario. The presence of abundant solar production always decreases the offtake peaks in summer and causes a higher spread of the peaks over the months. The yearly maximal offtake peak will typically also slightly decrease.

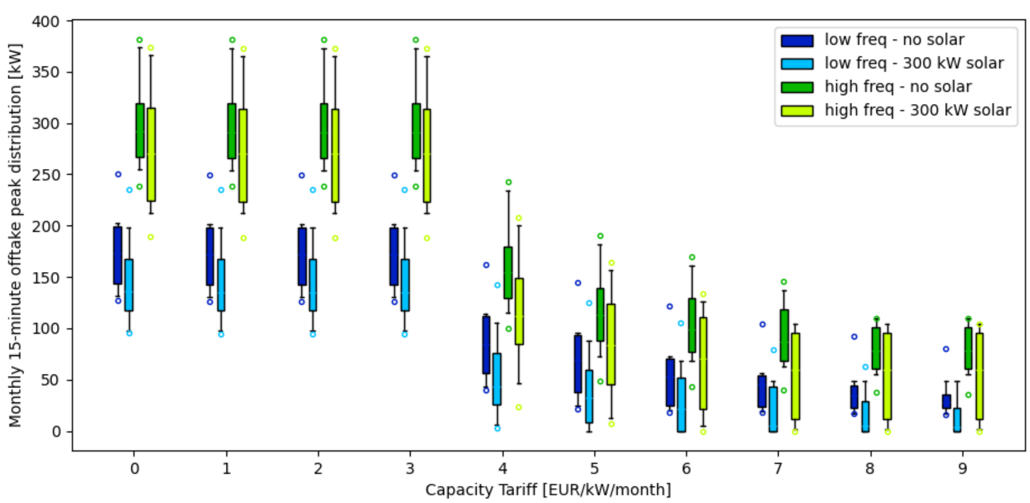

Figure 46: Boxplot 15-minute off-take peak for UC3 (fast charging passenger cars) for a specific battery cost of 400 EUR/kWh

Figure 47 shows for the same subset of scenarios (3A, 3C, 3G, 3I) how the annualised cost breakdown looks like. The annualised capex is calculated as a yearly depreciation cost based on the lifetime and the initial capex. In the scenarios with a large PV installation, the net supplier energy cost can be negative. This means that the total revenues for injecting energy into the grid are bigger than the total costs for taking energy from the grid. A second observation is that at higher capacity tariffs and in the scenarios with abundant solar production, the cost are mainly depreciation costs on investments (PV + battery) and electricity supplier costs and grid costs are only a small part of the total cost.

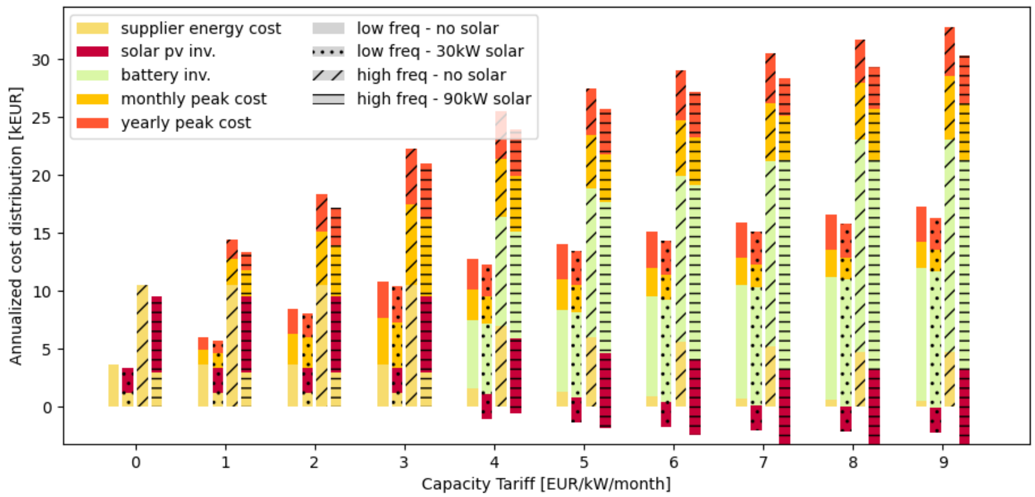

Figure 47: Annualised cost breakdown for UC3 (fast charging passenger cars) for a specific battery cost of 400 EUR/kWh

Conclusions of SSCH use case 3

- In use case 3 (fast charging hub), a battery appears to be useful for multiple realistic scenarios for low to medium battery investment costs and for medium to high-capacity tariffs.
- For each simulated grid capacity tariff, a different threshold for battery investment prices is found from which point they become profitable. The higher the grid capacity tariff is, the higher the specific battery investment cost may be.
- The presence of a solar installation has a rather low impact on the optimal sizing of the battery but has a clear impact on the total exploitation cost of the site.
- The optimal size of the battery increases with increasing the utilisation rate of the fast-charging infrastructure. However, the additional benefit of a bigger battery decreases with increasing utilisation rate.
- At a certain solar installation size threshold, the marginal benefit for increasing the size of the solar installation is small. This means that there is a notable synergy for a rather small solar installation on site with the fast-charging hub of use case 3. For example, the annualised cost reduction of installing a 60 kWp PV-installation at the fast-charging hub with the medium utilization scenario (scenario 3E compared to scenario 3B) is approximately 5000 euro. Transferring from scenario 3E to 3H and increasing the 60 kWp PV-installation to 300 kWp will only result in an additional 10000 euro cost reduction (see Figure 42). When the solar installation size is increased, a part of the solar installation will have very few interactions with the charging hub but act as a stand-alone installation with a high percentage of injection to the grid and a low ROI.

3.4 Passenger cars: day carpark

Description of SSCH use case 4:

The set-up is a day carpark with 12 electrical chargers of 11 kW each. The drivers are considered employees that arrive in the morning (at varying times) and depart in the evening (at varying times) and only in the week. They come in with different state of charges and the average charging need is 14 kWh (approximately 85 km). Not all charging points are used every day but each charger has a probability of 90% every day that an employee will connect.

Three different operational strategies are simulated:

- Uncoordinated: the vehicle starts charging at maximum power at the moment of arrival and keeps on charging at maximal charging power until the battery is full.
- Smart: the charging power is optimized, considering the economic reality (typically making use of low energy prices and keeping the grid off-take peak as low as possible). The charging power is unidirectional from grid/battery to vehicle.
- V2G: similar as the smart charging case, but bidirectional. This means that the vehicle can also be discharged, and the power flow can also go from vehicle to grid/battery.

For each operational strategy a case is simulated with and without solar. The ideal solar installation is selected based on the yearly energy consumption (which is around 50 MWh).

Table 6: Overview of the scenarios investigated for use case 4 based on solar installation size and charging operation.

	Uncoordinated	Smart	V2G
No solar	4A	4B	4C
50 kW	4D	4E	4F

Results of SSCH use case 4

For each of the scenarios (4A to 4F), the optimal battery size, the highest yearly peak and the corresponding annualised costs for the SSCH are calculated. Each output is calculated for a range in capacity grid costs (0-9 EUR/kW/month) and a range in battery costs (200-600 EUR/kWh) and presented in Figure 48 to Figure 53 for scenario 4A to 4F respectively. The results are presented in sensitivity graphs to generate generic figures that can be used during a pre-design phase. Based on the capacity tariff and the simulated specific battery investment cost, the estimated optimal battery size of the SSCH is calculated. This optimal size is furthermore influenced by the other parameters like energy costs, levies on energy, consumption profile, interest rates, grid expansion costs etc., which were fixed in our simulation. For this reason, the results of the simulations should mainly provide insights into whether the installation of a battery makes sense in typical use cases and the expected order of magnitude of operational and investment costs and battery size. Yet for an exact business case and sizing, a specific analysis should be made using more precise data specific to the case.

Scenario 4A: 12 chargers, no solar, uncoordinated charging

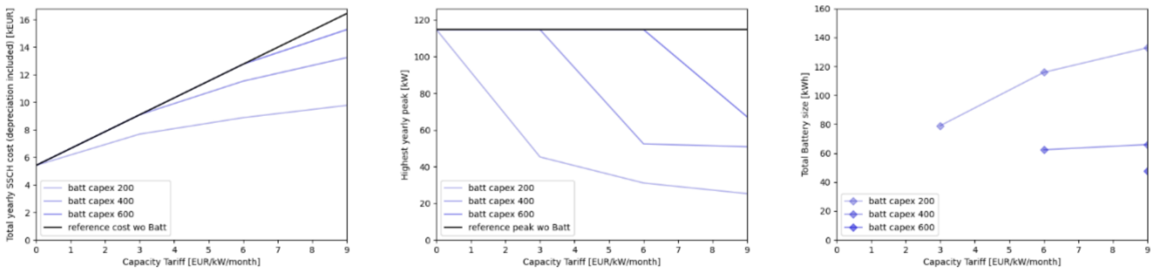

Figure 48 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 4A

Scenario 4B: 12 chargers, no solar, unidirectional smart charging

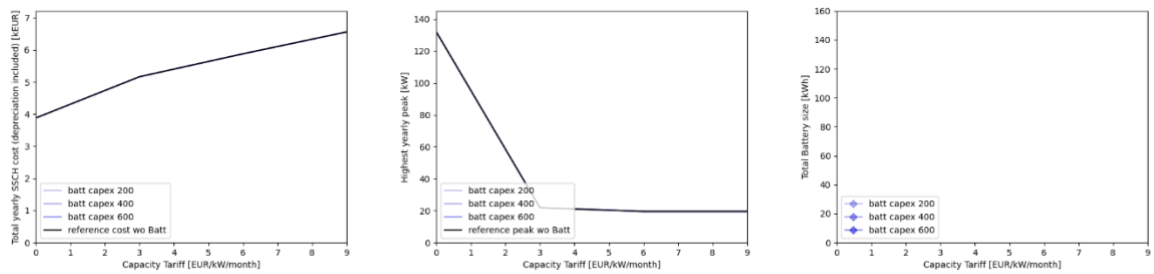

Figure 49 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 4B

Scenario 4C: 12 chargers, no solar, bidirectional (v2g) smart charging

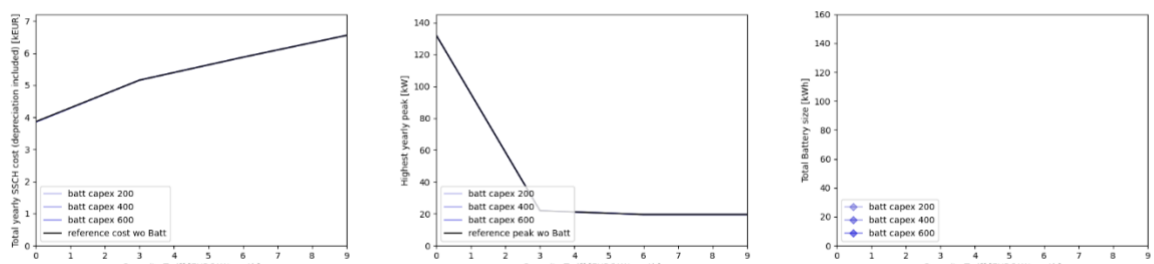

Figure 50 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 4C

Scenario 4D: 12 chargers, 50 kW solar, uncoordinated charging

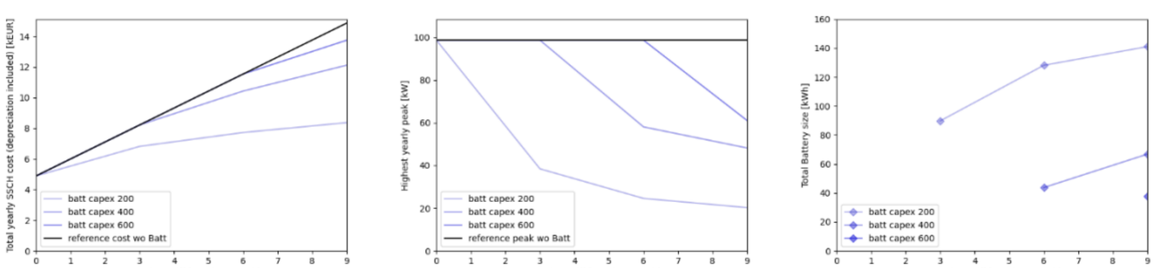

Figure 51 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 4D

Scenario 4E: 12 chargers, 50 kW solar, unidirectional smart charging

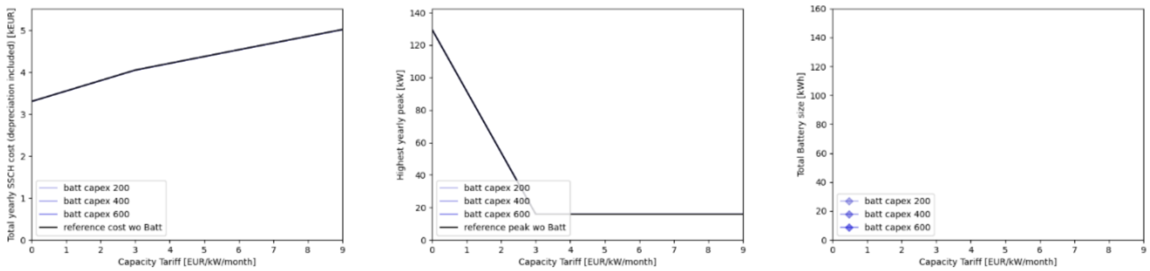

Figure 52 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 4E

Scenario 4F: 12 chargers, 50 kW solar, bidirectional (v2g) smart charging

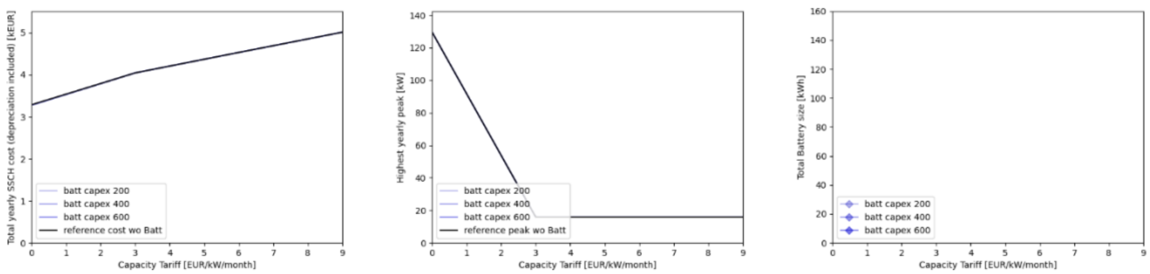

Figure 53 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 4F

Figure 48 to Figure 53 show some clear trends:

- A higher capacity tariff results always in a higher yearly cost.
- A higher capacity tariff results in a smaller off-take peak.
- Batteries are typically not an interesting investment in this use case unless:
    - There is no possibility for smart charging (uncoordinated charging)
    - Battery investment prices are on the low end, and
    - The capacity tariffs are on the high-end.
- The presence of a solar PV installation has a very small but positive impact on the profitability of a battery.
- Batteries will not be installed when (unidirectional or bidirectional) smart charging is implemented.
- Even without a capacity tariff (0-point on the x-axis of Figure 48 to Figure 53), smart charging leads to lower costs. This means that due to the dynamic electricity off-take contract, load balancing is always an interesting operational strategy

Summary analysis for a specific battery investment cost of 400 €/kWh

Figure 54, Figure 55 and Figure 56 show a comparison in between different scenarios for a fixed specific battery cost of 400 EUR/kWh for respectively optimal battery size, annualised cost and yearly grid off-take peak. At a specific investment cost of 400 EUR/kWh, most of the scenarios will not incorporate a battery in their optimal design. For this reason, a very low specific battery investment cost of 200 EUR/kWh is also simulated to be able to analyse the energy system dynamics. These results are added to Appendix III for reference.

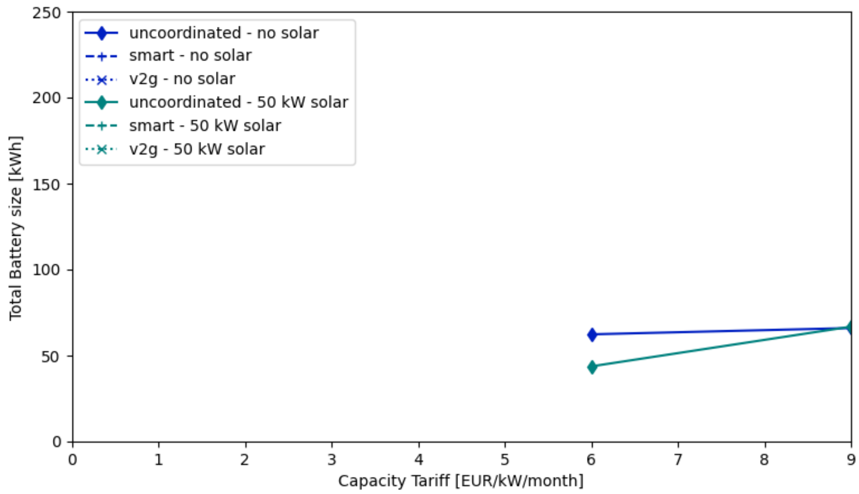

Figure 54: Optimal battery size for UC4 (over day passenger cars) for a specific battery cost of 400 EUR/kWh

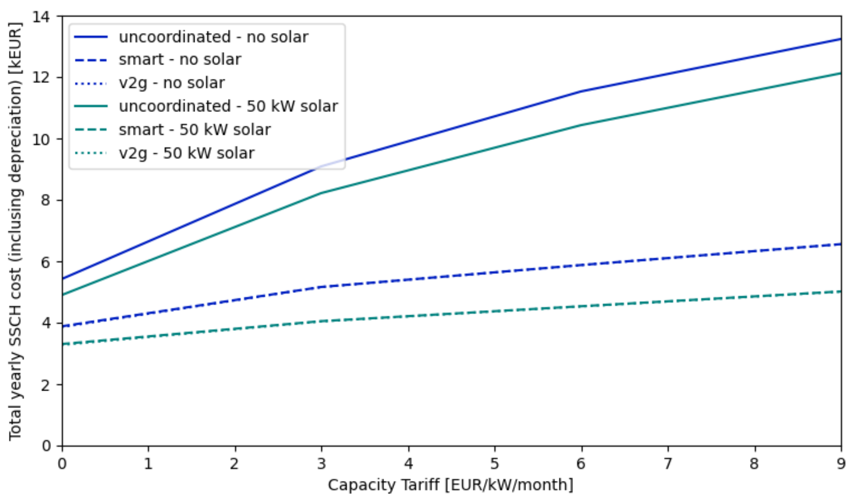

Figure 55: annualised yearly cost for UC4 (over day passenger cars) for a specific battery cost of 400 EUR/kWh

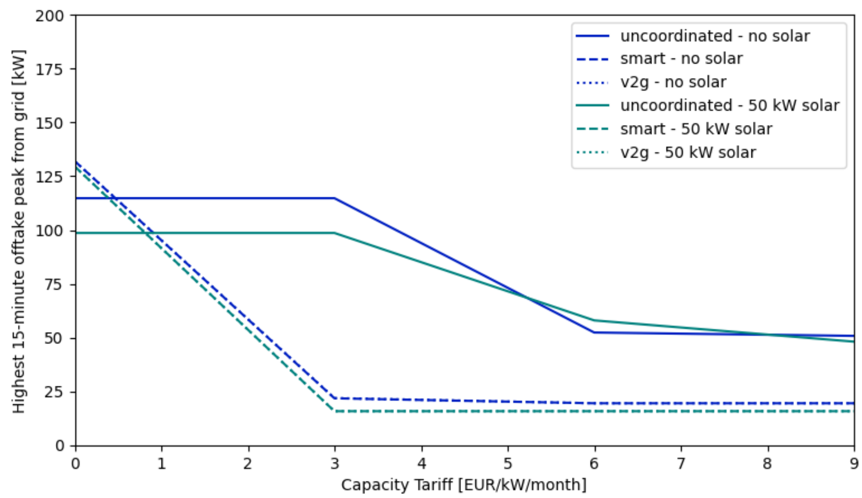

Figure 56: maximal yearly peak for UC4 (over day passenger cars) for a specific battery cost of 400 EUR/kWh

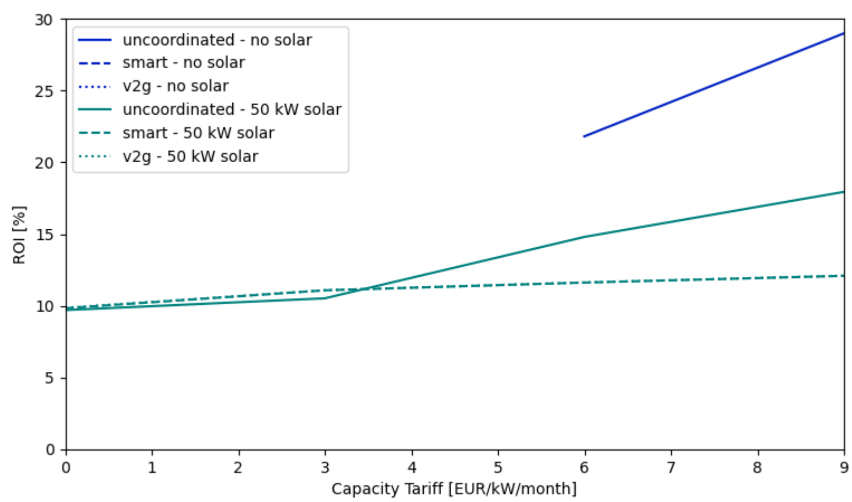

Figure 57: Return on investment for UC4 (over day passenger cars) for a specific battery cost of 400 EUR/kWh

In Figure 54 to Figure 57, the 'v2g'-curves are not visible. They coincide almost completely with the 'smart'-curves, which means that no clear benefit or difference for bidirectional smart charging in comparison to unidirectional smart charging is detected for this specific set-up of over day passenger car charging.

Some other conclusions are:

- The presence of a solar installation has a positive impact on the yearly cost of the charging hub.
- Smart charging (unidirectional or bidirectional) has a very big impact on the total annual costs. Total costs can be reduced by more than 50% when capacity tariffs are high. Even for low-capacity tariffs, the economic benefits are substantial. See Figure 55.

- The presence of a solar installation has a small negative impact on the optimal size of the battery. However, batteries will still only be profitable at high-capacity tariffs.
- At high-capacity tariffs and uncoordinated charging, a battery becomes interesting. The peak reduction potential in this scenario realised by installing the battery is smaller than the peak reduction achieved when smart charging.

Figure 58 shows the monthly peak distribution over the year for the uncoordinated charging scenario and the v2g charging scenario, with and without solar. The presence of solar in the system lowers the optimal set point for peak shaving (even in winter) slightly. Smart charging however, has a clear impact on the monthly grid off-take peaks. The financial impact of these grid off-take peaks is shown in Figure 59 which shows the annualised cost breakdown. The annualised investment cost for solar installations and new batteries is calculated as a yearly depreciation cost based on the lifetime and the initial capex.

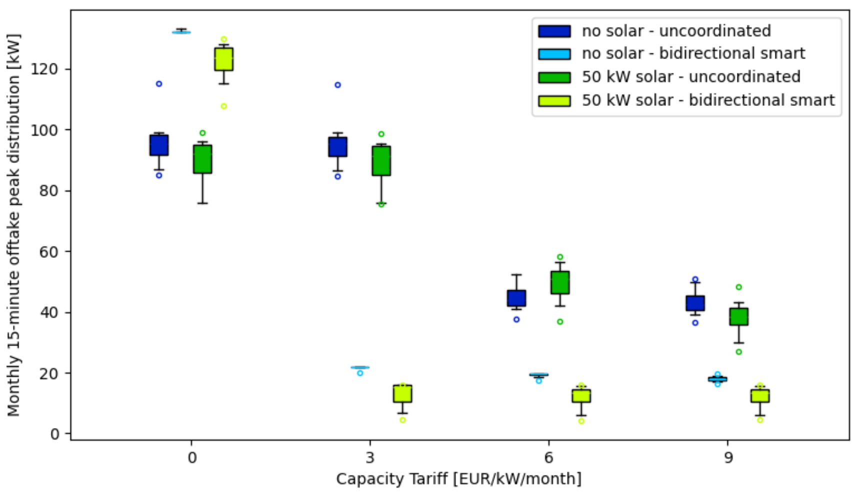

Figure 58: boxplot with monthly peak distribution UC4 (over day passenger cars) for a specific battery cost of 400 EUR/kWh

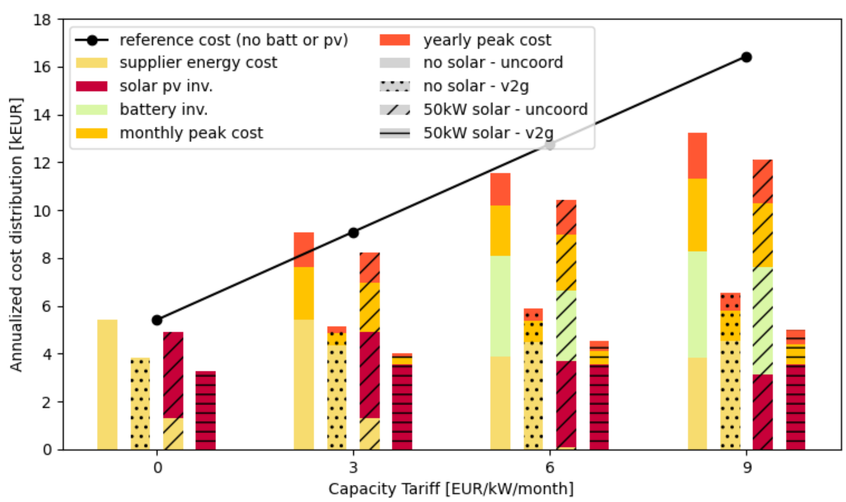

Figure 59: cost breakdown for UC4 (over day passenger cars) for a specific battery cost of 400 EUR/kWh

Conclusions of SSCH use case 4

- A typical day parking does not meet the requirements to be an interesting case for battery investments. Only for very low battery prices (200 €/kWh), medium to high grid capacity use tariffs and absolutely no coordination in charging behaviour, a battery can become profitable.
- Investment in a solar installation results in a total cost reduction in all simulated scenarios.
- Unidirectional smart charging results in a very large reduction of off-take peaks and a clear operational cost reduction, with or without solar production on site .
- Bidirectional smart charging (v2g) has a very limited impact on top of the benefits of unidirectional smart charging. This means that for this use case unidirectional smart charging delivers already the required flexibility to minimize operational costs.
- The optimal monthly or yearly peak is a balance in between flexibility towards the energy market to reduce energy costs and minimizing the off-take peak to reduce the grid capacity use costs.
- The presence of a small solar installation has a clear impact on the grid off-take peaks in summer (as the cars are charged during the time of solar production) and a small impact on the grid off-take peaks in winter.

3.5 Combined high potential cases

Description of SSCH use case 5

Use case 5 is a combination of a slow charging parking (UC4) and a charging station for a ferry that is sailing on a predefined planned schedule (UC1). The parking lot is equipped with 11 chargers with each a (dis)charging power limit of 22 kW. The ferry that charges at the SSCH is comparable in behaviour as the ferry of UC1 but is scaled down with a factor 4 and only simulated for a 15-minute detention time for a total round-trip time of 1 hour. The ferry sails from 8 a.m to 19 p.m (11 charging sessions per day), every day of the year.

Two different behaviour regimes are implemented for the car users: a day parking regime and a night parking regime. The day parking regime has a very high probability that multiple cars are connected to the SSCH when the ferry is charging and sailing. The night parking regime has a very high probability that the charging needs of the cars will never coincide with the charging needs of the ferry.

Three different operational strategies are simulated for the car charging infrastructure:

- Uncoordinated: the vehicle starts charging at maximum power at the moment of arrival and keeps on charging at maximal charging power until the battery is full.
- Smart: the charging power is optimized, considering the economic reality (typically making use of low energy prices and keeping the grid off-take peak as low as possible). The charging power is unidirectional from grid/battery to vehicle.
- V2G: similar as the smart charging case, but bidirectional. This means that the vehicle can also be discharged, and the power flow can also go from vehicle to grid/battery.

The ferry will always charge on demand and no flexibility or different charging strategies are foreseen. Table 7 presents the scenarios for use case 5.

Table 7: Overview of the scenarios investigated for use case 5 based on parking type and charging operation.

	Uncoordinated	Smart	V2G
Over day parking	5A	5B	5C
Overnight parking	5D	5E	5F

Results of SSCH use case 5

For each of the scenario set-ups (5A to 5F), the optimal battery size, the highest yearly peak and the corresponding annualised costs for the SSCH are calculated. Each output is calculated for a range in capacity grid costs (3-9 EUR/kW/month) and a range in battery costs (200-500 EUR/kWh) and presented in Figure 60 to Figure 71 for scenario 5A to 5F respectively. The results are presented in sensitivity graphs to generate generic figures that can be used during a pre-design phase. Based on the capacity tariff and the simulated specific battery investment cost, the optimal battery size of the SSCH is calculated. This optimal size is furthermore influenced by the other parameters like energy costs, levies on energy, consumption profile, interest rates, grid expansion costs etc., which were fixed in our simulation. For this reason, the results of the simulations should mainly provide insights into whether the installation of a battery makes sense in typical use cases and the expected order of magnitude of operational and investment costs and battery size. Yet for an exact business case and sizing, a specific analysis should be made using more precise data specific to the case.

In order to highlight the benefit of combining the use cases into a charging hub. Scenarios in Table 7 will also be calculated as the parking lot and the ferry are connected separately to the grid as a reference. Each of the scenarios in Table 7 has a reference scenario where the costs, yearly peak and optimal battery sizes are the sum of the ones from a ferry charging and a car parking as if they were optimized and operated as a stand-alone. the cost, yearly peak and optimal battery size in these reference scenarios are the sum of respectively the cost, the yearly peak and the optimal battery size of the ferry charging hub and the EV charging hub when optimized and operated as a stand-alone.

Over day car parking and ferry combined in one charging hub

Scenario 5A: Over day uncoordinated charging of cars, 104 kWh/round trip ferry charging

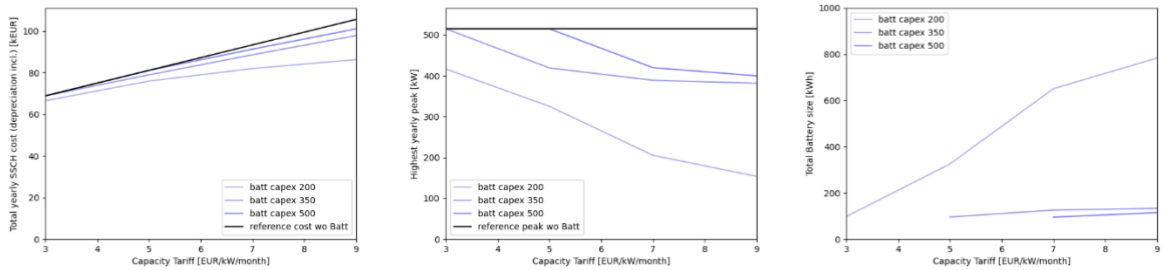

Figure 60 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 5A

Scenario 5B: Over day smart charging of cars, 104 kWh/round trip ferry charging

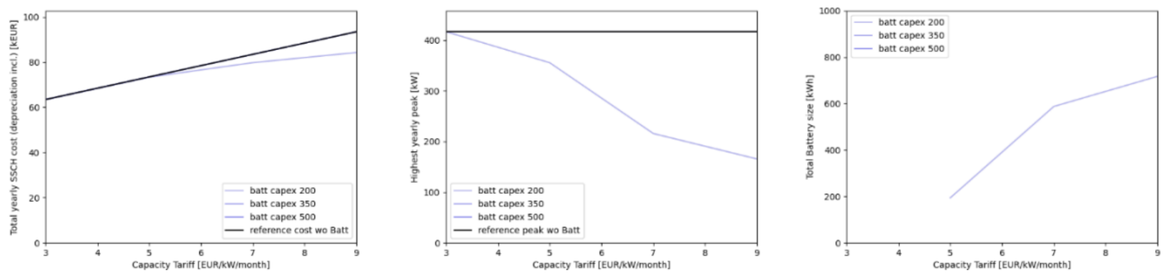

Figure 61 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 5B

Scenario 5C: Over day v2g charging of cars, 104 kWh/round trip ferry charging

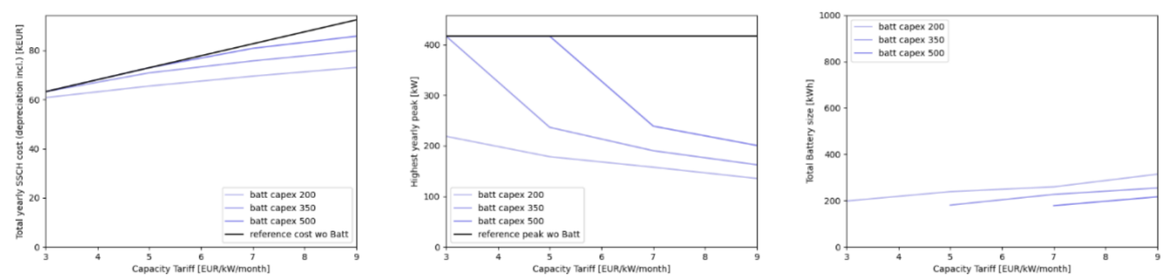

Figure 62 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 5C

Over day car parking hub separated from ferry charging hub

Scenario 5Aref. Over day uncoordinated charging of cars, 104 kWh/round trip ferry charging (at separate locations)

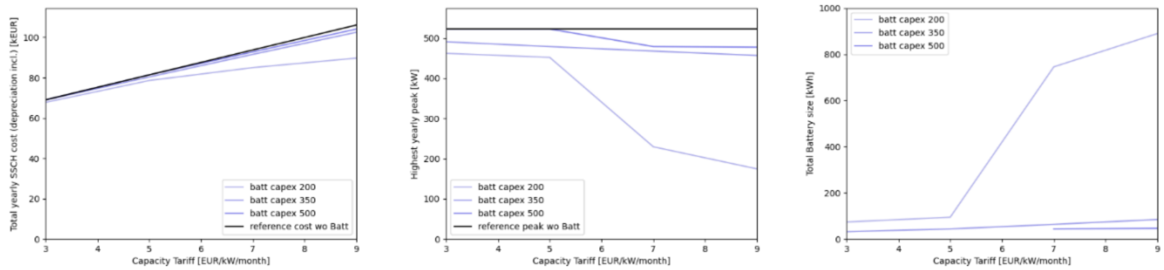

Figure 63 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 5Aref

Scenario 5Bref. Over day smart charging of cars, 104 kWh/round trip ferry charging (at separate locations)

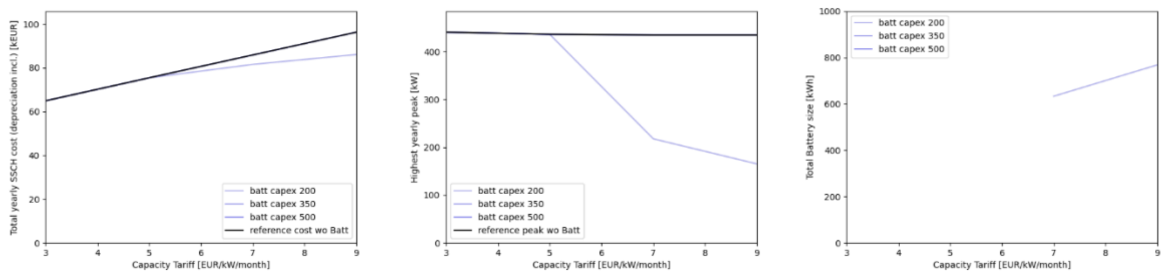

Figure 64 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 5Bref

Scenario 5Cref: Over day v2g charging of cars, 104 kWh/round trip ferry charging (at separate locations)

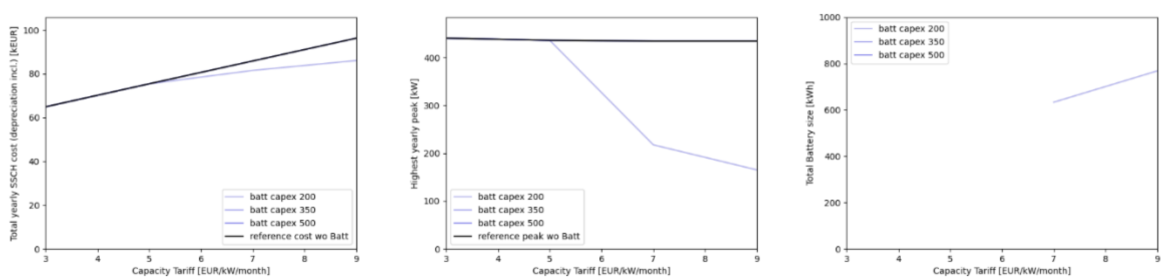

Figure 65 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 5Cref

Figure 60 to Figure 65 show the sensitivity graphs of a charging behaviour of day car charging combined with a ferry sailing and charging on a fixed schedule during the day. The combined charging hub (Figure 60-Figure 62) and the separate charging hubs (Figure 63-Figure 65) have a different behaviour. The behaviour of the separate charging hubs is, as expected, similar to the combined behaviour of use case 1 and use case 4. The combined charging hub, however, shows some specific dynamics:

- The smart charging case (Figure 61) and the v2g case (Figure 62) show a complete different behaviour:
    - In the v2g case, a high peak reduction is achieved for small battery sizes

  - Even for high battery prices, a (small) battery remains interesting, which means there is a high compatibility in between the v2g charged cars, a small battery and the ferry charging.
- In the separated case, a battery becomes only interesting for very low battery prices. When both consumers are combined in one charging hub, a battery is interesting for higher battery prices. The impact of a battery (concerning peak reduction and cost reduction) is bigger as well in the combined charging hub set-up.
- Typical behaviour of decreasing offtake peak, increasing price and increasing battery size for increasing capacity tariff is still present in this use case.

Overnight parking and ferry combined in one grid connection and one charging hub

Scenario 5D: overnight uncoord. charging of cars, 104 kWh/rnd trip over day ferry charging

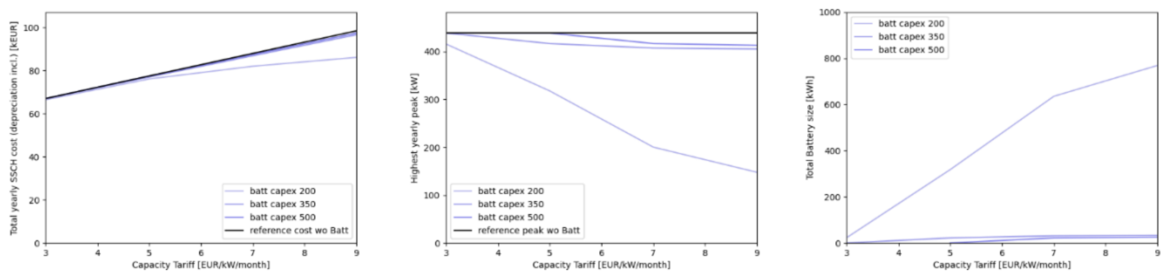

Figure 66 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 5D

Scenario 5E: overnight smart charging of cars, 104 kWh/round trip over day ferry charging

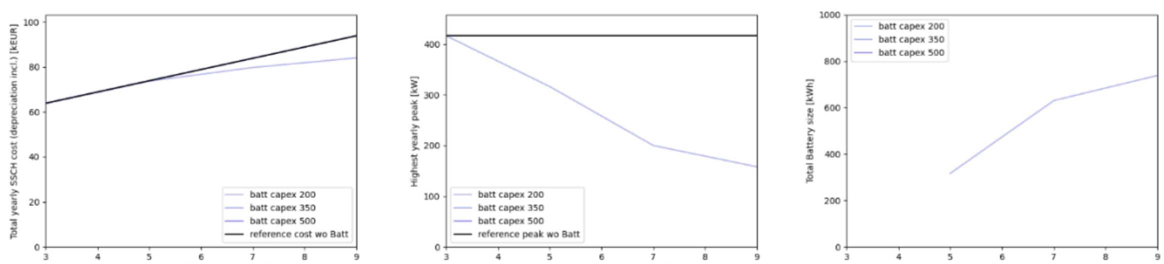

Figure 67 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 5E

Scenario 5F: overnight v2g charging of cars, 104 kWh/round trip over day ferry charging

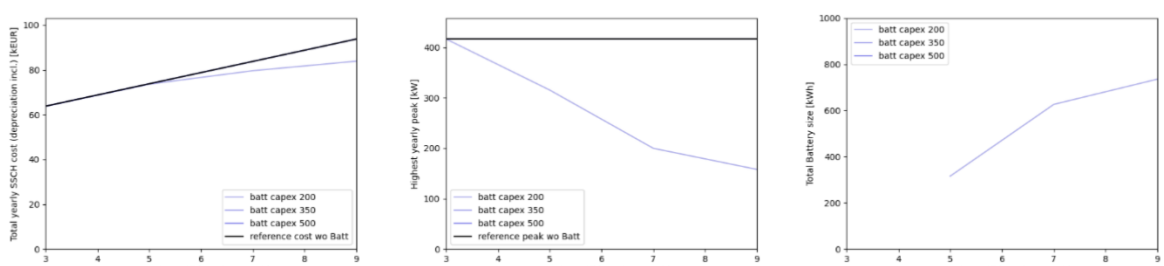

Figure 68 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 5F

Overnight parking hub separated from ferry charging hub

Scenario 5Dref: overnight uncoordinated charging of cars, 104 kWh/round trip over day ferry charging (at separate locations)

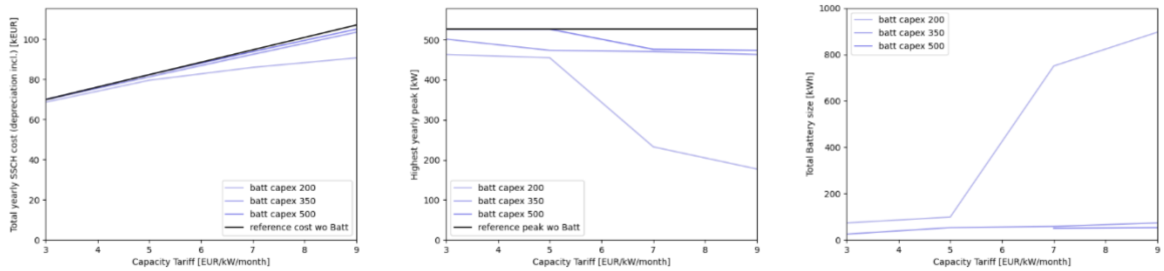

Figure 69 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 5Dref

Scenario 5Eref: overnight smart charging of cars, 104 kWh/rnd trip over day ferry charging (at separate locations)

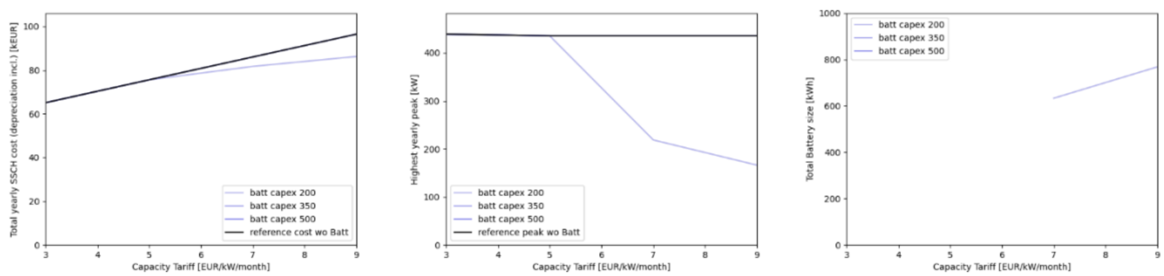

Figure 70 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 5Eref

Scenario 5Fref: overnight v2g charging of cars, 104 kWh/round trip over day ferry charging (at separate locations)

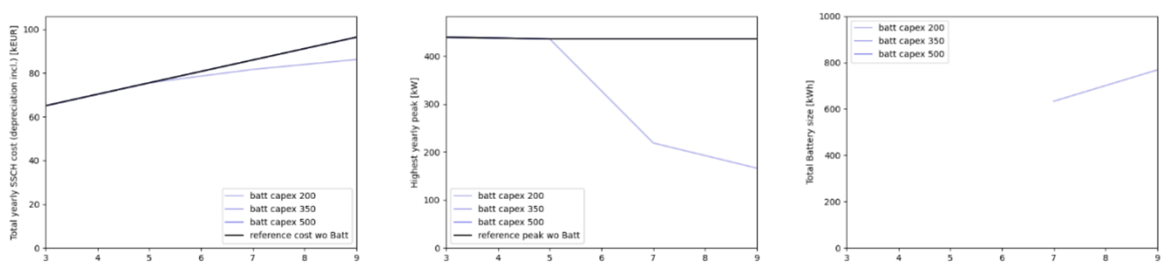

Figure 71 Sensitivity graphs of Total yearly cost (left), Highest yearly peak (middle) and battery size (right) for different battery CAPEX in function of the capacity tariff for Scenario 5*Fref*

Figure 66 to Figure 71 show the sensitivity graphs of a charging behaviour of overnight car charging combined with a ferry sailing and charging on a fixed schedule over day. The optimal design behaviour of these overnight car charging set-up is different from the over day car charging set-up.

- The smart charging case and the v2g charging case show similar behaviour, even in the combined charging hub case. This means that the advantages of combining a v2g charging parking lot with a ferry disappears completely when the cars are not present at the right time.
- For all scenarios with overnight charging, cost and peak reductions become less visible and also in fewer cases a battery is a logical investment, compared to the scenarios with over day car charging.
- Typical behaviour of decreasing offtake peak, increasing price and increasing battery size for increasing capacity tariff is still present in this use case.

Summary analysis for a specific battery investment cost of 500 €/kWh

Figure 72, Figure 73 and Figure 74 show the comparison in between all different scenarios for a fixed specific battery cost of 500 EUR/kWh for respectively annualised cost, yearly grid off-take peak and optimal battery size. These graphs allow a more in-depth comparison in between the scenarios, as all scenarios can be compared directly.

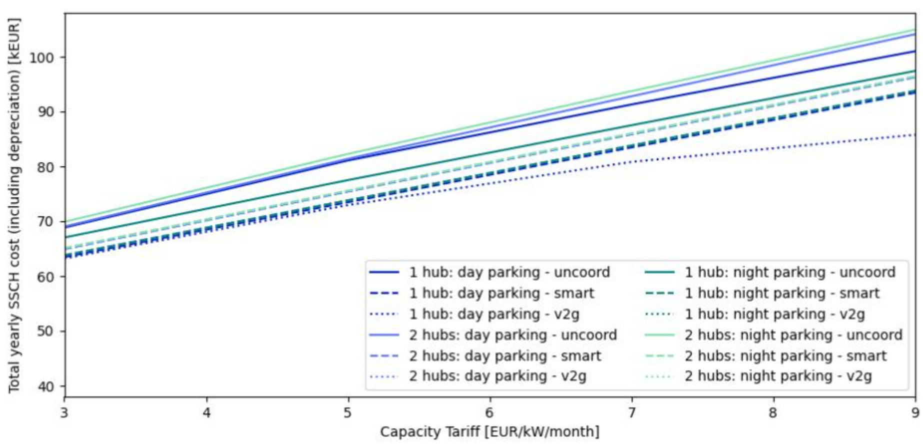

Figure 72: Total annualised SSCH cost for the charging hubs with an optimal battery size at a specific battery cost of 500 €/kWh.

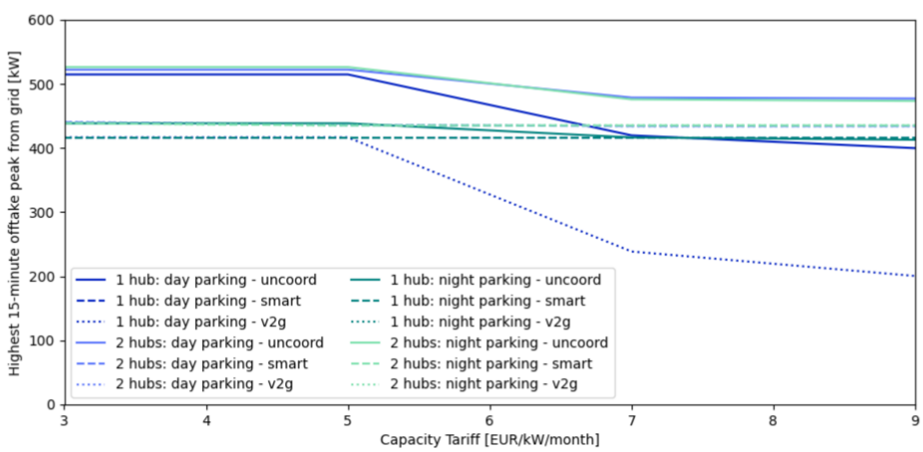

Figure 73: Total yearly SSCH peak for the charging hubs with an optimal battery at a specific battery cost of 500 €/kWh.

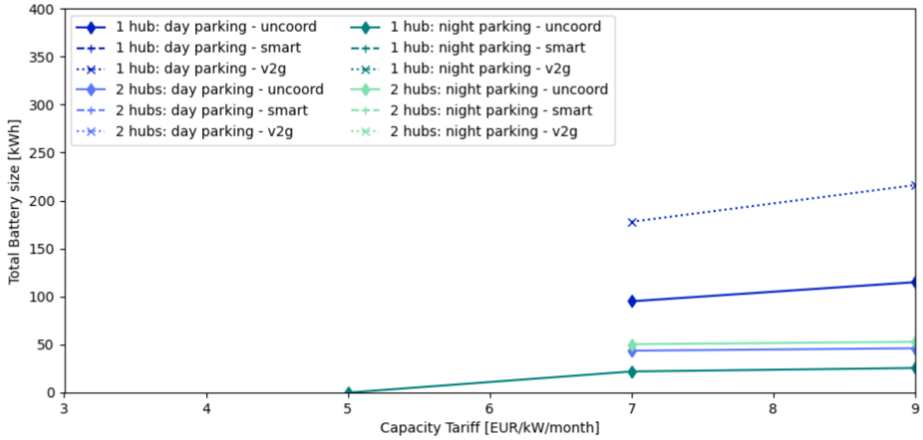

Figure 74: Total optimal battery size for the charging hubs at a specific battery cost of 500 €/kWh

Conclusions of SSCH use case 5

- Stacking the charging needs for the car parking and the small ferry in one charging hub is always cost effective compared to separating the charging needs in two charging hubs. . However, in the scenario of a day parking with uncoordinated charging, with high battery investment costs and a low-capacity tariff, the economic benefit will be very small or even non-existent. This is shown in figure 72 when comparing '1 hub: day parking – uncoord' with '2 hub: day parking – uncoord' for low-capacity tariffs (left side of the figure).
- When the yearly charging demand (energy volume) is equal for day parking and night parking, the total costs are similar.
- Without flexibility (battery or smart charging), overnight charging of passenger cars combined with over day ferry charging makes better use of the available grid capacity in comparison with over day passenger car charging, where the demand of vehicle charging coincides with the demand for ferry charging. This results in a lower yearly peak and a lower combined cost for the exact same energy needs for the overnight park compared to the day park, as can be clearly seen in Figure 72 and Figure 73, when comparing '1 hub: day parking – uncoord' and '1 hub: night parking – uncoord' for low capacity tariffs (left sides of the figures.
- Implementing smart charging at the car parking has the potential to decrease the grid off-take peak down to the charging power of the ferry. This means that the cars will only be charged at the time slots when the ferry is not charging.
- When smart charging is implemented, yearly costs, optimal battery sizes and grid offtake peaks are similar for the ferry combined with a night parking and combined with a day parking. This is shown in Figure 72, Figure 73 and Figure 74 when comparing scenario '1 hub: night parking – smart' and scenario '1 hub: day parking – smart'.
- When bidirectional smart charging (v2g) is implemented for the passenger cars, the operational costs could be extremely reduced when the ferry is combined with the day car parking. In other words, with bidirectional charging, a coinciding presence of the cars and the ferry is extremely beneficial in terms of operational costs of a combined charging

hub. This cost saving potential is big enough to justify installing a bigger battery (even for higher specific battery investment costs) to cover for the stochastic reality of not having cars present at all times the ferry needs to charge.

General conclusions

The work in this report provides insights into the possible impact and the business case of installing batteries in different SSCH set-ups (use case 1-5) with and without the presence of on-site renewable energy production. It should be noted that despite some general guidelines and trends can be constructed from the results of the simulations performed in this study, the results are always dependent on the inputs and parameters used for the scenarios and model. To allow for some generalization, this study has defined several different use cases (type of vehicle, type of charging) and scenarios (sizes of solar production, schedules, …). All scenarios are simulated for a range of specific battery costs and grid costs.
However, stochasticity in weather patterns, different energy offtake contracts and future energy price scenarios are not part of the research conducted in this report. Therefore, the results of this study can be seen to understand general tendencies but should not serve as exact numbers for the design of charging hubs. Any design of a charging hub will be specific to the use case and will require selecting the right input and calibrating the model parameters.

Another important remark is that in all calculations the grid connection cost (which is typically very location and connection size dependent), the investment in charger infrastructure and the renumeration system (revenue created by selling charging sessions) are not part of the optimization. The analysis in this report focusses on the second order design and operational choices and succeeds to give answers to the following questions:

- Can the investment in batteries reduce my total exploitation costs?
- How big will my ideal battery be for a typical charging hub set-up?
- What is the impact of the capacity tariff and the battery investment cost on the optimal battery size and the exploitation cost of my charging hub?
- Can the investment in solar production capacity reduce my total exploitation costs, and what is the impact of the presence of a solar installation on my optimal battery size?
- What is the impact of implementing smart charging strategies in my system on my total exploitation costs without changing the consumer behaviour.
- What type of consumer synergies should I look into when trying to optimize the use of my charging hub?

Figure 75 gives the overview of the use-cases analysed in this study. Use case 5 is a combination of use case 1 and use case 4. Based on these categories some generic trends are listed below as conclusions.

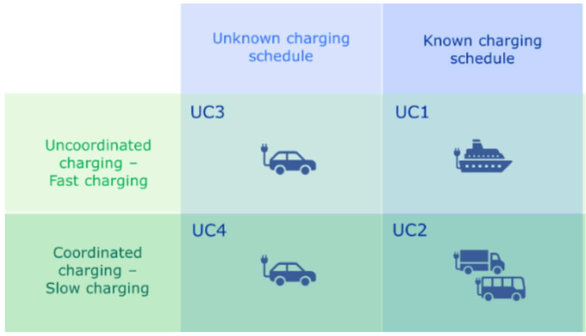

Figure 75: Use case categorisation

1. Batteries appear typically not to be profitable in both use case 2 (overnight charging of buses) and use case 4 (day parking for passenger cars). Unidirectional smart charging has a major impact on the off-take profile, off-take peaks and grid capacity use costs. Even for low grid capacity tariffs, the peak load is typically directly fully reduced to the same level as for high-capacity tariffs. This is due to the fact that there is no investment cost involved. Smart charging is in these use cases very relevant and efficient. Making the smart charging bidirectional (v2g), does not have an additional observable positive impact on the operational costs. Also, for this type of slow-charging cases , the installation of stationary batteries is usually redundant.

2. Batteries are clearly an interesting investment for UC3 and UC1, especially when the peaks are short, predictable and well spread out.

   a. For ferries: the shorter the detention time in comparison with the sailing time, the more interesting batteries become. (UC1)

   b. For a fast-charging station: the lower the chance multiple charging sessions coincide or follow each other immediately, the better the battery performs in minimizing the grid off-take peaks and optimizing the operational costs (UC3)

3. Use case 5 shows that it is economically interesting to combine charging demand of different use cases. Combining charging demand can be done in different ways. When vehicle to grid (v2g) charging is not implemented it is economically optimal to make sure the charging time does not coincide, this can happen in two different ways:

   a. Combining a day charging need with a night charging need (e.g. night parking for passenger cars and a ferry which sails and charges only during the day), or

   b. Implementing smart charging (e.g. a ferry charging hub combined with a day parking for passenger cars that will only charge the cars at the timeslots when no ferry is charging) When charging time does coincide, implementing smart charging will result in When no smart charging is applied this means

When vehicle to grid charging is implemented, the requirements are completely opposite: it is economically interesting to have the charging times of the different use cases coincide as much as possible. For example, the presence of a passenger car parking with vehicle to grid charging capabilities can achieve large peak reductions for a ferry that needs to charge during the day at high power rates.

In conclusion: combining different consumer typologies with different charging needs in one hub has the capability to optimize the operation of the combined charging hub and leads automatically to cost reduction potential.

4. Solar installations are in almost all cases an interesting investment, however they have a rather limited impact on the need and the optimal size of the battery.

Appendix I

Result summary Use Case 1 with a spec. batt. cost of 500 €/kWh

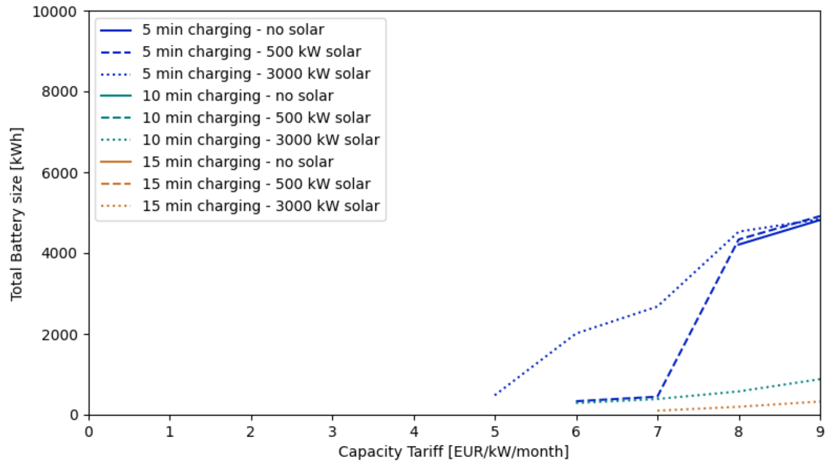

Figure 76: Summary optimal battery size for UC1 (specific battery cost of 500 €/kWh)

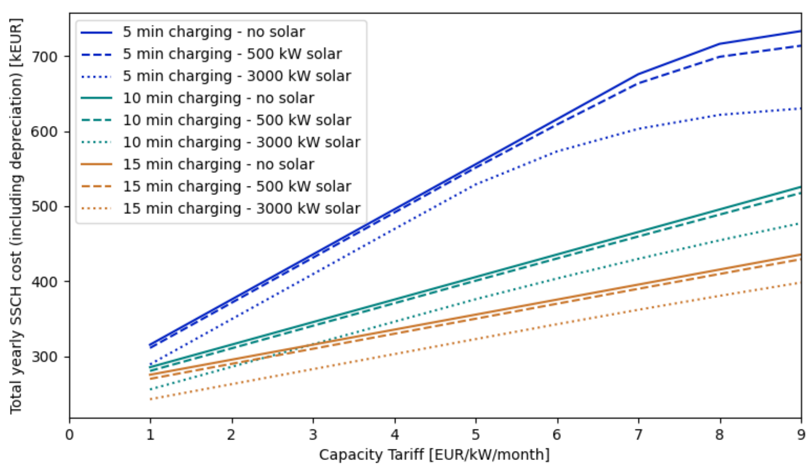

Figure 77: Summary annualised cost for UC1 (specific battery cost of 500 €/kWh)

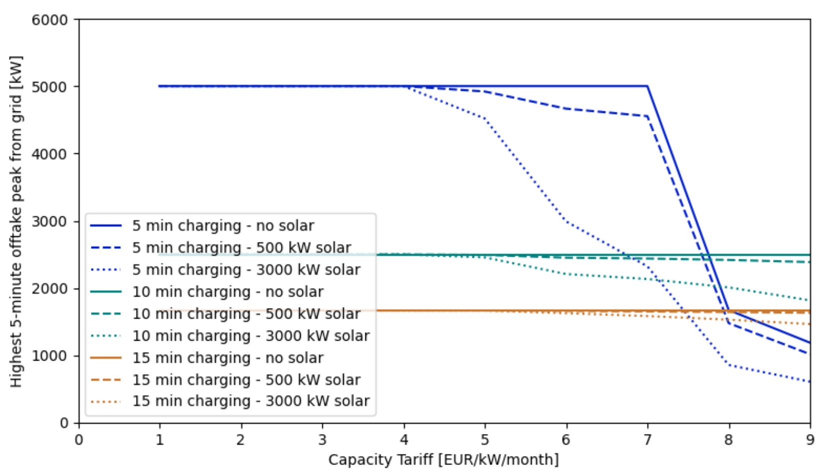

Figure 78: Summary highest yearly grid off-take peak from the grid for UC1 (specific battery cost of 500 €/kWh)

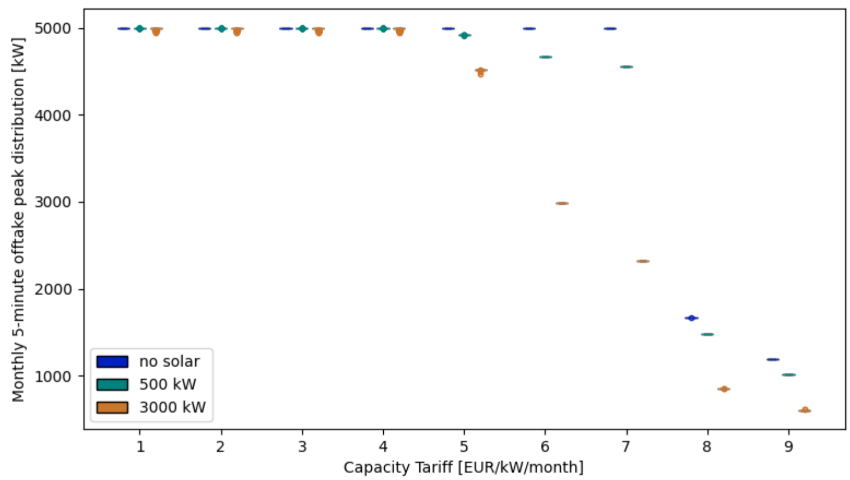

Figure 79: boxplot monthly grid off-take peaks (specific battery cost of 500 €/kWh)

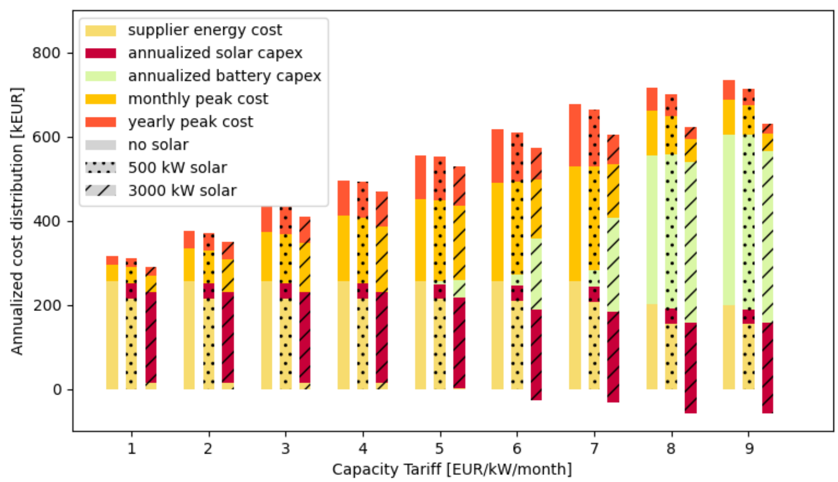

Figure 80: Cost breakdown for UC1 (specific battery cost of 500 €/kWh)

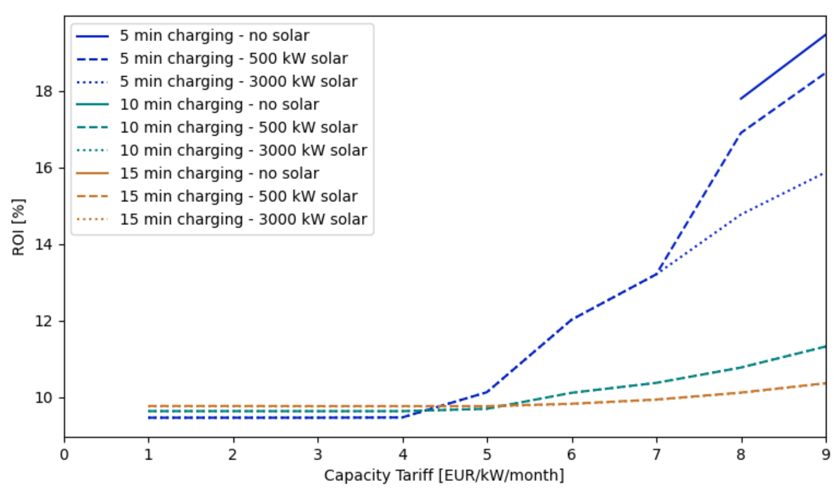

Figure 81: ROI for UC 1 (specific battery cost of 500 €/kWh)

Appendix II

Result summary Use Case 2 with a spec. batt. cost of 400 €/kWh

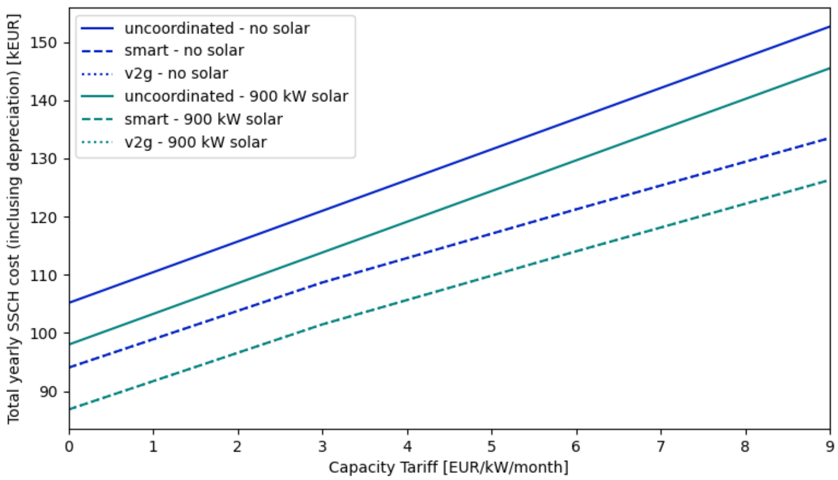

Figure 82: Total yearly costs for UC2 (overnight bus charging) for a specific battery cost of 400 EUR/kWh

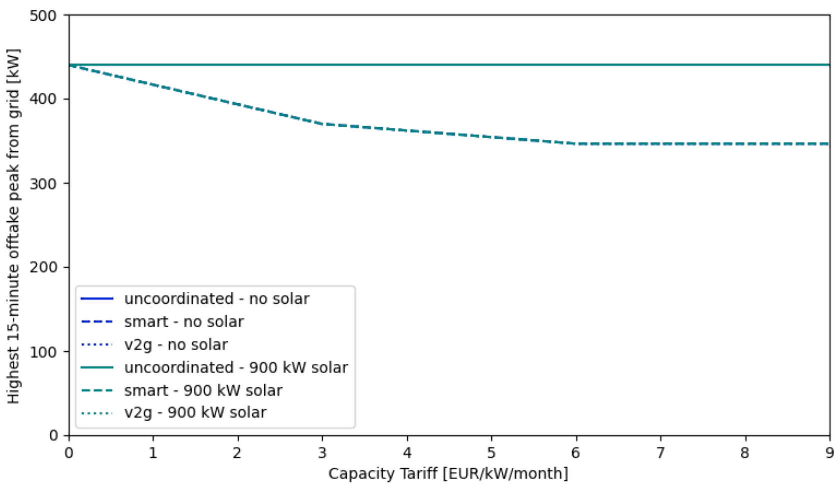

Figure 83: Highest 15-minute peak for UC2 (overnight bus charging) for a specific battery cost of 400 EUR/kWh

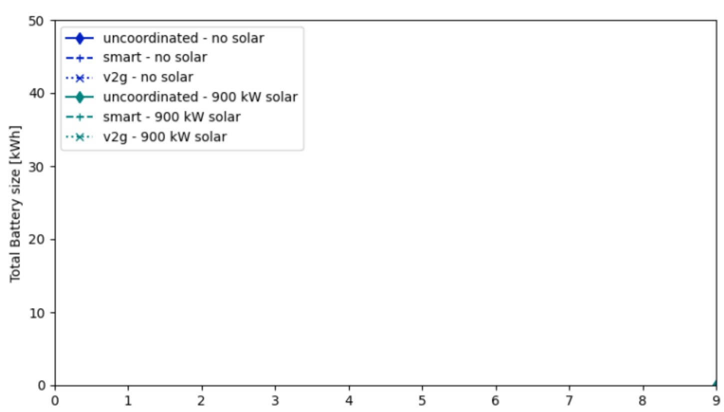

Figure 84: Optimal battery size for UC2 (overnight bus charging) for a specific battery cost of 400 EUR/kWh

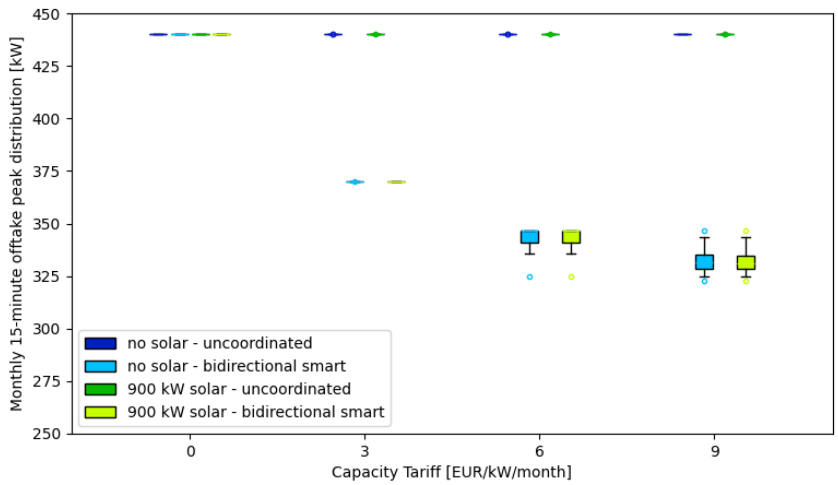

Figure 85: Boxplot 15-minute off-take peak for UC2 (overnight bus charging) for a specific battery cost of 400 EUR/kWh

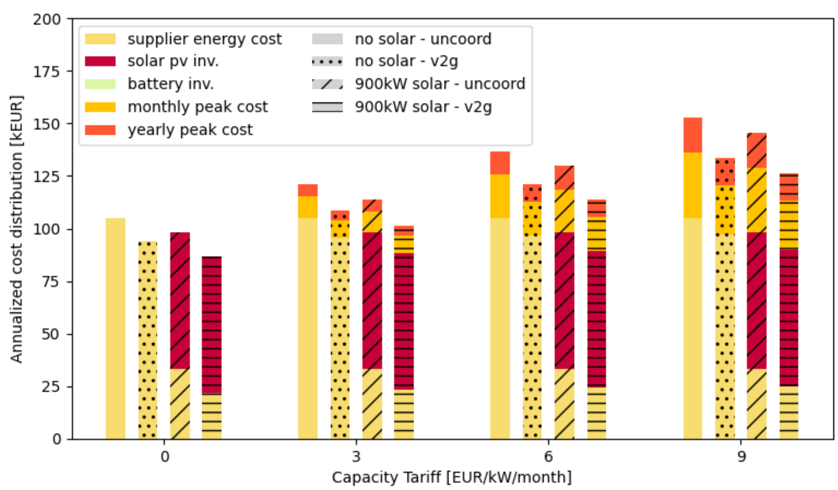

Figure 86: Annualised cost breakdown for UC2 (overnight bus charging) for a specific battery cost of 400 EUR/kWh

Appendix III

Result summary Use Case 4 with a spec. batt. cost of 200 €/kWh

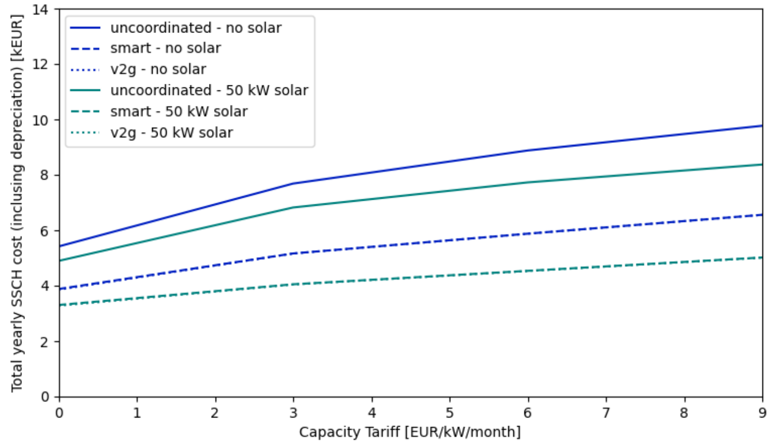

Figure 87: Annualised cost of UC4 with a specific battery cost of 200 €/kWh

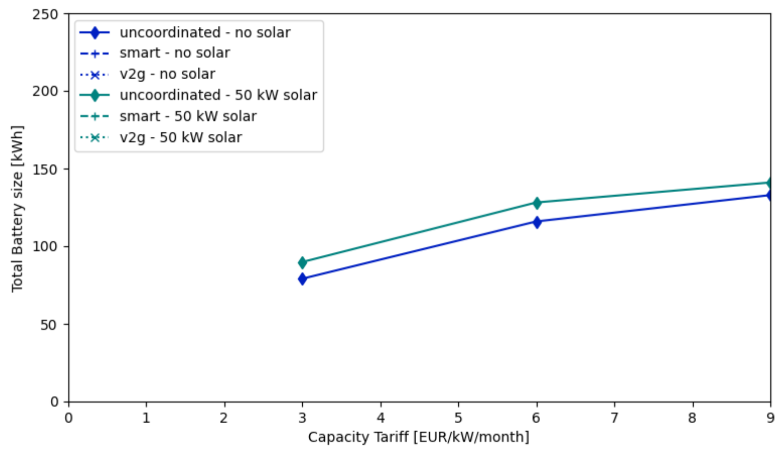

Figure 88: Optimal battery size of UC4 with a specific battery cost of 200 €/kWh

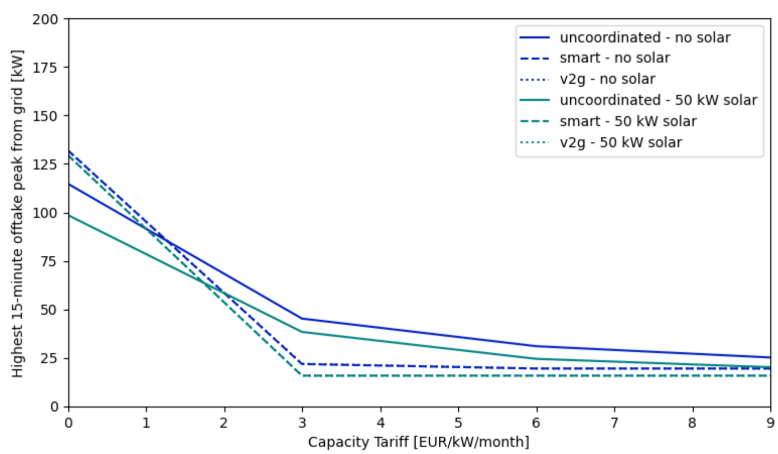

Figure 89: Yearly peak of UC4 with a specific battery cost of 200 €/kWh

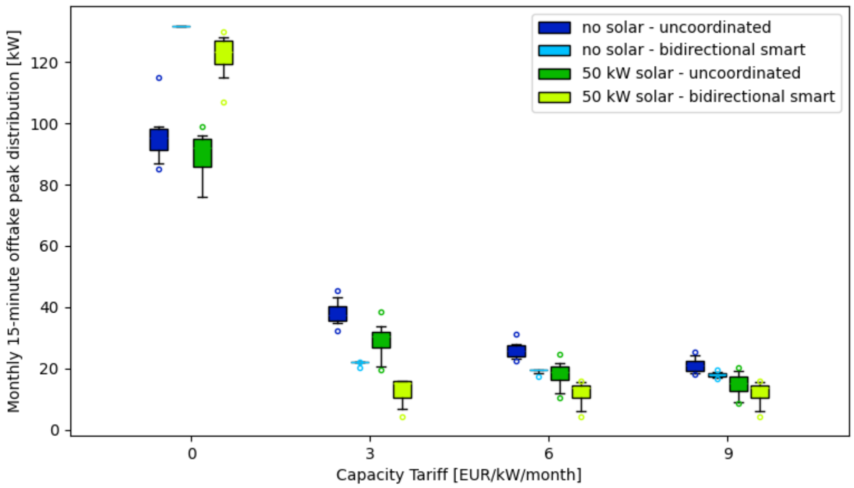

Figure 90: boxplot monthly peaks of UC4 with a specific battery cost of 200 €/kWh

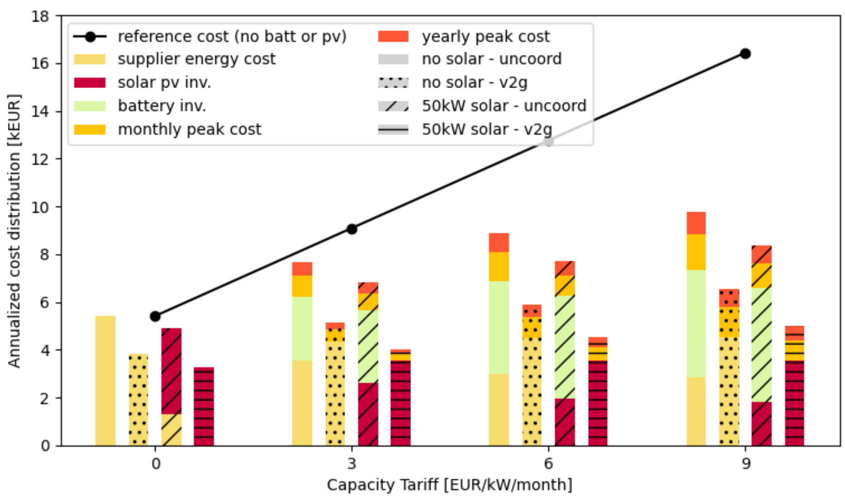

Figure 91: Annualised cost breakdown of UC4 with a specific battery cost of 200 €/kWh

Appendix IV

Summary analysis for a specific battery investment cost of 200 €/kWh (Use Case 5)

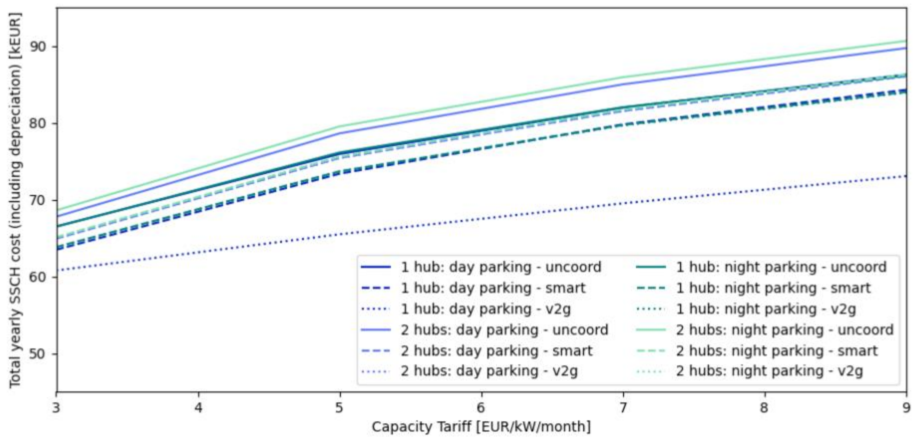

Figure 92: Total annualised SSCH cost for the charging hubs with an optimal battery size at a specific battery cost of 200 €/kWh.

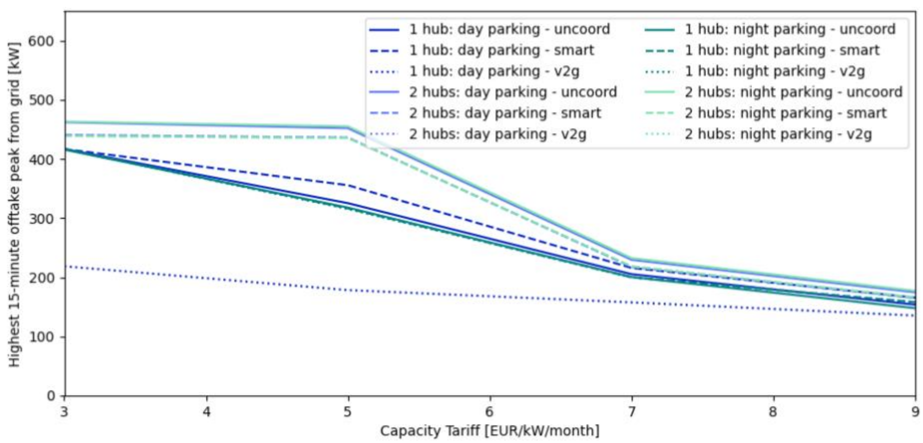

Figure 93: Total yearly SSCH peak for the charging hubs with an optimal battery at a specific battery cost of 200 €/kWh.

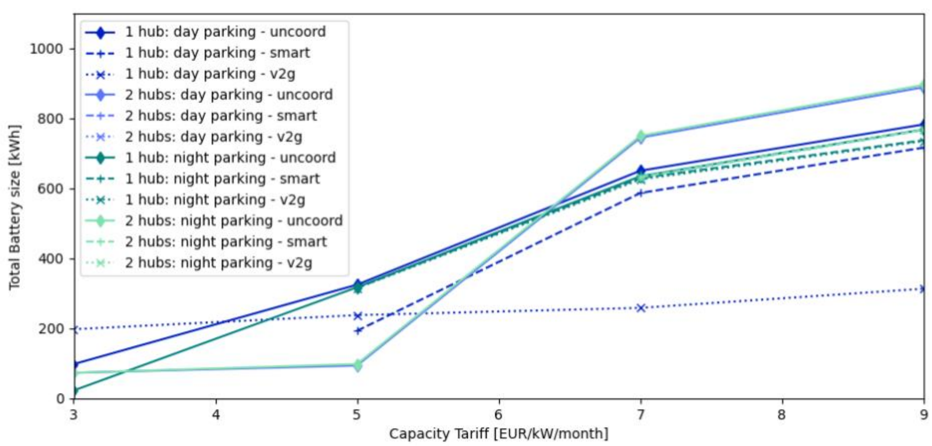

Figure 94: Total optimal battery size for the charging hubs at a specific battery cost of 200 €/kWh

Summary analysis for a specific battery investment cost of 350 €/kWh (Use Case 5)

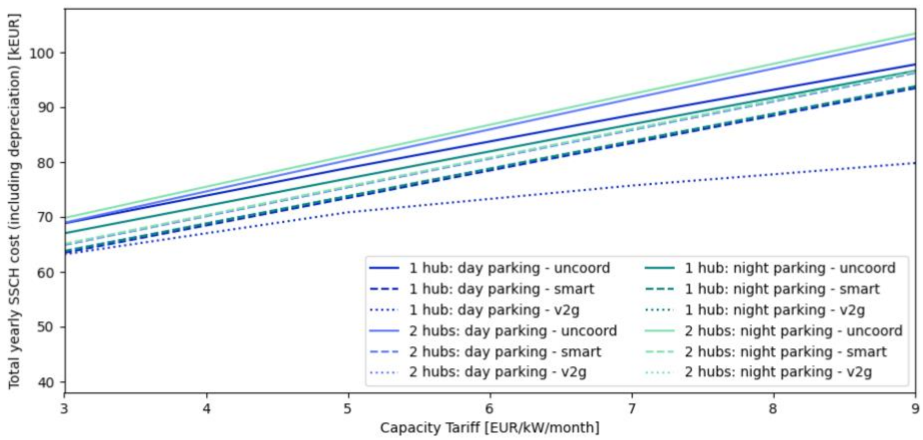

Figure 95: Total annualised SSCH cost for the charging hubs with an optimal battery size at a specific battery cost of 350 €/kWh.

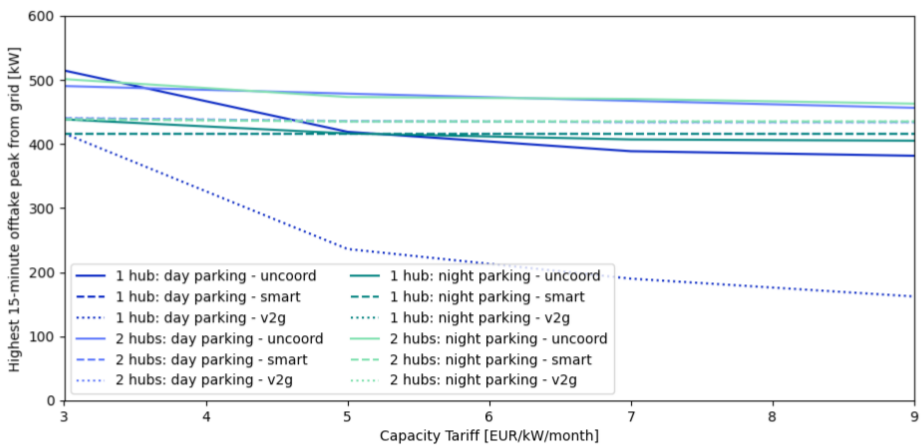

Figure 96: Total yearly SSCH peak for the charging hubs with an optimal battery at a specific battery cost of 350 €/kWh.

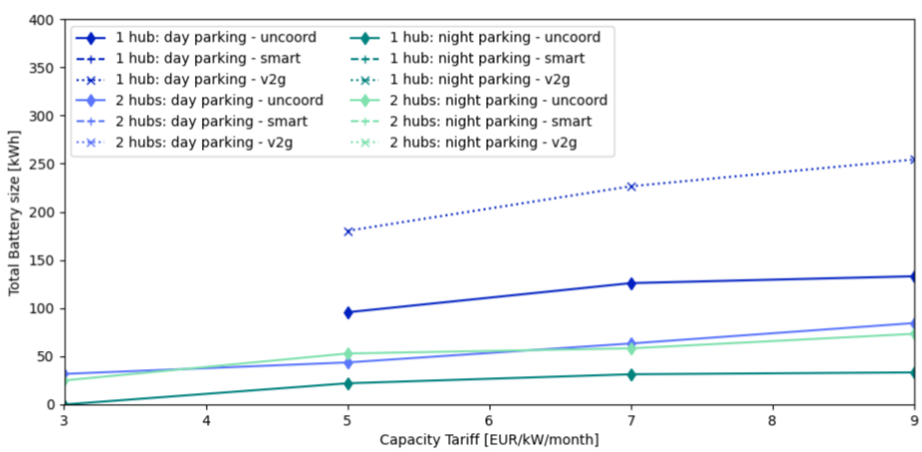

Figure 97: Total optimal battery size for the charging hubs at a specific battery cost of 350 €/kWh

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Felice, A. (2024). *A technical, economic and environmental optimisation model for the energy system of the future.* Brussel: VUB.

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