Diploma Thesis

Comparative Analysis of Algorithms for coordinated electric vehicle charging

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Diplom-Ingenieur
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by

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Abstract

The expansion of electric vehicles as a substitute for internal combustion engine vehicles is in full swing in 2022. Electrical grids and explicitly the Austrian Low Voltage grid have to react to the increasing energy demand and especially peak loads. As electric vehicles(EVs) have high power charging characteristics, they have a strong impact on the low voltage grid, which is not designed for these types of loads. There is a strong temporal effect, with EVs returning home in the evenings and being charged immediately. With growing market pressure of electric vehicles expected in the near future, this will lead to grid overloading situations, especially in the evenings, when the grid is already maximally utilized. To avoid costly grid enforcement, coordination algorithms are being developed, which reduce the charging speed of charging stations according to the current grid situation. In this work, four papers with five different coordination algorithms were discussed and evaluated. The formulation of an evaluation metric is the central objective of this Master Thesis. A selection of quality aspects was chosen, to cover all important features of a system. Aspects outside the defined scope or equal in all algorithms, were dropped. Discrete requirements were formulated, to reach points in a category. The categories are weighted, to represent their influence on the overall quality. The resulting final scores represent the quality of an algorithm. To optimize the evaluation, a survey was conducted among experts in the topic, to reach objective results. Finally the results were discussed and recommendations for further action made. The best algorithm according to this thesis, is based on an artificial neural network, which uses historic data of a controlled grid section as well as live exogenous data, like temperature and solar irradiation to estimate the current grid situation and adjust the charging rates accordingly.

Contents

Acronyms

ANN Artificial Neural Network. 20

BEV Battery Electric Vehicle. 8

EV Electric Vehicle. 15

FCEV Fuel Cell Electric Vehicle. 8

GDP Gross domestic product. 60

LV Low Voltage. 15

PLC Power Line Communication. 34

PoSyCo Power System Cognification. 28

PV Photovoltaic. 12

Glossary

cognification The concept of adapting an otherwise inflexible system with an sensors, actors and an intelligent network to create a more dynamic range of operation. 58

grid Here grid always refers to the electricity distribution grid and mainly the voltage levels of 0,4kV. 11

prosumer Grid customer which also operates a production plant. The production plant is mostly a PV-plant.. 54

wallbox A wallbox is a connection device between one or multiple electric vehicles, or a charging stations, with the electric grid. It is a not specifically defined Term. In the scope of this work, it is used as a receiving device, to provide a uniform communication interface with any coordination algorithm. . 16

Chapter 1

Motivation

1.1 Electric Energy as replacement technology for fossil fuels

As the effects of greenhouse gas emissions on global climate become increasingly evident, large-scale effort is put into the transition into renewable energy technologies. These technologies have in common, to minimize emissions of greenhouse-gases and using resources which are available in large enough quantities for intermediate or long-term use. Current energy systems heavily rely on fossil fuels and their derivatives, which allow easy transportation and storage of large amounts of energy. As the production of synthetic fuels with similar properties has not developed far enough to be an economically viable option, different approaches for many problems need to be considered. Electrical energy systems have been developed alongside and in conjunction with fossil fuel technologies since the beginning of industrialization. Therefore, they are technologically advanced and have great potential for replacing fossil fuel technologies in many applications. The two largest energy demands of a society are heating and mobility.[2] For heating, many different options are available, depending on the location, the surroundings and the specific requirements of the customer. The first measure that has to be taken in any case, is the reduction of the energy demand. For buildings this means investing in high air-tightness, thermally insulating windows and equipping a building with a thermal insulation system. Water or large concrete structures can in many cases be used as a thermal storage, to store renewable energy over the course of up to several days. Heat pumps are able to provide efficient heating as well as cooling functions. The production of hot water and steam can be achieved directly electrically, with high-temperature heat-pumps or using biomass-furnaces fueled by wood chips or pellets. The second big energy demand, mobility, is currently also in the process of being converted to alternative technologies. Liquefied natural gas has been used for many years as a less climate harmful energy medium. Although the emission of CO2 is significantly reduced, the low energy efficiency and the continued emission of CO2 make this technology no suitable long-term alternative. Another promising technology is the use of hydrogen for internal combustion, or more commonly in fuel cells. Here, in the best case, green hydrogen, which has been produced by electrolysis from renewable electricity, is being supplied under high pressure to the vehicle. The vehicle is equipped with an internal fuel cell, which converts hydrogen and oxygen from the outside air, to water, releasing electric energy and heat in the process. The vehicle is then driven by electric motors. Although this technology seems promising as a renewable energy storage possibility, there are large losses in the energy path. Electrolysis has a real-life efficiency of 60-80% [17] with compression, storage and refueling processes also having significant energy demands. Hydrogen fuel cells in vehicles have an efficiency of approximately 50-65%, further decreasing energy usage. As the hydrogen might be produced in times of cheap, renewable energy, as a short term storage, this might be accepted. Major barriers for fuel cells are currently the high price and low lifetime of the fuel cell itself, as well as the lack of infrastructure and large scale industry. According to Cox et al.[4] Fuel celled vehicles(FCEVs) have an unfavorable impact in terms of life cycle cost, compared to Battery electric vehicles (BEVs).

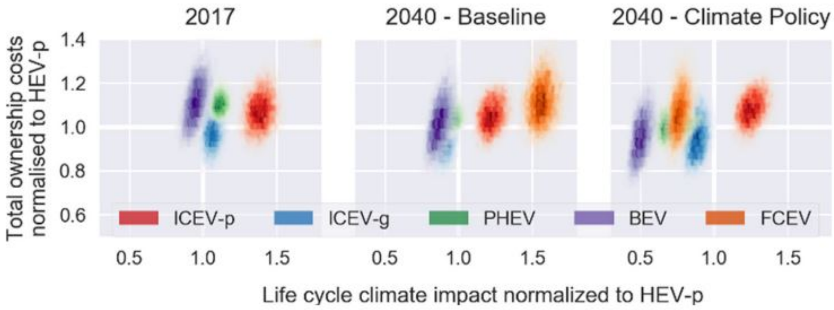


Fig. 1.1: Total cost of ownership and life cycle costs of different vehicle technologies. Hybrid Electric Vehicle- petrol (HEV-p), Internal Combustion Engine(petrol, gas), Plug-in Hybrid EV, Battery EV, Fuel Cell EV. Two different scenarios with one baseline, and one carbon-reduced electricity source. Source: [4]

From the standpoint of the year 2022 a transition from internal combustion engines to fully and hybrid electric vehicles can be expected within a short time frame. As the sale of new combustion engine vehicles within the European Union will be prohibited by 2035[9], companies have a strong incentive to switch to sustainable alternatives. The battery pack, for a long time the critical cost component of an electric vehicle is continuing to be more affordable, as production volumes are rising. 1.2

New support infrastructure needs to be constructed to accommodate this technology within the existing energy network.

On the one hand, electric energy demand will increase, on the other hand, the peak load demand will increase as well. Increased energy demand can be largely compensated by economic processes and dispatching additional power plants if necessary. According to studies, the overall additional electrical energy demand will rise by 16% if full vehicle electrification is reached. The overall primary energy demand for transportation will drop by 2/3. [11] Peak loading capacity is limited by the maximum current a single grid component can support. This is especially critical for underground cables and transformers, which can be easily damaged or destroyed by overload conditions. As studies suggest, overload conditions caused by electric vehicle charging especially occur on evening of workdays, with commuters returning home and recharging their vehicles.[22] With low average daily driving distances and high-power charging stations, this produces a significant peak load in the low-voltage grid. The traditional approach to solve this problem is the reinforcement of the low voltage grid or restrict the consumer peak load if necessary. This is a cost intensive and not necessarily long-term solution. The new solution discussed in this work, are simple coordination algorithms, which monitor the low voltage grid state and communicate with the charging stations to temporarily decrease their power to avoid overloading of equipment, like transformers, ground cables and power lines and enabling optimal use of these grid components. Different control strategies have been discussed, a selection of which are being evaluated in this work.

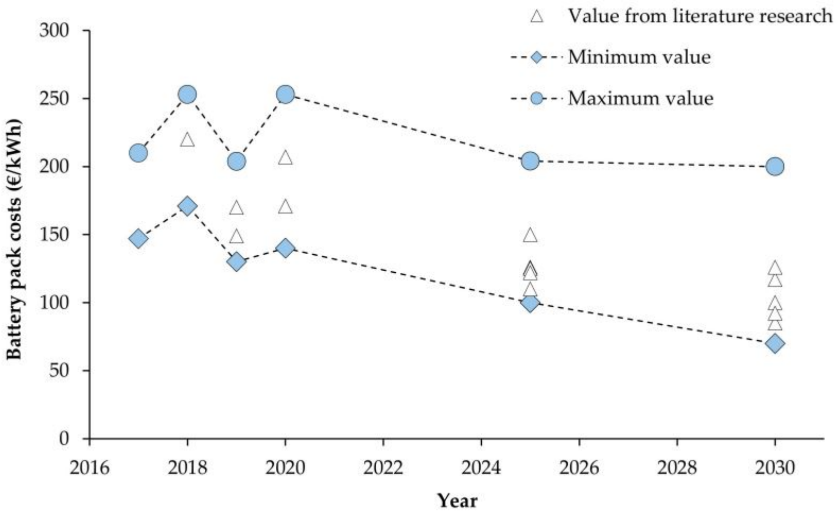


Fig. 1.2: Development of battery pack costs, all cell types, Source:[16]

1.2 Temporal inflexibility of electric energy and energy storage

Different to other forms of energy, the storage of electric energy is a challenge, that has not been fully solved on a grid scale. Pumped hydro storage, is to this date the only large scale possibility of storing electric energy economically. Although high power capacities are available, energy storage capabilities are very limited and localized in relatively remote areas. In the last few years, breakthroughs have been made in the field of accumulators, electrolysis and fuel cells for storage, but no economic viability has been reached so far. Especially in the field of EV-battery cells, prices have dropped dramatically within the last few years. In Figure 1.2 from the 2020 perspective, it can be seen that the 2022 battery pack price is estimated to lie between 125 and 225$/kWh. In reality battery prices are currently between 130 and 135$/kWh [10] with rapid development of more affordable and sustainable technologies.

Through electric vehicles,a high capacity of storage capabilities is being implemented in the electric grid. The availability of flexible loads gives in the first step the possibility to coordinate their impact depending on the grid situation. The second step is often called "Bidirectional Charging" with EVs providing energy back to the grid, or a household. Many EV-Producers already provide this ability, but further development and regulation is necessary to support this function. Due to high production prices and relatively small storage capacities, battery storage will unlikely be implemented on a grid-wide scale to balance intermittent renewable energy production. It is more likely, this challenge will be solved using so called "power to x" technologies. Here electricity is used, to generate electro-chemical products, to be used for energy storage or industrial processes. Most important is the generation of green hydrogen and it´s derivatives, produced by water electrolysis. Hydrogen itself can be stored and transformed back into electricity using fuel cells or turbines. The transformation into synthetic fuels and synthetic carbohydrates however, has the potential for simple, large scale storage as well as seamless integration into the current fossil fuel infrastructure. Intensive research is being conducted in finding economic and and sustainable processes. Low efficiencies during transformation are being accepted by utilizing highly economic but intermittent energy sources.[6] Due to still limited production of renewable energy and high electric energy prices, this promising technology will reach it´s optimal operation environment, once large renewable energy surplusses are available.

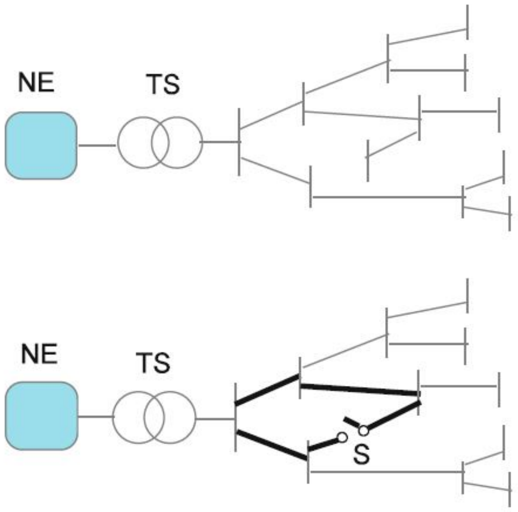
Chapter 2

Technical Background

2.1 Conventional Low Voltage Grid Topology

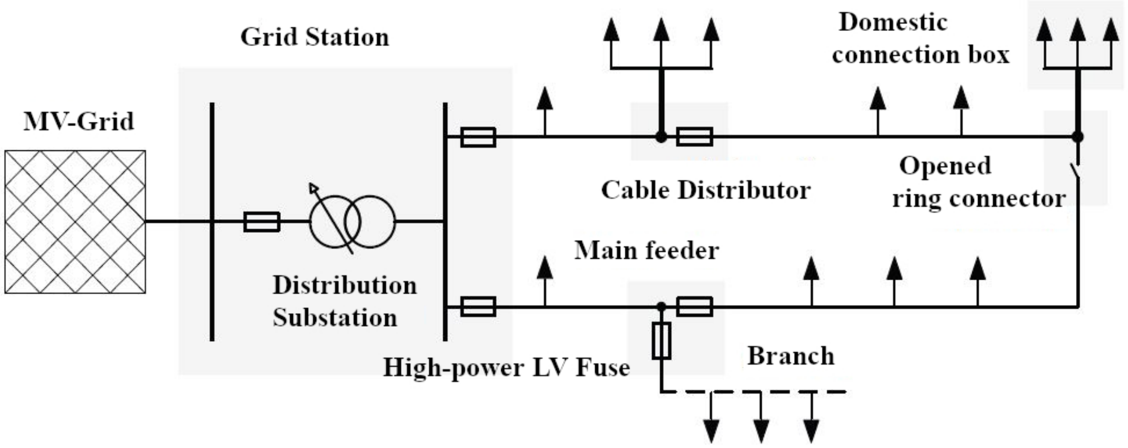
The electric grid is structured in layers, with the highest layers supporting large distance transportation functions and are traditionally fed by large-scale power plants. Lower grid layers not only operate on lower voltages, but also include smaller power plants, as well as large business and industrial customers. The lowest level, grid level 7, connects businesses with small energy demand and private households to the grid. In Austria this low voltage grid is generally operating on 400V voltage and connects via transformers, which are denoted as grid level 6, to grid level 5 which is operating between 1-36kV. Transport grids are constructed in a netted topology, to increase grid reliability and better utilize grid capacities. This comes with higher maintenance effort, to stabilize the grid. For low voltage(LV) grids, a radial structure is preferred, as it is cost-effective and easy to maintain. To increase reliability, connection points between radial grids can be added (Figure 2.1), to be capable of switching off isolated grid sections, without cutting supply to all grid segments further down the faulty line.

Fig. 2.1: Grid topologies for LV-grids, Top: Isolated Radial Grid, Bottom: Radial grid with connection point, NE: Grid Feed-in, TS: Transformer Station, S: Connection point. Source:[5]



In Figure 2.3 a detailed view on a typical LV-grid is provided. It can be seen that multiple main feeders are connected to the common low voltage bus bar. The gray box represents the distribution station, with a circuit breaker for each feeder. There are additional gray boxes for peripheral cable distribution boxes, with additional circuit breakers. From these boxes, branches are heading out to several customers. Each of the arrows represents one house connection. It can be seen that this grid includes a connection point, to close the ring structure if necessary.

Fig. 2.2: Exemplary radial network, Redrawn from:[14]



2.2 Grid dimensioning

The conventional way to dimension low voltage grids, is to estimate the expected loading by using standard load profiles [3] and concurrency factors of the current or future customers. As consumers are increasingly also acting as producers, the power flow direction in whole low voltage feeders is not only being reduced, but in some cases even reversed. Large consumers, as EVs, hot-water-production and heatpumps, increase the peak energy demand and change the concurrency factors of the consumers significantly. Normally low voltage grids are constructed with a large safety margin, to allow for peak loads. If this margin is exhausted however, grid reinforcement through increase of cable diameters and higher capacity transformers is necessary. These investments are capital intensive and are to be avoided where possible, without risking grid supply security. Especially underground cables and transformers are sensitive and would be destroyed by many overloading-situations. They are therefore equipped with dedicated circuit breakers, which will trip according to a specified trigger characteristic.

2.3 Necessity for capacity coordination

Traditionally, production plant maximum feed-in and consumer plant maximum connected power are limited by the grid operator according to the grid capacity these plants are connected to.[27] In Figure2.3 an exemplary situation for several feeders in a low voltage network is shown. In this simulated case, it can be observed that voltage levels drop continuously, which is a sign for a lack of decentralized production. Line loading, on the other hand is highest in main branches close to the transformer and decreases towards the end of each feeder. In case there are production plants, not only the voltage level in the feeder rises, but also the line loading at the feeder beginning decreases. Historically, this is not a problem if the capacity allocation by the grid operator is performed correctly and grid participant do not violate their maximum allowed capacity shares. High penetration of electric vehicles and other high-power loads like continuous-flow water heaters cause high peak demands, even if power capacities are met. On the other hand, photovoltaic(PV) systems have very short-term peak loads, and it is reasonable to allow the connection of plants

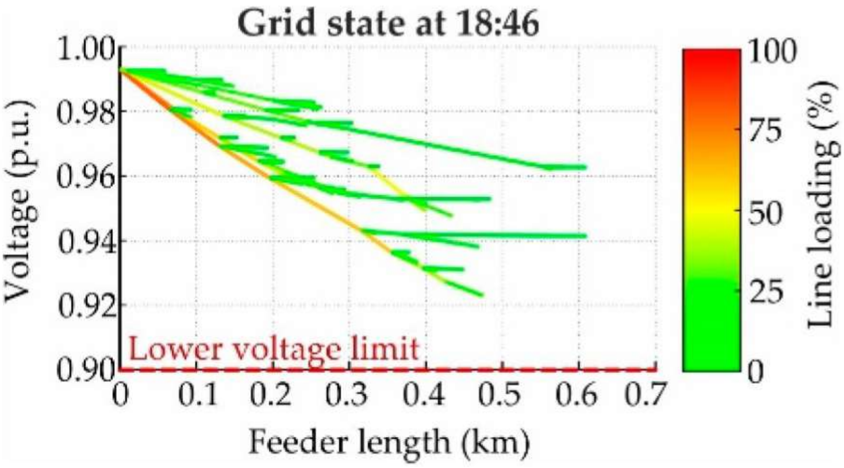


Fig. 2.3: Voltage drop in a typical feeder structure, Source:[25]

to a grid, which have a much higher peak power than the grid at the connection point. Presently the grid operator can limit the maximum allowed feed-in power, regardless of the current grid situation, or demand an automated active power adjustment, depending on the grid voltage and frequency. In the case of large production plants >100kWp the grid operator must be capable of remotely reducing the power feed-in, if necessary. [27] The other solution, which allows for a more efficient use of the grid, is the management of grid loading capacities. Part of this capacity management is the coordination of high-powered loads to reduce grid capacity requirements. High loads in combination with high decentralized production may additionally lead to grid overloading in peripheral sections, without violations of voltage or loading level at the feeder beginning.

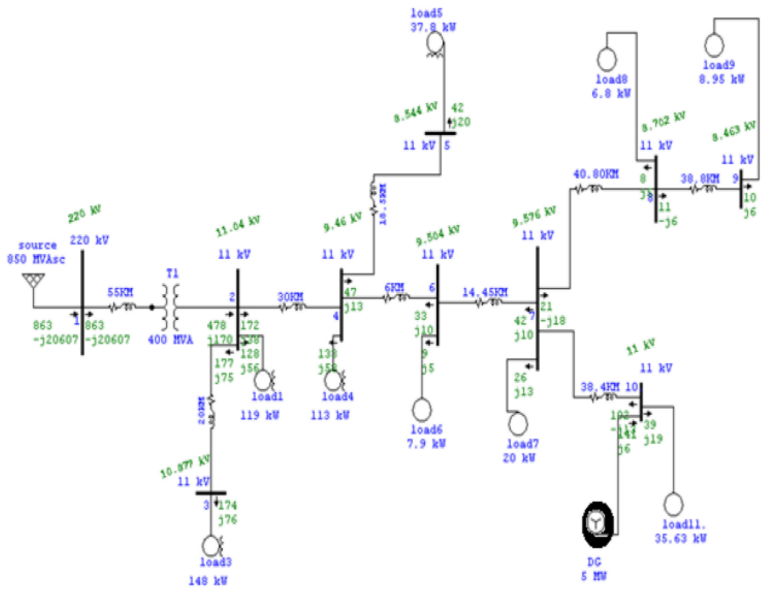


Fig. 2.4: Typical loadflow calculation user interface, 11kV grid section with 220kV supply, Source:[15]

2.4 Load flow calculations

In a meshed network, determining the physical energy flows within the individual grid sections is not easily accomplished. The mathematical tool to design and operate these grids, is the load flow-calculation. It gives insight into a steady state grid situation, concerning voltage levels, power system elements conditions and possible overloading situations. The active and reactive power flows are determined by specifying producers, loads, line properties and transformers.[19] It essentially consists of a mathematical model, with a set of nodes each with an active and reactive power parameter, a voltage magnitude and a voltage phase angle. Power lines, cables, transformers and loads are included as active and reactive loads. As indicated in 2.4 distributed generators can be included as power sources(DG). The main power source in traditional low voltage grids is the higher voltage grid of the medium voltage grid connected via a distribution transformer. As an idealized power system has no energy storage possibilities, all active and reactive power flows must be balanced at all time. Within this thesis, some described algorithms use load flow calculations to determine grid loading for some more complicated grid topologies.

Chapter 3

Scope

3.1 System boundaries

As this thesis is touching many other topics within the development of "Smart grids", system boundaries must be drawn, to keep the volume of the work within reasonable limits and be able to develop the topic in appropriate depth. The comparisons in this thesis are specifically focused on LV-grids in Austria. Although an adaptation for higher grid layers seems plausible, residential charging of electric vehicles mainly occurs at the low voltage level. Fast public charging is also not a part of the scope, as the charging processes are distributed differently, more evenly and appropriate design choices are made, to avoid grid congestion in the first place. Large scale, high-power charging station are frequently connected to a higher grid layer.

Many of the described systems can potentially take over additional tasks, besides EV charging coordination. As a high level grid-specific communication system is employed, many functions can be fulfilled. The later described rating factor "Adaptability" touches the possibility of secondary uses, in a superficial way. Only general assumptions are made, judging by the type of communication system and processing capabilities.

3.2 Energy losses

There is also no focus on energy losses as a result of high-power charging which can be reduced by slow charging speeds. This is an argument for the advantages of coordinated charging strategies but not relevant for grid congestion.

3.3 Scenario selection

3.3.1 Overloading in the evenings

The versions in the different algorithms and all other assumptions were based on the scenario of a grid overload-situation in the evening. There are several reasons for this determination. The first one is that especially low voltage grids with a large amount of residential customers was considered. From historic data it is well documented, that residential customers have pronounced demand peaks at noon and in the evenings.[3] This can be explained by the high energy demand of cooking, cleaning and entertainment devices. During off-work days, statistically the highest energy demands are recorded during noon. At workdays however, the bulk of energy demand occurs in the evening, as many people do not eat at home and will only cook in the evenings. Also other energy intensive activities like washing clothes, dishwashers or watching TV will more likely occur in the evening hours. The other assumption is, that electric vehicles will, by default, be plugged in upon arrival at home and charged uncoordinated until being fully charged. As the average driving distance per day in Austria is just over 30km [21] and most latest EV-brands have ranges of more then 250km, only a small share of the capacity will be necessary to be recharged. The time of this recharging [22] is overlapping with the evening demand peak and is the most critical situation for EV-induced grid congestions. As only a relatively small amount of energy needs to be replenished, delaying the charging process for a few hours, has minimal impact on the user.

3.3.2 One signal per feeder

Another selection that was made, was to choose the algorithms which relied on a "one signal per feeder" strategy. This has two reasons: The first is, that Algorithms 3 and 4 function on a system, that will reduce all charging loads within one feeder equally, to avoid congestions. Algorithms 1 and 2 are based on a permission-system, with some of the algorithm being distributed to the wallboxes to optimize grid utilization. Algorithm 5 is working on different concepts altogether. To keep some level of comparability, this compromise was made. It can be argued, that one signal per wallbox will yield the most efficient grid utilization, especially if used in combination with an artificial neural network modeling grid behavior. The second reason is the avoidance of high communication requirements. Using one signal per feeder, in some algorithms a single binary signal is sufficient, to give a power reduction demand. This avoids cost, and many privacy issues, which will be discussed in Chapter 6.5.

Chapter 4

Algorithms

The algorithms or systems chosen for the evaluation within this work have in common, that they rely on a centralized control strategy. The focus lies on European low voltage grids with their implementation carried out by the grid operator. This regulated and unified strategy has many technical and regulatory advantages, but several hurdles that must be addressed. As there are many works, concerned with a similar topic, a small representative selection of comparable systems was made to facilitate the evaluation. Specifically, 4 scientific papers were chosen, which describe several different options on how to implement the system. The actual algorithms were described within the publications in the form of flow-charts or as text with examples of simulations given in most of the cases.
For this evaluation, the algorithms were not simulated as no additional benefit was identified. As a basic software simulation with ideal communication and no consideration of the hardware used for implementation, is an ideal case, real performance might deviate. Only functional aspects are tested using a simulation, which is only one part of the evaluation and therefore an excessive effort for the scope of this work.

The evaluated algorithms will be described briefly to give an overview over their functionality.

4.1 Algorithm 1

Daniel-Leon Schultis (2021), *Sparse Measurement-Based Coordination of Electric Vehicle Charging Stations to Manage Congestions in Low Voltage Grids* [25]

The main achievement of algorithm 1 is an efficient method of state estimation, using dispersed voltage measurements at significant points within the considered feeders. Using these voltages and an underlying model for each feeder, a high degree of accuracy can be achieved in the load flow calculation. A permission token system is used, sending one signal per feeder. If a congestion is detected within one feeder, all wallboxes receive the same binary permission signal. The developers of system 2 are investigating three different options how the permission signal is processed within the wallbox. Option number one is, to switch all wallboxes to the maximum or minimum value, depending if a permission is received or not. Option two sets a timer of power reduction for 30 minutes if no permission is received. After this timer has elapsed, the wallbox will check again, if a permission has been received and will as a consequence either increase its charging power or restart the timer. This is useful in the case of a fluctuating grid situation, with charging processes starting or ending, or other fluctuating loads or producers. The third option is to set the charging speed at the beginning of the charging process according to the current grid situation and not change it until the end of the charging process. Additionally there were different assumptions, for the start time of the charging process.

For the evaluation in this thesis, Option two for the wallbox Algorithm was selected, as it yields the best results within the scope of this work. "Simultaneous Charging in the evening" was selected, as it was identified to be the most realistic scenario as described in Chapter "Scope".

Fig. 4.1: Flowchart of Algorithm 1, Controller, Redrawn from [26]

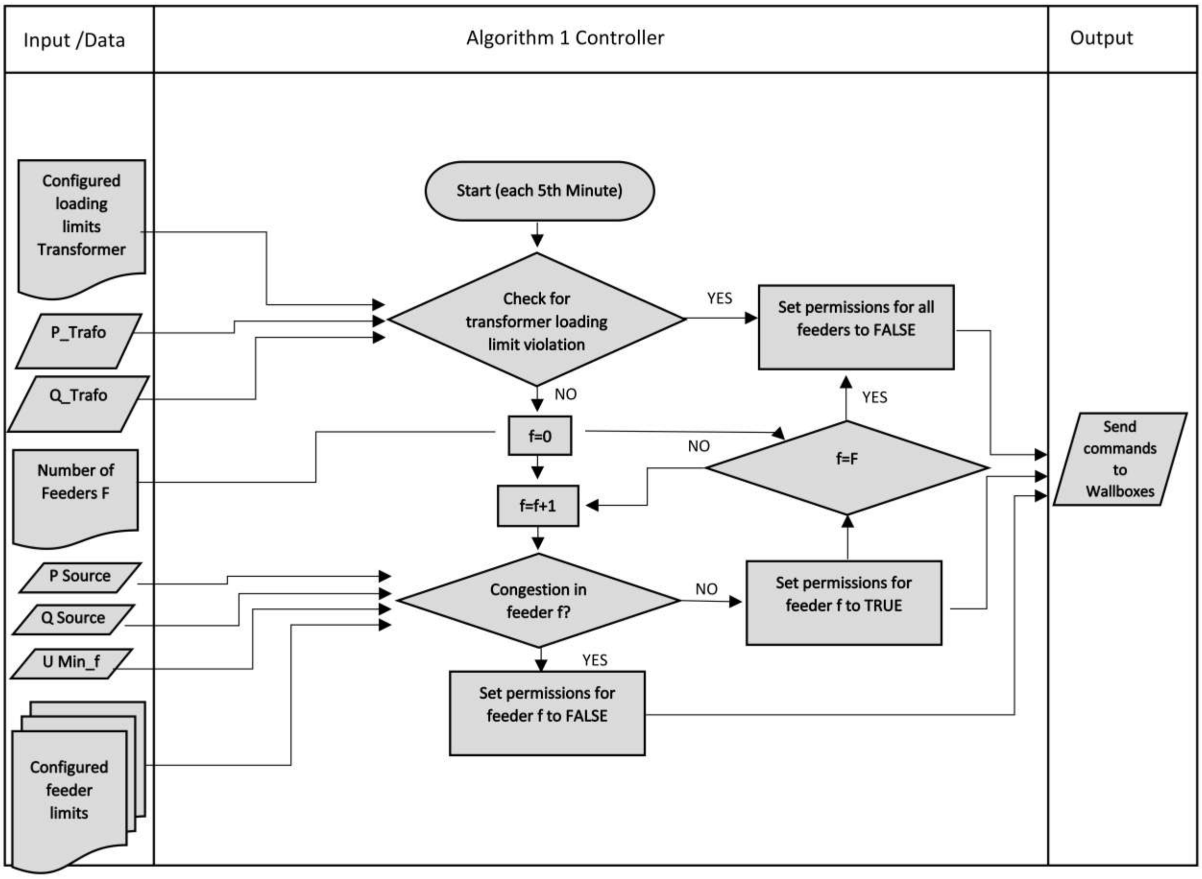


Fig. 4.2: Flowchart of Algorithm 1, Wallbox, Redrawn from [26]

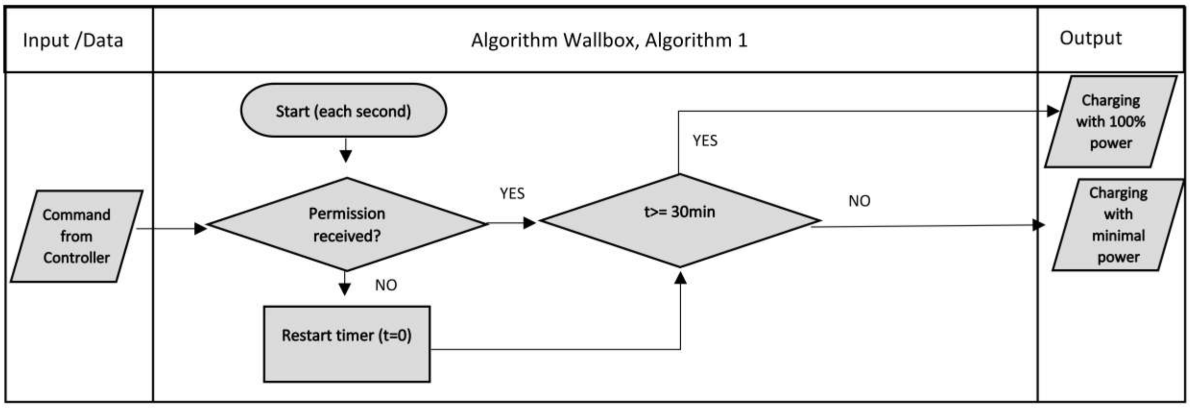
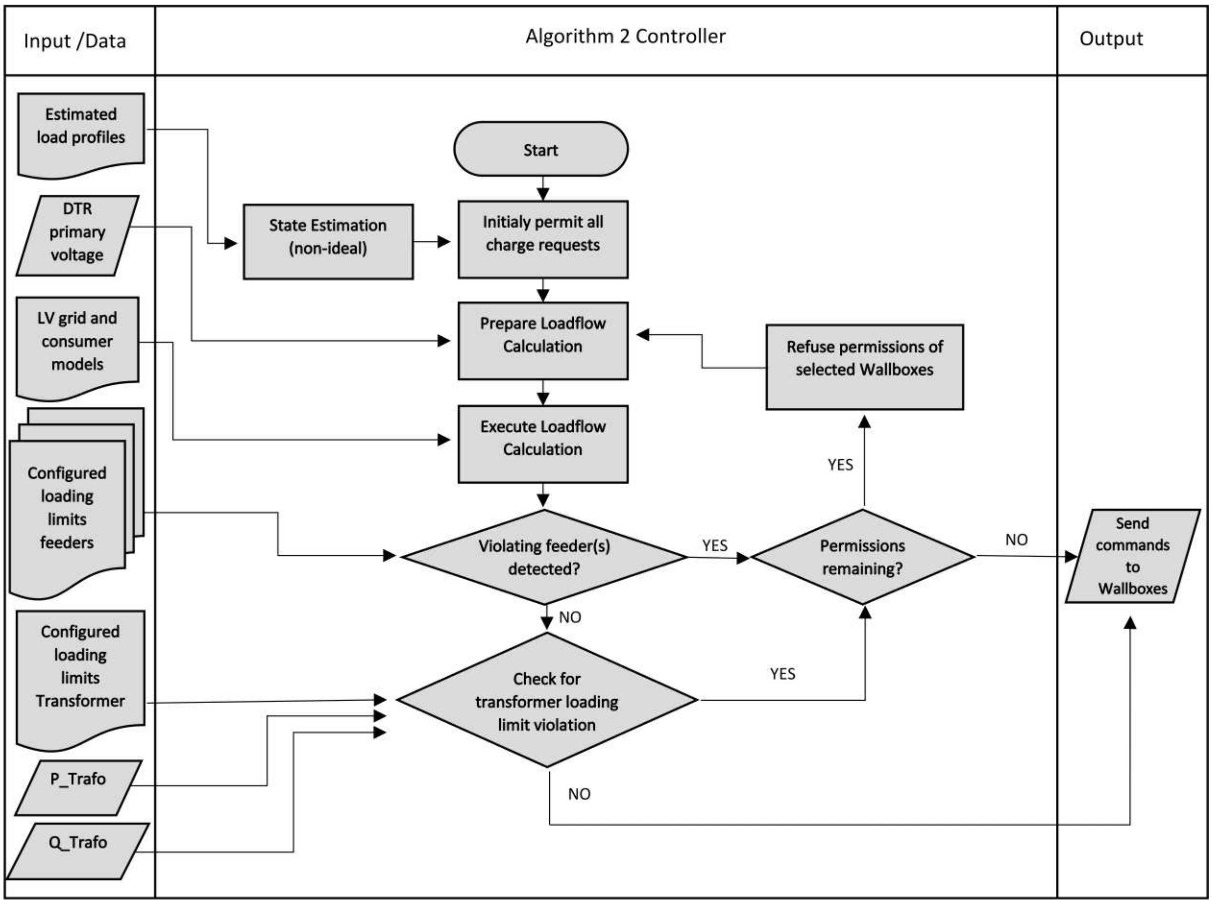


Fig. 4.3: Flowchart of Algorithm 2, Controller, Redrawn from [25]



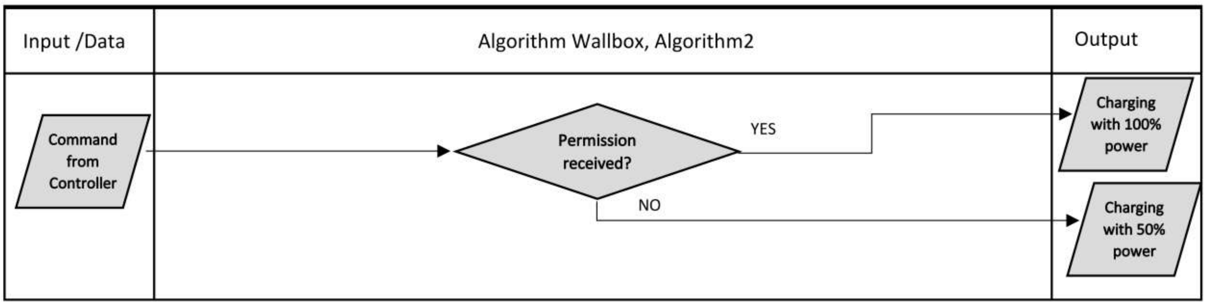
4.2 Algorithm 2

Daniel-Leon Schultis, Alfred Einfalt, Paul Zehetbauer, Daniel Herbst (2020), *Coordinated Electric Vehicle Charging-Performance Analysis of Developed Algorithms* [26]

This algorithm is relying on a state estimation using load-flow calculation and a power system model to estimate the current system state and possible overload situations. Two different scenarios are assumed: One with known ZIP-coefficients of the consumer plant, one with an unknown, constant power model. The second assumption is the real case, with an not fully determined grid situation. For simulating a coordination algorithm, Device and Producer-models are implemented in PSS-Sincal for conducting Load-flow-calculations of a simulated grid situation. The coordination algorithms were created using Matlab. The two tools communicated with each other using the COM-interface. Charging power for the electric vehicles is set in a way, so grid congestions are provoked. The coordination algorithm was based on the concept of giving permissions to the wall-boxes to increase their charging power from a minimal value, to a maximum value. It was tested which level of specificity for the permissions is necessary, by testing one signal per LV-grid, one signal per feeder or one signal per wallbox.

For the evaluation the version "One signal per feeder" and "Non-ideal state estimation" was chosen, as it yielded good coordination results, with low communication requirements. It is most similar to the other evaluated systems.

Fig. 4.4: Flowchart of Algorithm 2, Wallbox, Redrawn from [25]



4.3 Algorithm 3 and 4

Sebastian Deters, Bastian Pfarrherr, Thomas Werner, Wiebke Fröhner, Alfred Einfalt, Detlef Schulz (2019), *Technical, Economic and Regulatory Aspects of Distributed Monitoring and Control of Private Chargers in Low Voltage Networks* [7]

These two systems are essentially the same algorithm with different approaches to estimate the current grid state. The setup is similar to the other algorithms, with a central controller located within the distribution station and communicating with the distributed wallboxes, which here are called "connecting devices". An addition to algorithm one and two is the establishment of a communication possibility with a central IT-system. This gives the possibility, to remotely access the control algorithm for monitoring and adaptation possibilities. The algorithm itself is operating with locally measured real time data. Algorithm 3 is assuming a low voltage grid, with a low amount of distributed energy production plants. This reduces the complexity of the state estimation and essentially only the voltages and currents at each feeder beginning are measured. It is assumed, that the measured current is exclusively flowing through the weakest grid segment, which is defining the maximum allowable current. This is a very conservative approach, which limits the possibility to reach high grid utilization and prohibits the development of decentralized energy production. Algorithm 4 is assuming, that a higher amount of distributed energy production is present. The use of an artificial neural network (ANN)is suggested. This network, trained on historic demand data and measurements, is estimating the current grid situation based on power measurements at the feeder beginning, as well as exogenous data, specifically solar irradiation and outside temperature at the distribution station. Historic in this context can mean the year before, the month before, the day before or any other time frame which works well to estimate the correct system state. This data could be smart-meter measurements from some customers, and a centrally computed load flow calculation. The decentralized controller has low computational efforts and research shows very good functionality for this use.[30] By sending out a relative set-point for each individual feeder, instead of a binary permission signal, more accurate control of the loads is possible. The charging reductions are shared between all grid participants. The communication possibility with a central IT-system enables monitoring and adaption of the system and continuous optimization of the ANNarti.

Fig. 4.5: Flowchart of Algorithm 3 and 4, Controller, Redrawn from [7]

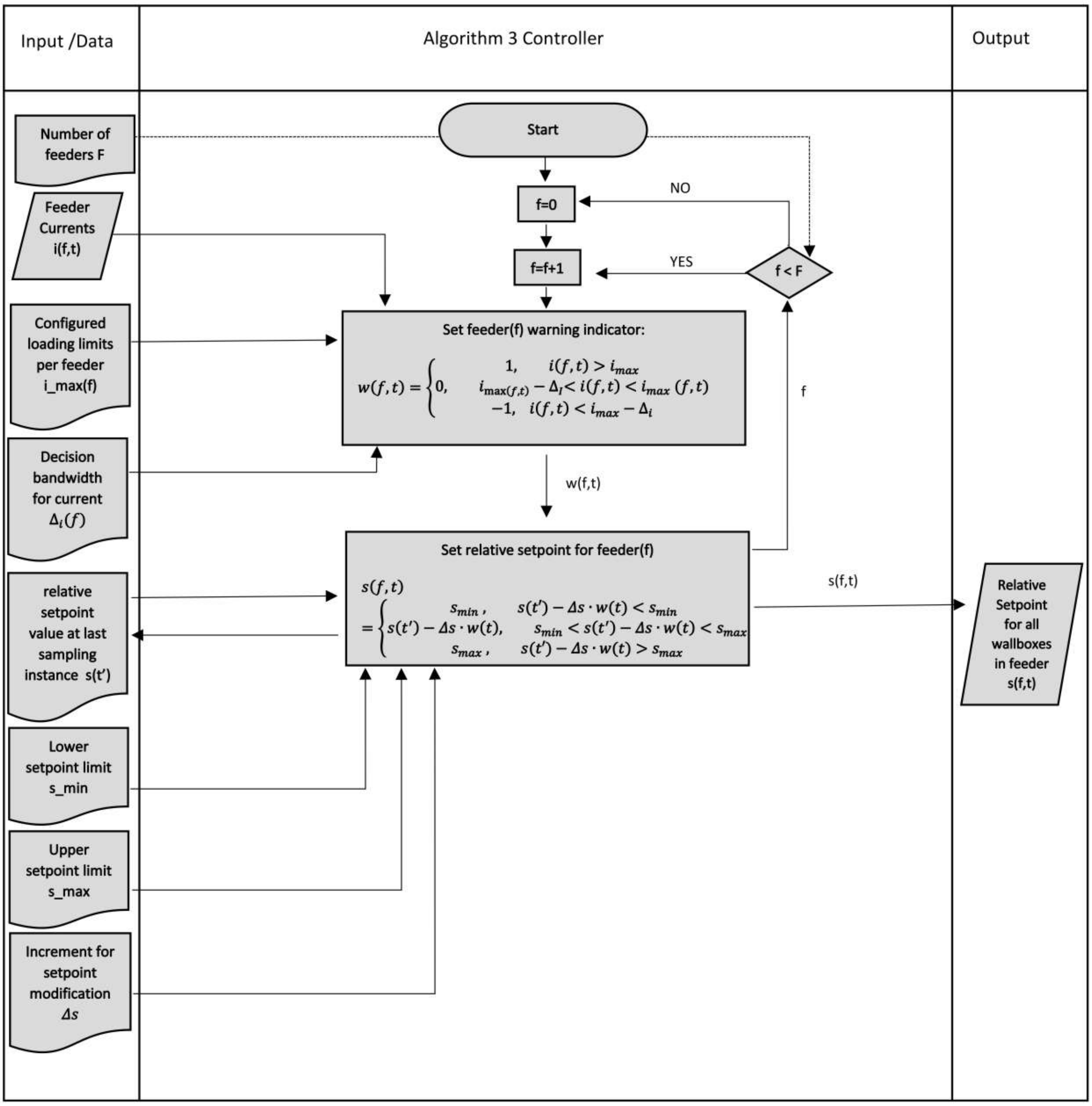
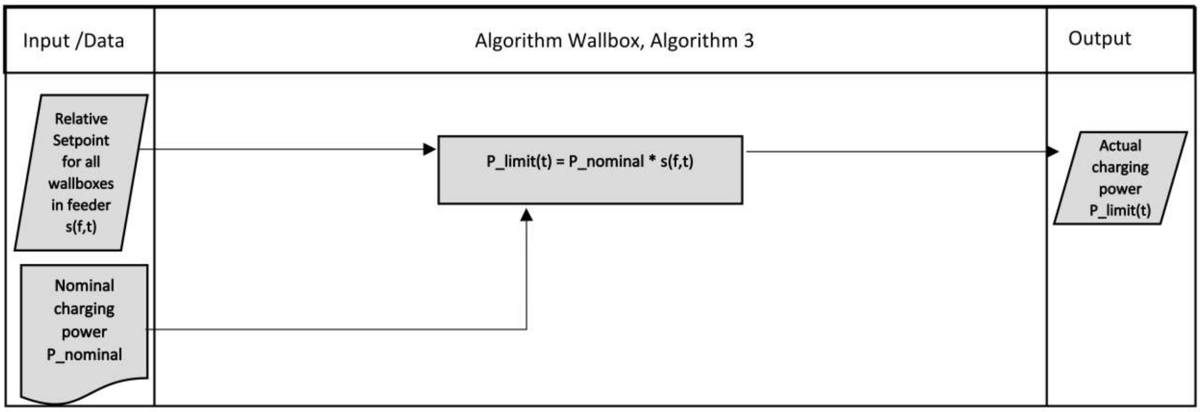


Fig. 4.6: Flowchart of Algorithm 3 and 4, Wallbox, Redrawn from [7]



4.4 Algorithm 5

Bharath Varsh Rao, Mark Stefan, Thomas Brunnhofer, Roman Schwalbe, Roman Karl, Friederich Kupzog, Gregor Taljan, Franz Zeilinger, Peter Stern, Martin Kozek (2021), *Optimal capacity management applied to a low voltage distribution grid in a local peer-to-peer energy community* [28]

The last evaluated system has a very different approach and scope compared to the rest of the algorithms. The system described in the paper is functioning as a complete control network, not only managing grid capacity, but also fulfilling the function of a local energy trading platform. Therefore only a few of it´s multiple functionalities were included in the evaluation. The capacity management and control of so called "controllable busses" is very similar to the other algorithms. A controllable bus in the scope of this system is a generalized term describing controllable producers, consumers and storage devices. The system assumes, each customer in it´s controlled area have employed measurement devices which measure the current active and reactive power consumption, voltage and phase angle. This information is transmitted to the network in 1 minute intervals. The system is communicating via a Blockchain structure. This is functioning by generation of blocks with transactions, which contain the respective data. Therefore a measurement device similar to a smart meter, as well as a receiving device in form of a wallbox are necessary. Both devices communicate with the other participants in the network, via a processing and networking device and a not closer specified communication pathway. Non-controllable customers are participating in the energy community, by transmitting smart meter measurement data. This measurement does not seem to be real-time, therefore the standard smart meter communication path is likely to be used. The second function of this algorithm is to provide a smart-contract trading network between the participants in an energy community. It does not only manage the distribution of the produced energy by controlling loads, but additionally fulfills smart contracts, tracks energy flows and functions as payment settlement service. There is also a large potential for additional functions, as the communication system potentially provides fast and secure communication between each participant. It is the only system that does not necessarily be controlled by the grid operator, but could be managed by a third party, or an energy community itself.

After this overview, it can be seen, that the approaches to reduce grid impact of electric vehicles are very different from each other and are covering a wide range of scopes. As defined in Chapter 3, not all functionalities are being included in this evaluation, to give be able to compare the relevant ones.

Fig. 4.7: Flowchart of Algorithm 5, Controller, Redrawn from [28]

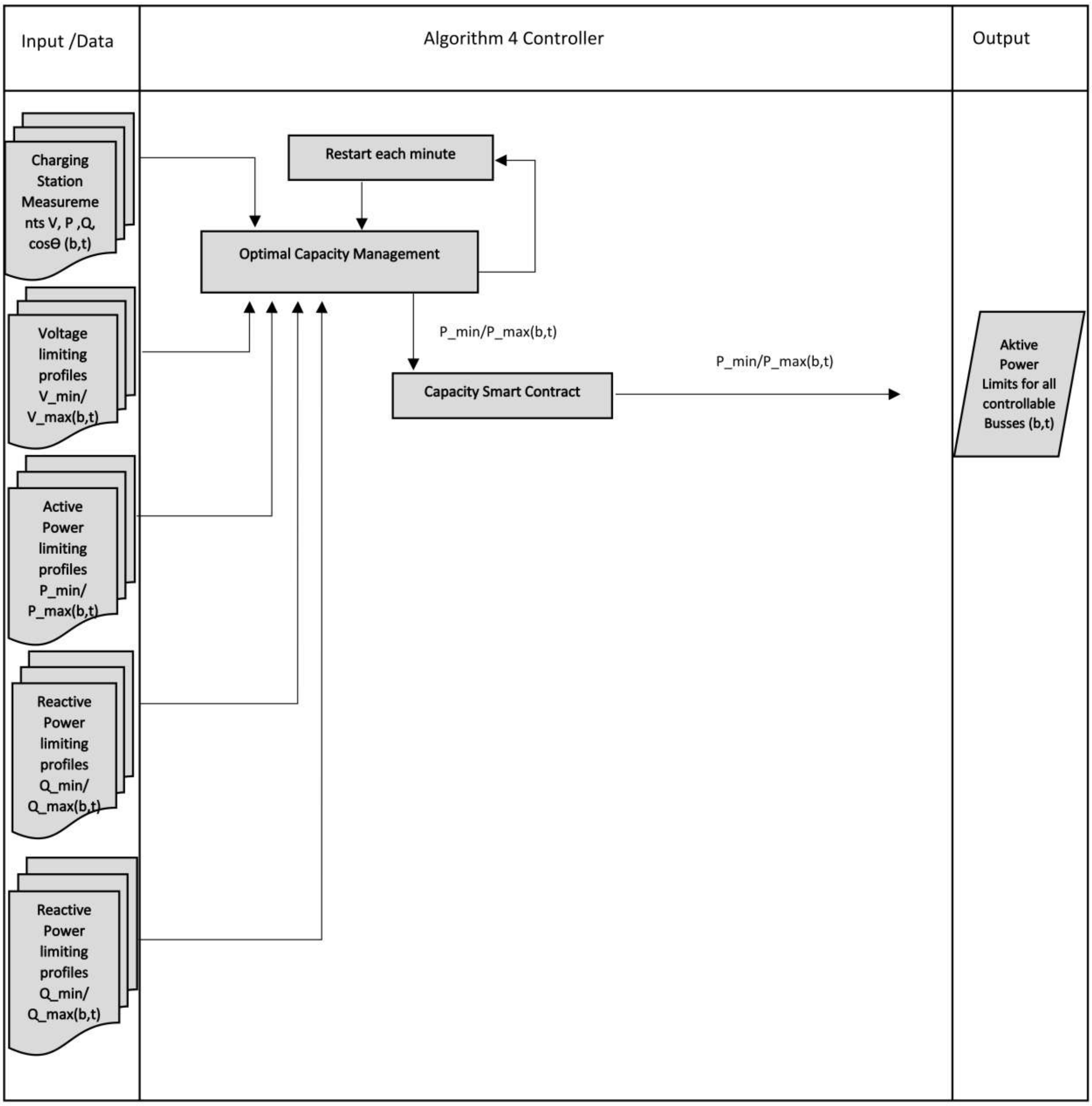
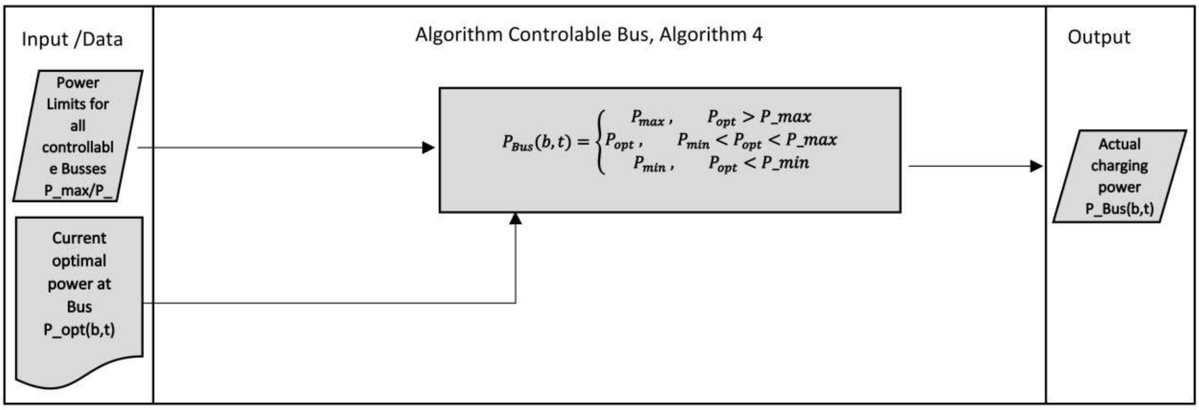


Fig. 4.8: Flowchart of Algorithm 5, Controllable Bus, Redrawn from [28]



Chapter 5

Methodology

The goal of this Diploma Thesis is to find an objective way of determining the quality of coordination algorithms for electric vehicle charging stations. This task is on the one hand very specific, as it neglects other possibilities of avoiding grid congestion and focuses on the issue of electric vehicles. On the other hand, only very generalized consideration is given to the technical details of the algorithms, as a level of comparability has to be reached. In the following the development of the used rating system is being described.

5.1 Evaluation using rating factors

According to [8] an evaluation is an "Activity to determine the suitability, adequacy and effectiveness of the considered unit, to achieve it´s specified goals." The evaluation process for the Algorithms was developed from steps, described for general product evaluation.[29] Although the methodology had to be adapted and reduced, it is a good guideline for a large range of evaluations. Any evaluation is based on quantitative or qualitative properties which can be measured objectively or subjectively. To make the evaluation representative and subjective, properties have to be defined, which fulfill a number of criteria:

1. Criteria have to be equal-natured. Critical dropout criteria, cannot be mixed with uncritical aspects.
2. Only criteria can be used which are valid for all variations.
3. Criteria have to be free of duplication.
4. Criteria have to be free of contradictions.
5. Criteria have to be free of contrariness.
6. Criteria must be combined to as few as possible to reduce complexity.
7. The criteria have to cover the set requirements fully.

For many evaluations, the use of a "value function" with a nonlinear value development might be adequate. In this case due to the nature of the criteria a discrete evaluation system was chosen. The quality aspects were reduced to general evaluation factors, which symbolize the quality of an algorithm in this respect. The evaluation was simplified by assigning discrete values between 1 to 4 to each of the aspects. This evaluation is based on the ubiquitous 5-star rating scheme originating from hotel and restaurant ratings. In it´s original use, it specifies specific quality attributes, that can be expected when visiting a restaurant or hotel.

The rating is building up on itself, which means that all of the underlying points have to be fulfilled for a certain rating. This was done to include more aspects within one rating factor. This way, the fulfillment of more important aspects forms the basis for additional but less important aspects.

In other more modern areas, like users rating businesses or movies, the use tends to be ambiguous and highly subjective. By assigning quality criteria like “acceptable” or “near flawless” to the number of stars in a 5-star rating system, user experiences can be valued more accurate. For the evaluation on hand, a specific rating system was created. For represent-ability purposes, it was attempted to find a set of rating rules, which could be applied to all aspects of the algorithms in the same way.

The rating factors were split up in two groups: Quality and Quantity Quality aspects define aspects which can be evaluated using discrete requirements. For the definition of these, the evaluation approach of “functional suitability” defined in the ISO/IEC 25010 standard was used as guidance. [24] Here functionality is split up in the sub-characteristics functional completeness, functional correctness and functional appropriateness. Functional completeness: ***The degree to which a set of implemented functions covers the specified tasks and meets the users‘ objectives. It is understood as the ability of the system to provide the specified requirements in the product requirements specification.*** In the case of the evaluated systems, it can be assumed that they will be implemented in a complete way. As the evaluation is mainly based on simulations, this sub characteristic will not be important for evaluation. Functional correctness: “The degree to which a product or system offers correct results, with the required degree of precision. Functional correctness is understood as the results generated by the requirements as expected.” This is covering the need of the system to fulfill it´s main task of keeping line-, and transformer-loading within the specified limits. For the evaluated systems, simulations from the papers in which they are introduced are taken as a reference. If the system has only been described theoretically, assumptions must be made. Functional appropriateness: “The degree to which the functions facilitate the accomplishment of the tasks and objectives that have been set. Functional appropriateness is understood as the system to carry out the requirements that are needed for the different usage objectives that have been specified.” In the context of this evaluation this addressing the different use-cases a system may be able to fulfill. If the system can be used for secondary tasks, or easily adaptable, it is a more secure investment and a higher quality system.

5.2 Quality Aspects

The factors rated by this scheme are: Performance, Adaptability, Regional Applicability and Privacy/Security The exact evaluation scheme with primary and secondary requirements for each factor will be described in the next chapter. Following overall evaluation scheme was defined:

Points	Criteria
1	The primary requirements were not achieved completely.
2	The primary requirements have been met.
3	Primary and secondary requirements have been met.
4	Requirements are being met in the best possible way regarding the scope of the evaluation. Primary and secondary requirements are being fulfilled optimally.

5.3 Quantity Aspects

The same requirements can be reached with different amount of efficiency. For this specific comparison, a low implementation threshold and high level of operational security is priority. Efficiency covers capital expenses for hardware, software, and workforce during the first implementation as well as maintenance and scale-up. This comparison only makes sense for the same scope and objective of the system, which is not the case for all investigated algorithms. Some algorithms have secondary functionalities which increase their complexity and price. The rating is therefore adjusted to also consider these positive properties. The thresholds for this evaluation are not exact and are meant to serve as an orientation for the sake of comparability. They are quantified by outlining a completed system and retracing the necessary steps and hardware to reach operation. Especially labor cost is difficult to judge so it is avoided to make poor assumptions. The results are meant to serve as a indication for realizations made during the research for the topic and serve further discussions. A detailed description of the used thresholds is given in the concerning definition of the rating factors. The factors rated according to this scheme are "Implementation" and "Scale-Up" According to these ideas, following validation scheme was defined:

Points	Criteria
1	The most expensive solution of the investigated algorithms.
2	More expensive.
3	More economic.
4	The most efficient solution of the investigated algorithms.

5.4 Weighting factors

Equally important as the individual quality criteria, is their influence on the overall system quality. The method was adopted from [29]. The individual quality measures resulting from the previous evaluation step can be expressed as m_{ij} for each algorithm i and each rating criterion j. By multiplying the measures m_{ij} with a weighting factor w_j and adding the resulting values, a rating number r_i for each algorithm can be found.

$$w_i = \sum_{i=1,j=1}^{n;k} w_j * m_{ij}$$

n number of different algorithms, k number of rating criteria, i algorithm version, j rating criterion, w_j weighting factor (in percent), m_{ij} measures

The weights are a distribution of percentages over the number of rating criteria j and add up to 100%.

$$\sum_{j=1}^{k} w_j = 1$$

5.5 Expert group survey

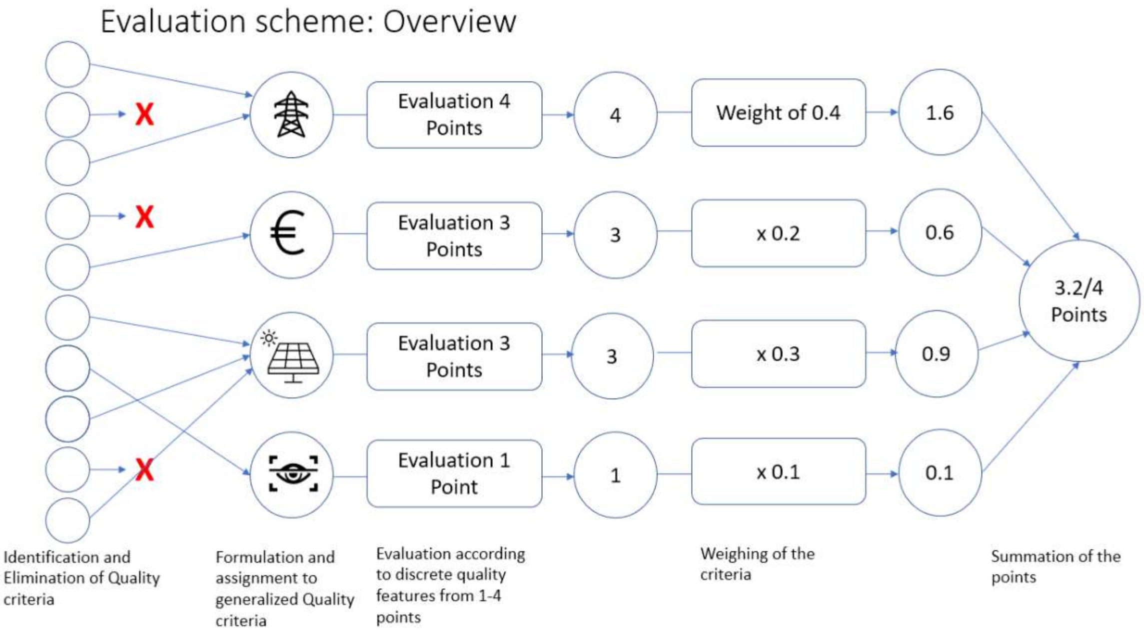
As the criteria setup of the rating system as well as the weighting factors are initially highly dependent of the subjective view of a single individual, the quality of the final result is questionable. Therefore another approach from [29] was chosen, to include an expert group for both the rating and weighting scheme. As this evaluation was conducted alongside the more extensive PoSyCo project, input from experts coming from different areas of expertise and familiar with the topic was immediately available. The methodology for the evaluation was presented within an online meeting after which a short discussion was held. The participants where then invited to take part in an online survey. As the participants answered the survey independent from each other, social conformity biases were avoided.[1] The survey included the inquiry for the participants name and specialty, to connect the results with the specific viewpoints and to reach out for further discussion if needed. The evaluation scheme was again described in detail and the opportunity, to give feedback to each of the evaluation criteria was provided. Finally each participant was asked to give their opinion to distribute the weighting factors. It was found, that although experts were consulted, the individual opinions strongly deviated from each other. An initial suggestion for the weighting distribution was given, which also slightly influenced the results. The relatively low number of participants as well as the strong differences or indecisiveness of the answers suggested a higher number of participants with an even higher degree of specialization than in this evaluation. Still it is the closest approach to a representative result and the average of the weighting factors w_j was calculated as result. The expert opinions and their written feedback to their rating factors was included in the discussion of the results. The individual feedback for the criteria-point-system was directly adopted in the present version.

5.6 Overview

In Figure 5.1 a visualization of the rating process for one Algorithm is presented. The process is started on the left, with gaining a general overview over the topic via literature review and discussions with different stakeholders. Unspecific quality criteria are found, which are listed up. In the first step, criteria are eliminated, which are either outside of the scope of the evaluation, repetitive or knock-out criteria. The remaining unspecific criteria are prioritized and compacted to a smaller number of generalized criteria. The sub-criteria are stacked, with less important characteristics being only counted in the score, if more important characteristics are fulfilled. The individual weight of the criteria was defined by expert survey.

For the evaluation of an algorithm, it is checked against the rating criteria and awarded a certain amount of points. These points are then multiplied by the corresponding weights and added to a final score.

Fig. 5.1: Overview of an exemplary rating process



This method was chosen for an optimal coverage of the algorithms. In the next chapter, the application of this method is described.

Chapter 6

Evaluation

Following the definition of the evaluation method, a consistent scheme was defined to cover all relevant points. The process was first to read and understand the algorithms and write down their basic functionalities. Next, starting from holistic quality attributes, more specific quality factors were derived. This was a loose process of brainstorming, where certain factors were combined and others added or deleted completely. In the end, from the many quality attributes that were identified, five factors were defined to represent the overall system quality:

6.1 Factor Performance and Safety

The most important factor is the ability of an algorithm to score its main objective of protecting grid infrastructure without disruption of supply to all users of the grid. The requirements are comparable to those of grid protection equipment.[5] This includes the reliable, accurate and fast detection of a critical situation as well as a selective and appropriate reaction to mitigate it. Short-circuit safety in the low voltage grid is assured by the technique of grounding the star-point and use of high short circuit currents for rapid fault detection and switching of the appropriate fuses. Overloading of equipment, especially underground cables, is prevented by circuit breakers with specific tripping characteristics. Overloading of segments of power lines and cables far away from the transformer at times of high decentralized production and demand, is currently avoided through limited power allocation for such grid users. This way future grid safety is ensured, but not necessarily safety of supply. By allowing the integration of large numbers of EV-charging stations using coordination algorithms, the grid is theoretically operated above its capacity limits. It must be ensured by design, that errors in the coordination-system, will not lead to an overloading of the grid and a subsequent supply failure. This can be achieved by setting a safe minimum charging power in the charging stations on which will be dropped back if the control algorithm system or communication fails. Another performance aspect is the transient behavior of the grid reacting to a coordination algorithm. Voltage and loading oscillations must be avoided, as limits might be violated at their peaks and charging hardware damaged. As a secondary performance aspect, line loading should be held at its configured limit. This optimizes charging time and uses grid capacity optimally.

6.1.1 Algorithm 1: Schultis, Sparse Measurement

The configured limit for loading, which is set very conservatively at 60% capacity, is violated by the algorithms which use timers to wait for the next permission. Power oscillations are produced, which reduce controllability of the system. By increasing waiting times, oscillations are decreased, but still occur. This problem could be partly mitigated, by setting pseudo-random delay-timers within a certain range. Oscillations would still occur, as all controllable loads are set to their minimum at the same time, if violations of the configured limit occur. The conservative measure of reducing charging power until the end of a charging cycle avoids violation of the configured

Points	Criteria
1	Maximum equipment loading has been exceeded. And/Or suboptimal equipment utilization.
2	Maximum equipment loading has not been exceeded, violations or oscillations (within one computation cycle) above the configured loading limit. And/Or suboptimal equipment utilization.
3	Maximum equipment loading has not been exceeded, but oscillations above the configured loading limit. Or suboptimal equipment utilization.
4	Maximum equipment loading has not been exceeded, no violations and no oscillations at the configured loading limit. Additionally optimal equipment use.

Tab. 6.1: Performance and Safety, Evaluation Scheme

limits, but can be viewed as an inelegant solution, as available loading capacity is not used, and the charging time affected negatively. The primary requirement of avoiding loading limitation is mostly met.

Using the best suited variety of this algorithm it scores 3 Points for Performance.

6.1.2 Algorithm 2: Schultis et al., Coordinated Charging

In several of the modelled scenarios of this algorithm, not only the configured, but also the nominal loading limits are being violated. This is due to long waiting times between measurements and a high configured limit at 90% of loading capacity. In the more realistic scenario, of a non-ideal state-estimation, loading is being held very accurately at the configured limit, therefore optimizing line loading and charging time.

The variety of this algorithm most suited for comparison is “one Signal per Feeder” with “non-Ideal state estimation”. It scores 3 points.

6.1.3 Algorithm 3: Deters et al., Insignificant Production

As this algorithm has not been simulated in the corresponding paper, the evaluation for functionality will be based on description. The algorithm includes an increment for setpoint corrections, which allows finetuning to optimize transient behavior. This should avoid oscillations. Given a short enough sampling time, the algorithm can follow the configured limit very accurately. In this variant of the algorithm, overloading is detected by measuring the current at the feeder beginning. If this current exceeds a set limitation, a warning indication is given. As it is not mentioned specifically, it must be assumed, that the maximum current limitation is set by the device or power line with the smallest maximum current, which is transmitting the whole power. This is not critical for functionality but makes optimal grid utilization impossible. As this algorithm fulfills all requirements but the equipment utilization, it scores 3 points.

6.1.4 Algorithm 4: Deters et al., Generalized Solution

This algorithm has an identical approach to Algorithm 3, except it using state estimation by implementing a simple artificial neural network. The functionality of this state-estimation approach is being described in (Werner et al, 2018) and shows a high level of accuracy. This allows for the implementation of large amounts of decentralized production and consumer loads. Loading of single grid segments is estimated using only a small number of real-time data inputs. Again, high level communication is not only possible between controller and user, but also between grid operator and controller, which allows for higher level functionalities. For performance, this algorithm scores 4 points.

6.1.5 Algorithm 5: Bharath et al. et al.

As this system is generally focused on a slightly different scope, performance evaluation is not easy. In the current version of the algorithm, only voltage violations are being monitored, not line loading. In the simulation, the voltage band is being maintained accurately within its configured limits. Implementation of load-flow analysis similar to Algorithm 3 and 4 seems simple, as high-level processing, communication and sensor data are available. Safety features are not being described but can be implemented effortlessly. The interesting aspect of this system is it´s high versatility. It is used not only for managing grid capacity, but additionally to process a real-time peer to peer market settlement process. As well as energy management within the renewable energy community. For performance, this algorithm scores 4 points, as it is reasonable to assume it would fulfill its primary requirement and has the possibility to integrate a wide variety of secondary features.

6.2 Factor Adaptability

As the low voltage grid historically had the simple task of distributing energy unidirectional, from higher grid levels down to the consumer, minimal effort was put into grid control measures. Distribution stations and distribution network include by far the most infrastructure facilities of any electricity grid and are therefore a significant cost factor. For "digitalization" of these grid elements, large investments will be necessary. This includes hardware, software and especially personal cost during construction and operation. Before making an investment decision, it is important for any measure taken in this environment, to be on the one hand suited for solving the problem of grid stabilization but also adapt this functionality as requirements change and be adapted to fulfill as many secondary tasks as possible. This evaluation can be seen as coarse overview, as not all technical details for communication infrastructure or future use-cases can be provided. The primary requirement for this factor, is for the system to fulfill its primary function, if changes are made on the physical grid or user composition. An automatic adaptation is as an instance an algorithm, that is being adapted continuously, using new historic grid data or live data streams. As this function is more important, it is a prerequisite for scoring a higher number of points. Another requirement is the integration of other actors, which can be controlled jointly or separately from the charging stations. The best-case scenario is a distribution grid with full communication infrastructure, in which user-stations can communicate with the central controller, as well as each other, to coordinate flexibilities, grid stabilization functionalities, or fulfill energy-community tasks.

Points	Criteria
1	Adaptations for changing user-composition and feeder-structure necessary.
2	Automatic Adaptation on changes.
3	Automatic Adaptation on changes, additionally, extension for additional controllable actors possible.
4	Automatic Adaptation on changes, additionally, extension for additional controllable actors and bidirectional communication possible.

Tab. 6.2: Adaptability, Evaluation Scheme

6.2.1 Algorithm 1, Schultis, Sparse Measurement

This algorithm uses a unidirectional powerline-communication. For privacy reasons and reducing complexity, user stations are not able to communicate with the central controller. This means only passive tasks may be implemented. As there is only one binary signal per feeder, all controlled loads will be restricted equally. As there are already significant oscillations, using the same algorithms at the consumer, these would grow in amplitude and destabilize the grid situation further. Scaling up this system is very easy and only requires the integration of additional user stations or adjusting the limits at the central controller.

For these reasons this algorithm is scoring 2 points.

6.2.2 Algorithm 2, Schultis et al., Coordinated Charging

Here a unidirectional binary signal is sent to the user wallbox. Three different variations, with one signal peer LV-grid, one signal per feeder and one signal per wallbox are investigated. For adaptability, there is no significant difference to Algorithm 1. For estimating grid congestions, user load profiles are used to calculate load flow. This requires a model of the grid topology and load composition of the consumer plants. Changes need to be detected and considered for correct calculation. This algorithm scores 1 points for adaptability.

6.2.3 Algorithm 3, Deters et al. Insignificant production

Here, an adaptable PLC communication system is described. It is not only possible to adjust the controller algorithm from a distance, but also for the customer plants to communicate metering data or other low-level information to the controller or network operator. This allows for a distributed control system, with individually controllable loads, actors and producers. Additionally, communication between grid participants is technically possible, which is promising for renewable energy communities. Basic data like 15-minute smart meter data or load reduction signals are transmitted via low frequency bands as CENELEC A, higher frequencies for non-function relevant information. This version of the algorithm does not account for notable decentralized production within the low voltage feeders. Therefore, it is not suited for the later integration of such plants. It is scoring 4 Points.

6.2.4 Algorithm 4, Deters et al. Generalized Solution

This algorithm is identical to the one before, except there being an artificial neural network to estimate the system state. The system can be continuously adapted to include different user compositions, grid topologies and use profiles. There is a wide range of possibilities for different levels of cognification to exist in the same grid. This algorithm scores 4 Points.

6.2.5 Algorithm 5, Bharath et al.

Because this system is designed in a way to execute higher level control tasks it is suited to fulfill several functions beyond the functionalities required in this comparison. The use of a blockchain for secure communication, allows for the transmission of a large range of information and the implementation of advanced control systems. The work by Bharath et al. not only suggests a centralized capacity management system using load flow-calculation, but also a real-time peer to peer energy market settlement process. Due to the fact, that this system requires a high level of connectivity between user, sensors and central controllers, several additional functionalities may be implemented. Focusing exclusively on adaptability, this system scores 4 points.

6.3 Factor: Regional Applicability

This evaluation factor was chosen to specify the suitability of the algorithm for different grid topologies. This applies especially to the differences between urban and rural grids, as the share of decentralized production compared to the intensity of consumer loads is significantly higher in rural areas. Several of the evaluated algorithms assume the highest line-loading to be located at the feeder-beginning, close to the transformer. This is only true if there are no large decentralized production plants. In traditional low voltage grids, the maximum allowed connected power is estimated by the grid operator using methods as stochastic diversity factors and standard load profiles (ELWOG). Standard load profiles are improved by large-scale smart meter implementation but cannot reliably predict large erratic loads as electric vehicle charging. To avoid overloads, high safety margins must be considered, which cause low grid utilization and reinforcement investments. With the emergence of renewable energy communities, renewable energy will be transported between grid participants. To allow the integration of large, decentralized producers, it is necessary to manage grid capacity more accurately. For a high-quality system, all variations in grid topologies must be covered. Secondary requirements are the applicability to a generalized grid situation.

Points	Criteria
1	No significant amounts of decentralized production possible.
2	Only small-scale decentralized production.
3	Large scale decentralized producers.
4	Reacts to all forms of producers/consumers and can be integrated in every grid.

Tab. 6.3: Regional Applicability, Evaluation Scheme

6.3.1 Algorithm 1, Schultis, Sparse Measurement

This algorithm is based on a collective view of the current grid situation. It uses consumer plant load profiles and a worst-case scenario to predict feeder congestions. This means it is assumed, that the full loading at the feeder beginning is flowing through the feeder segment with the lowest loading capacity. It scores 2 points.

6.3.2 Algorithm 2, Schultis et al., Coordinated Charging

Here historical and actual user load profiles are used to calculate LV grid load flow. For this grid topology must be specified. It is applicable to all grid situations and will consider overloads in grids with large amounts of production and renewable energy communities. It is scoring 4 points.

6.3.3 Algorithm 3, Deters et al. Insignificant production

This algorithm is assuming a simplified scenario without a noteworthy amount of distributed production. This is a valid assumption for most urban and selected rural LV grids. It is scores 1 points concerning regional adaptability.

6.3.4 Algorithm 4, Deters et al. Generalized Solution

This variation of the same system is performing state estimation using an artificial neural network. It is automatically adapting to the grid topology it is placed into and has the potential to continuously react to new grid situations. This makes it suitable for all applications. It scores 4 points.

6.3.5 Algorithm 5, Bharath et al.

This algorithm uses the holomorphic embedding load-flow method (HELM) to compute loading of grid segments, within a complete optimal capacity management (OCM) system. This can be considered the most comprehensive way of monitoring a LV grid, but also requires a high level of inter-connectivity. Because there is no restriction regarding regional applicability, this system scores 4 points.

6.4 Factor Scale-Up

As there is strong growth in the E-mobility market, grid-stabilizing measures will have to be implemented as fast as possible. This requires their integration to have a low threshold in terms of hardware, software, and personnel costs. If they are to be implemented in operational infrastructure, resulting supply-interruptions must be considered. This evaluation aspect is meant to judge the effort needed for implementing a coordination algorithm large-scale. Once a system has been developed and tested, it is being implemented into the existing infrastructure. The cost structure for implementing a developed system is different from a prototype, especially labor costs are much more sensitive. Another important issue is the large number of devices which need to be installed for a fully coordinated charging infrastructure. This emphasizes the need for a cost-effective and easy to install system. Another important aspect is the need for maintenance of any system parts, which will be included into this factor. As an exact breakdown of the needed hardware, steps for execution and personal costs are neither given in the evaluated papers, nor lie within the scope of this work, only a rough overview of the systems is given, and the results evaluated against each other. The algorithms evaluated here are all based on a centralized control strategy, with a controller sitting at the low voltage distribution station or a central community battery as in the case of Algorithm 5. These controllers mainly differ in their requirements for processing and communication, as load-flow simulation is relatively computation expensive and in several cases a communication link with the grid operator is required. More sensitive than the hardware cost are the personal costs for setting up an overlying control system, installation, and parametrization of the individual controllers.

Points	Criteria
1	Sensors and bidirectional communication at each controllable node and/or high computational effort.
2	More expensive (High communication requirements, high computational effort).
3	More economic (Low communication requirements, low computational effort).
4	The most efficient solution of the investigated algorithms (Minimal communication requirements, lowest computational effort).

Tab. 6.4: Scale-Up, Evaluation Scheme

6.4.1 Algorithm 1, Schultis, Sparse Measurement

Algorithm 1 is relatively simple and does not require any load-flow calculations. This means only the voltage at each feeder end and real-, inductive power and voltage measurements at the feeder beginning must be measured. The communication with the wallboxes and the peripheral voltage sensors is conducted via powerline communication. As the computing requirements are low, more than many feeders can be managed by a single controller in the distribution station. Hardware costs are: A controller capable of powerline communication, measuring devices for voltage, active and reactive power. For each feeder subsection: voltage sensors at the feeder end with powerline communication abilities. At the user's site there must be a PLC receiving unit either in form of a wallbox with receiving interface to the charger, or a charger which can take over these tasks. Personal is only required during set up or if there are changes in the grid topography. The parameterization of the system is critical, especially the estimated consumer loads. These need to be adapted for each feeder segment to correctly represent the specific user composition. Permissible maximum loading needs to be determined from grid data. For voltage-regulation, signals for each feeder-ends need to be set up. As all users in the feeder receive the same signal from the controller, the setup of each receiver within a feeder can be identical. This unidirectional communication possibility has comparably low requirements and scores 3 Points.

6.4.2 Algorithm 2, Schultis et al., Coordinated Charging

Here from three different simulated algorithm variants, the most comparative one was chosen for the evaluation. It is called “one command per LV feeder” with non-ideal state estimation. Again, one signal is sent to all wallboxes in a feeder via powerline communication. Loadflow-calculations are conducted using a deposited power system and consumer models and estimated consumer-plant load profiles. As for measurements this algorithm only requires the primary voltage at the transformer. A critical factor might be the need for LV-grid and consumer plant models. This means for each controller the grid topology and consumer composition need to be known. It is unclear if such information is easily available for the grid operator and how it would be practically implemented. Nevertheless, this requires a specific programming for each feeder and qualified personnel. It is also not clear how robust this model is to changes like additional electric vehicles or other additional loads, which would cause the model to be inaccurate. For the high computation requirements and significant skilled labor during implementation and operation, this algorithm scores 1 point for scale up.

6.4.3 Algorithm 3, Deters et al. Insignificant production

This system uses a simplified system by assuming only a small amount of distributed production. Measuring the feeder current and voltage at the distribution station is enough to estimate the current system state. This requires very little or already available measurement hardware and almost no computation abilities. Communication with the charging stations is conducted via powerline communication. Implementation does not need any higher-level programming and the only parameter to set is the maximum current limitation. The setting of this parameter is critical for system safety and a conservative setting, depending on the feeder composition, is necessary. This is the most economical solution, and it scores 4 Points.

6.4.4 Algorithm 4, Deters et al. Generalized Solution

The difference between this algorithm and Algorithm 4 is state estimation using an artificial neural network. The cited approach is using current and voltage measurements at the distribution station as inputs, as well as the outside temperature and solar irradiation as exogenous inputs. The controlling devices in this version have a powerline-communication link with a centralized IT-system, which allows for the gathering of training data for the ANN. The trained network can then operate without a centralized data connection in the distribution station with only local sensor inputs. The centralized computation requirements and specialized labor cost are noteworthy, especially for large scale implementation. For each distribution station, insignificant computing power is required. As the requirement for communications is relatively high, but computing requirements are low, this algorithm scores 2,5 Points.

6.4.5 Algorithm 5, Bharath et al.

The scope of the system exceeds the scope evaluated in this work which makes a direct comparison difficult. This algorithm is based on a blockchain-approach for communication and transactions. There are so-called “controllable busses” which in this case represent the charging stations at the customer site. Each controllable node has real time communication requirements, processing requirements and sensors for active and reactive power consumption, voltage, and phase angle. The central controller not only processes optimal equipment loading but also fulfills peer-to-peer market settling processes within an energy-community. Judging from the large amount of real-time sensor data, continuous optimization, settlement and communication processes, high computing requirements are assumed. Specific skills, as well as a large amount of metering and communication hardware are necessary to set up the system. It is not clear how high the scale-up cost is for each additional system. As renewable energy communities currently have a small economic profitability range, it is crucial to reduce implementation and running cost as much as possible. Judging by the high computational and communication requirements, this algorithm is the most expensive to implement and it scores 1 Point.

6.5 Factor Privacy and Security

This factor was chosen to cover issues arising from implementing communication and computation capabilities into a semi-private network. Although a detailed analysis lies outside of the scope of this work, the most important concepts will be addressed. Several of the evaluated algorithms use power-line-communication for fulfilling their task, which means many grid participant can access the encoded data stream. Power systems have been targeted by malicious attacks in the past and there are reports of smart-meters being hacked. According to (Faquir et al, 2020) the most common types of attack on a smart grid are phishing, denial-of-service, malware spreading, eavesdropping and traffic analysis. Phishing refers to the gathering of consumer information to gain access to protected systems, to reveal more sensitive information or get access to bank accounts. Denial of service is a way of manipulating a system in a way, so it is not capable of fulfilling it´s designed function. Malware spreading is a large threat in Internet of Things applications, as many devices can be affected within a short time. Eavesdropping and traffic analysis might be used in different ways, either for analyzing user behavior for criminal uses or selling user data for commercial uses. There are many strategies against cybersecurity threads. The simplest in case of smart-grid applications is the avoidance of non-essential user data, part of a strategy called “privacy by design”. Only essential user data is communicated, it is as user specific as necessary and will be stored only for as long as necessary. It is a requirement that users have access to their measured data and all data use is transparent. Another way for malicious actors to manipulate the system or other devices is through the availability of bidirectional communication. A higher-level communication link provides more possibilities for hackers or malware to access and spread. All systems which use simple binary signal have the security threat of some actor duplicating said signal, to either charge These thoughts were used as a basis for evaluating the communication part of the system, which is separated as follows:

Points	Criteria
1	User data is being communicated in public network.
2	Bidirectional communication in public network.
3	Only essential user data is communicated, specific Permission for a single wallbox.
4	No user data is communicated, Permissions for whole feeder.

Tab. 6.5: Security and Privacy, Evaluation Scheme

6.5.1 Algorithm 1, Schultis, Sparse Measurement

This algorithm does not need measurements at the consumer for operation. Only feeder-specific Voltage measurements are transmitted back to the controller, possibly via powerline communication. There is one binary signal being sent to all charging stations within one feeder. From a privacy standpoint, this is an optimal solution and scores 4 Points

6.5.1.1 Algorithm 2, Schultis et al., Coordinated Charging

For this system, the required real-time measurements are the voltage at the transformer. User data is not directly communicated but production and demand profiles are used. This data collection is done by the smart-meter network, managed by the grid operator. Safe communication methods have been established for smart meter data transmission, which is outside of the scope of this evaluation. The communication between a central IT-system, to distribute the load-profiles and consumer-plant models to the specific controllers is a private system and can therefore be assumed uncritical. Assuming the controller is managed by the grid-operator, the same privacy regulations for the use of metering data must be applied. As this algorithm is sending specific permissions to single wallboxes via power-line communication, this information might be intercepted and analyzed to determine charging behavior. According to the defined rating system it scores 3 Points.

6.5.2 Algorithm 3, Deters et al. Insignificant production

Again, a central IT-system is communicating with a central controller sitting at a distribution substation. The real-time measurements are performed within the distribution station, with no communication needs. The signal to the charging station is not binary, but a ramp between minimum and maximum charging power. The same signal is received by all charging stations, which reduce their power to a certain percentage of their maximum power limitation. This automatically favors charging stations with larger capacities. Additionally, the authorization to set the maximum power limitation must be controlled, as manipulation would allow users to charge their own vehicles unrestricted on cost of the community. Concerning Privacy and Security, this is a good solution, and it scores 4 Points.

6.5.3 Algorithm 4, Deters et al. Generalized Solution

This second variation of the same algorithm is using an ANN based on historic user data of the specific grid region, measurements at the distribution station and live weather data to estimate the grid status. Wherever historic load profiles of users are processed or stored, it must be ensured that this information is protected. All other aspects are equal to Algorithm 3, it therefore scores 4 Points.

6.5.4 Algorithm 5, Bharath et al.

As this System is based on a blockchain-network, it has a significantly different approach to communication. Sensor data from the customer site is written into a blockchain and transmitted directly with a centralized controller. Although it is encoded, user information is processed and stored temporarily at the central controller. Individual commands are sent out to each flexibility, in this case, the charging stations. It is difficult to judge the vulnerability of this system against threats or manipulation. As it is designed as a local peer-to-peer energy market, it can be assumed that the final system will score a high degree of user privacy. In scope of this evaluation, it is scoring 1 Point.

6.6 Weights

The second stage of the evaluation scheme consists of a consistent weighting of all evaluation factors. This is done to consider each factors contribution to an overall numeric quality measure. This step has significant impact on the result and an exact weight distribution is dependent on the subjective viewpoint.

The expert survey yielded following results:

Participant	Performance and Safety	Adaptability	Regional Applicability	Implementation Cost	Security and Privacy
Suggestion	30	20	20	10	20
1	30	15	10	15	40
2	20	20	20	20	20
3	30	20	20	10	20
4	40	10	10	25	15
5	30	10	10	30	20
6	30	20	20	15	15
7	30	10	10	40	10
Averages from survey	29.3	15	14.3	22.1	19.3

Tab. 6.6: Results from the expert survey

It can be noticed, that the results are very similar to the initial suggestion. Implementation cost seems to be much more significant, as initially expected. This mostly on the cost of adaptability and regional applicability. Combined with the background of the individual expert which is not publicized, this gives a lot insight to a general opinion about a topic.

6.7 Numerical Results

Summarized, the points from the rating factors were following:

Algorithm	Performance and Safety	Adaptability	Regional Applicability	Impl. Cost	Security and Privacy
Algorithm 1: Schultis et al., Sparse Measurement	3	2	2	3	4
Algorithm 2: Schultis et al., Coordinated Charging	3	1	4	1	3
Algorithm 3: Deters et al., Insignificant Production	3	4	1	4	4
Algorithm 4: Deters et al., Generalized Solution	4	4	4	2.5	3
Algorithm 5: Bharath et al. et al.	4	4	4	1	1

Tab. 6.7: Results from the Rating factors

Taking into account the described methodology and calculation, following final numeric rating values are obtained:

Algorithm	Points
Algorithm 1: Schultis, Sparse Measurement	2.9
Algorithm 2: Schultis et al., Coordinated Charging	2.4
Algorithm 3: Deters et al., Insignificant Production	3.28
Algorithm 4: Deters et al., Generalized Solution	**3.48**
Algorithm 5: Bharath et al. et al.	2.76

Tab. 6.8: Final Evaluation Scores

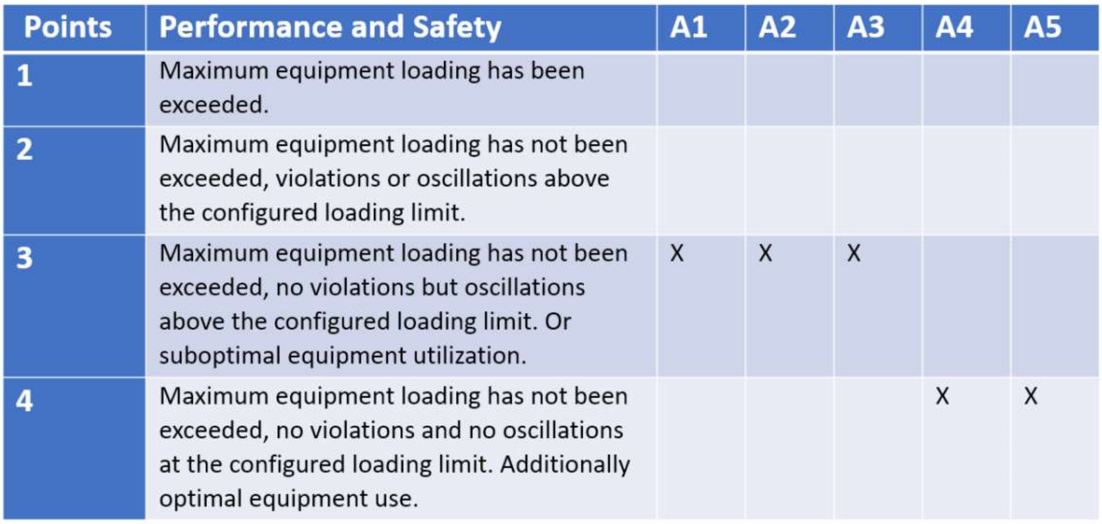
It can be seen that Algorithm 4, by Deters et al. with the version "Generalized Solution" scores the most points. This is the algorithm, which is using an artificial neural network, historic user data as well as real time environmental data, to predict grid loading. It is the most effective and easy to implement system in this evaluation. It also has the large advantage of having a direct connection to a centralized IT-network, which allows it to be adapted continuously to changes on the demand side or decentralized energy production.

Chapter 7

Summary of Results

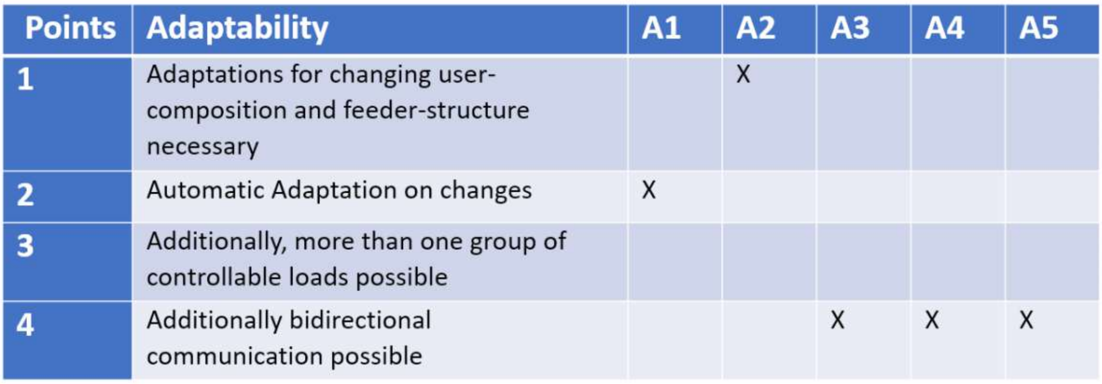
Following rating criteria and evaluations were reached by the individual system. The Algorithms are numbered from A1 to A5.

Fig. 7.1: Factor Performance and Safety



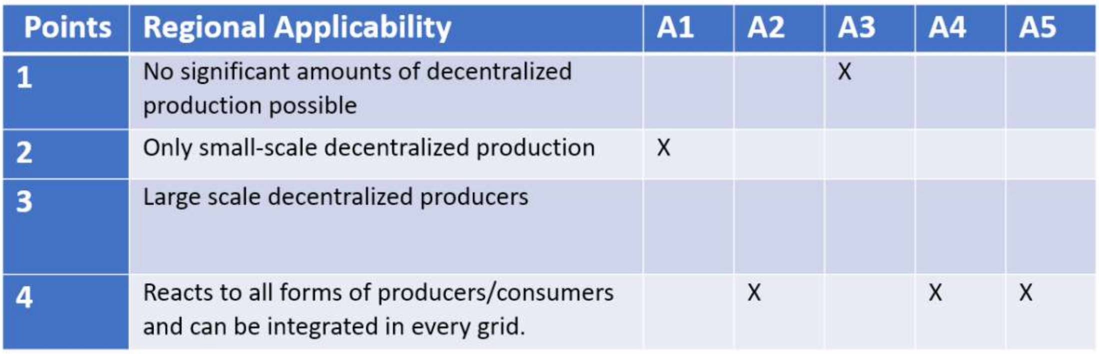
Points	Performance and Safety	A1	A2	A3	A4	A5
1	Maximum equipment loading has been exceeded.					
2	Maximum equipment loading has not been exceeded, violations or oscillations above the configured loading limit.					
3	Maximum equipment loading has not been exceeded, no violations but oscillations above the configured loading limit. Or suboptimal equipment utilization.	X	X	X		
4	Maximum equipment loading has not been exceeded, no violations and no oscillations at the configured loading limit. Additionally optimal equipment use.				X	X

Fig. 7.2: Factor Adaptability



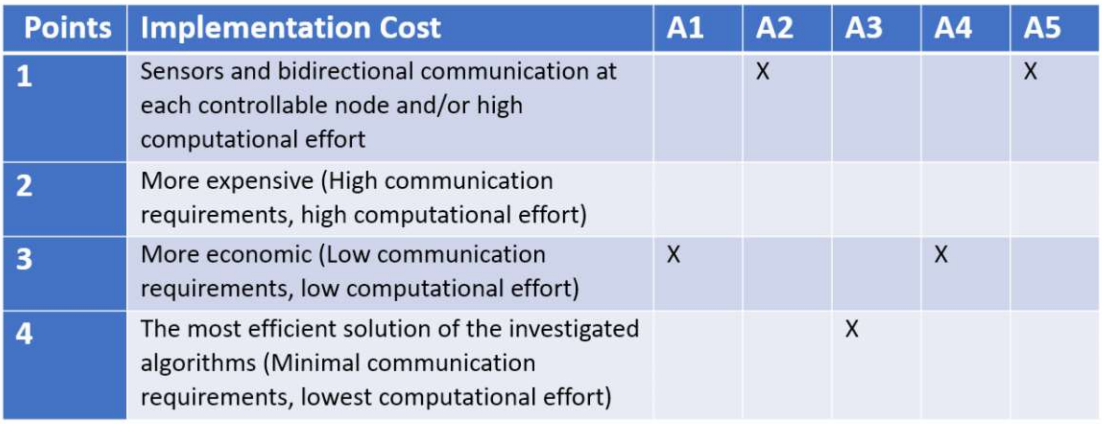
Points	Adaptability	A1	A2	A3	A4	A5
1	Adaptations for changing user-composition and feeder-structure necessary		X			
2	Automatic Adaptation on changes	X				
3	Additionally, more than one group of controllable loads possible					
4	Additionally bidirectional communication possible			X	X	X

Fig. 7.3: Factor Regional Applicability



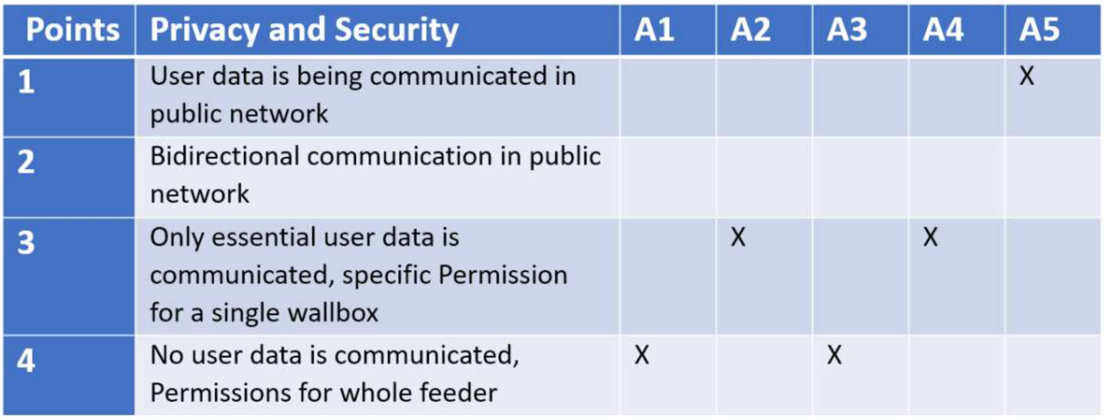
Points	Regional Applicability	A1	A2	A3	A4	A5
1	No significant amounts of decentralized production possible			X		
2	Only small-scale decentralized production	X				
3	Large scale decentralized producers					
4	Reacts to all forms of producers/consumers and can be integrated in every grid.		X		X	X

Fig. 7.4: Factor Implementation Cost



Points	Implementation Cost	A1	A2	A3	A4	A5
1	Sensors and bidirectional communication at each controllable node and/or high computational effort		X			X
2	More expensive (High communication requirements, high computational effort)					
3	More economic (Low communication requirements, low computational effort)	X			X	
4	The most efficient solution of the investigated algorithms (Minimal communication requirements, lowest computational effort)			X		

Fig. 7.5: Factor Security and Privacy

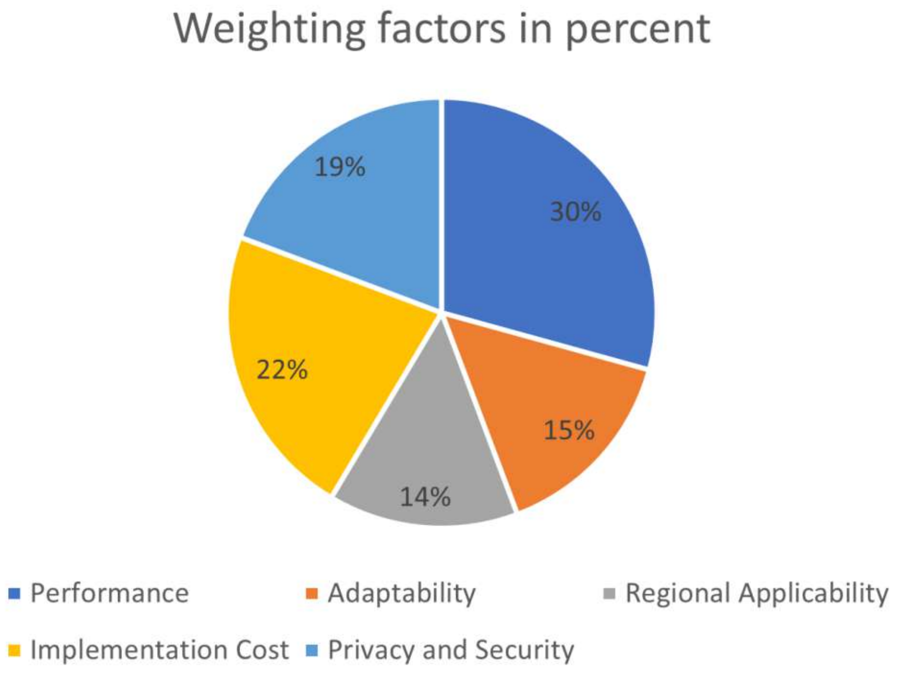


Points	Privacy and Security	A1	A2	A3	A4	A5
1	User data is being communicated in public network					X
2	Bidirectional communication in public network					
3	Only essential user data is communicated, specific Permission for a single wallbox		X		X	
4	No user data is communicated, Permissions for whole feeder	X		X		

Following a graphical presentation of the numerical results.In 7.6 it can be easily observed that following the expert survey, more then 50% of the weight is put on Performance and Scale-Up. As the survey was conducted among experts with a focus on economic aspects, these results are representative.

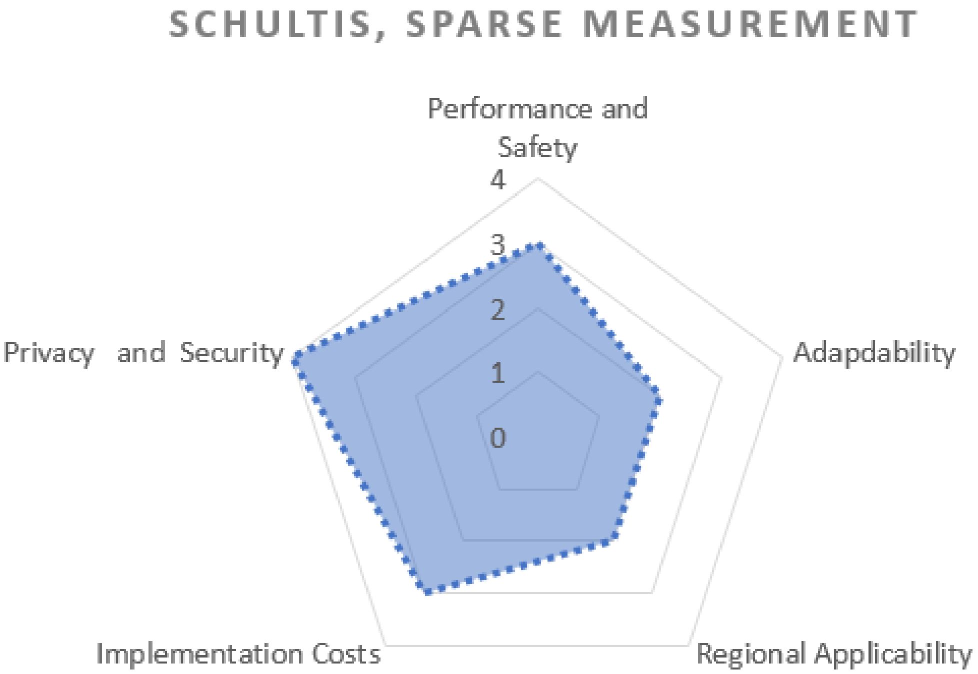
In the spiderweb-diagrams Figure 7.7 to Figure 7.11 a good graphical representation of the results is given. The level of coverage of the diagram area, also shows how well an algorithm is suited to cover it´s requirements. It can be seen, that Algorithm 4 is covering the largest area. This does not yet include the weights, but is a good overview over the algorithm performance

Fig. 7.6: Weighting factors resulting from expert survey



In the spiderweb-diagrams Figure 7.7 to Figure 7.11 a good graphical representation of the results is given. The level of coverage of the diagram area, also shows how well an algorithm is suited to cover it´s requirements. It can be seen, that Algorithm 4 is covering the largest area.

Fig. 7.7: Spiderweb diagram of Algorithm 1



It can be noticed immediately, that this algorithm has rather good overall qualities, as the shape is more or less rounded. As will be discussed later, the specialized design of this algorithm, makes it very effective and safe for the specific task, but lacking in adaptability for different scenarios.

In this graphic, it can be seen, that this algorithm is sacrificing adaptability and cost for high effectiveness and regional applicability.

Algorithm 3 has very high overall quality, but significantly lacks regional applicability, which significantly cuts its quality.

The highest rating algorithm, can be easily identified, by its rounded shape, which represents a good coverage over all considered aspects. Performance, Adaptability and Regional Applicability score full points.

In this graphic, the unbalanced qualities of this algorithm can clearly be seen. Although full points are awarded for performance, adaptability and regional applicability, privacy and implementation cost factors are neglected. Although these issues may be solved by further developing this system.

It can be seen, that Algorithm 4 is covering a large area in this spiderweb-diagram, which is a simple representation for its good functionalities. Nevertheless, these numerical and graphical results tell relatively little about the quality of the algorithms, which will be discussed in the next chapter.

Fig. 7.8: Spiderweb diagram of Algorithm 2

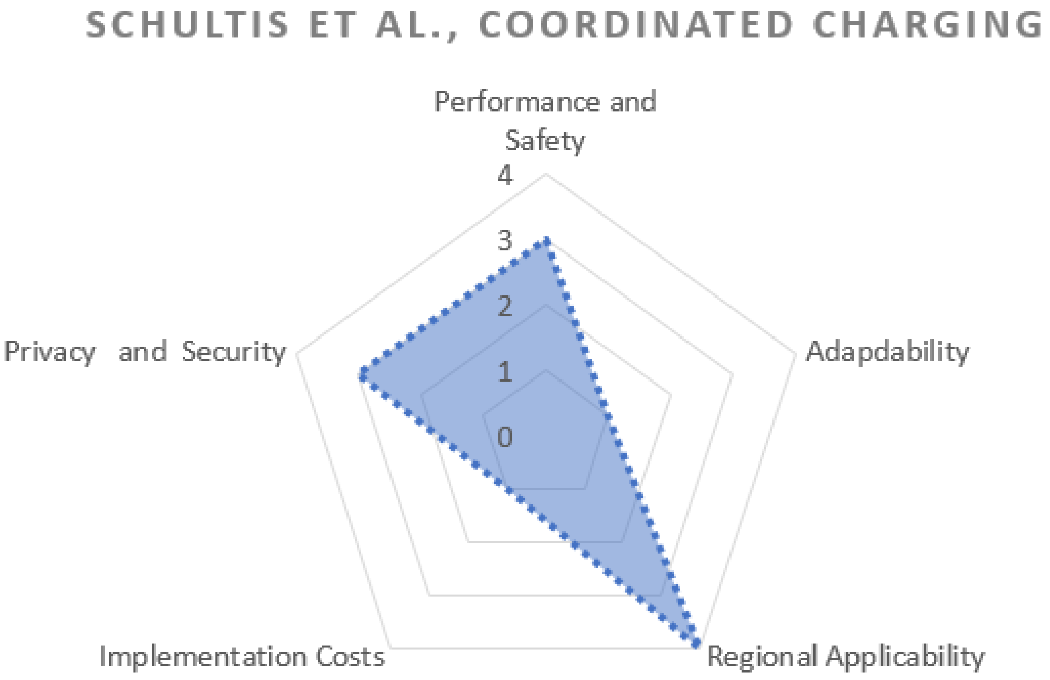


Fig. 7.9: Spiderweb diagram of Algorithm 3

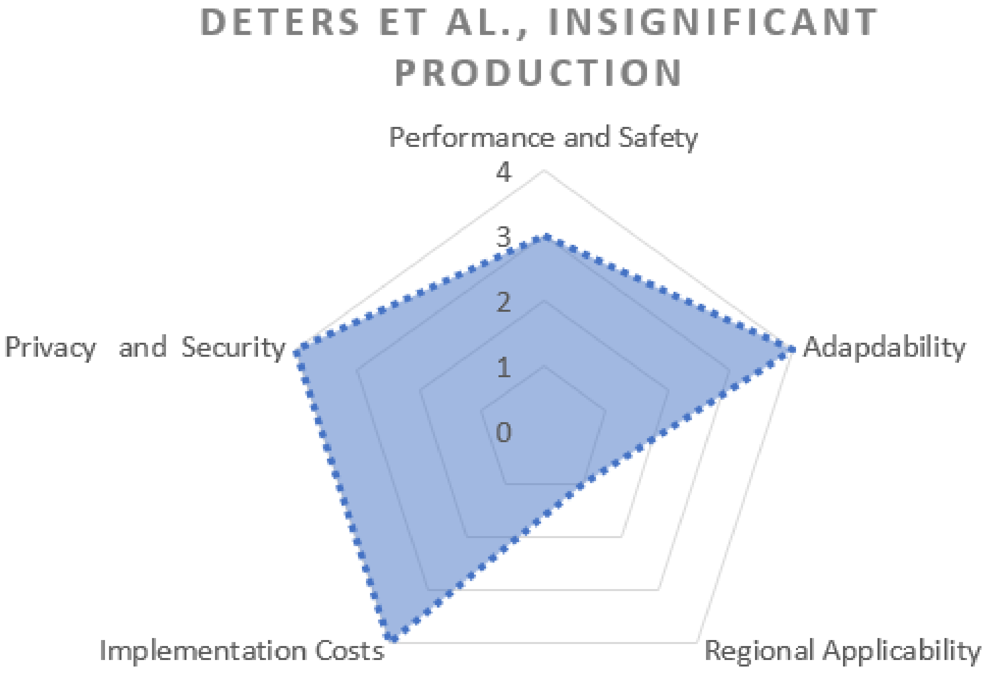


Fig. 7.10: Spiderweb diagram of Algorithm 4

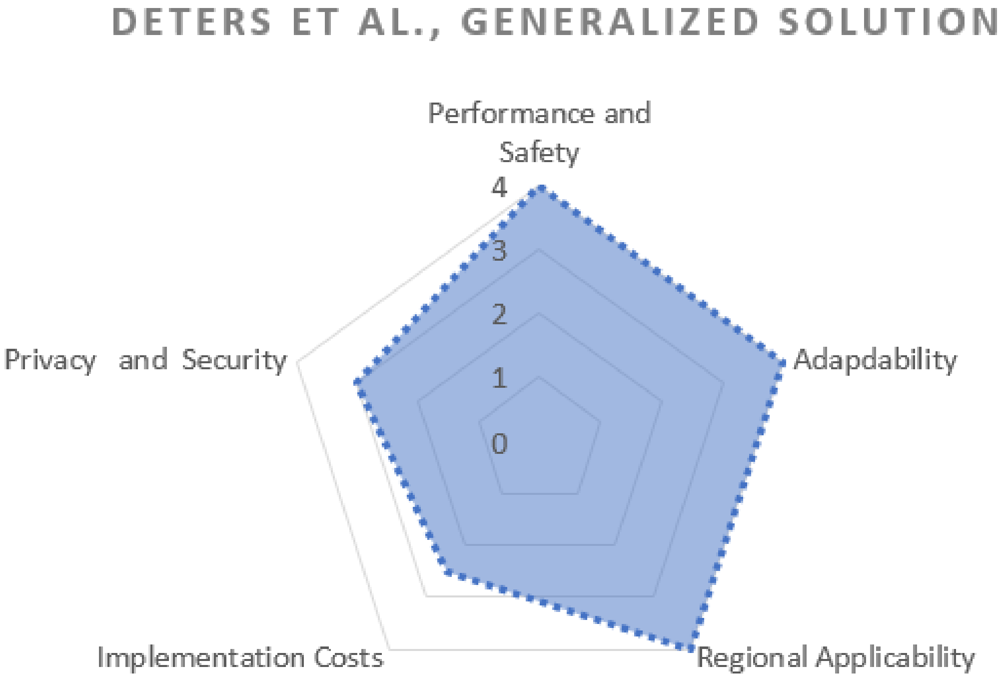
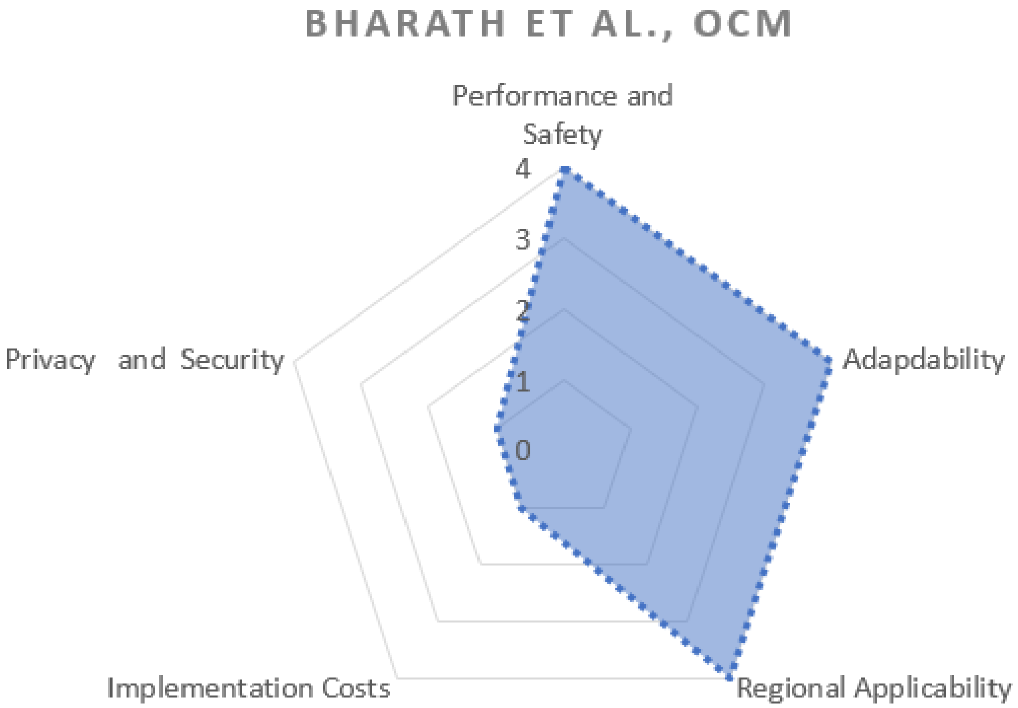


Fig. 7.11: Spiderweb diagram of Algorithm 5



Chapter 8

Discussion

In this chapter the results from the evaluation as well as other results from the different rating stages are being discussed, to put the numerical results into context. Subjective results, are being put into context and questions for further research are being discovered.

8.1 Rating Factor "Privacy and Security"

After receiving feedback from experts it was found that this factor, according to Wartzack[29], might be considered a knock-out criterion,if it is not fulfilled. As privacy requirements are significant, a system which is not fulfilling basic conditions will not be allowed to be implemented. Therefore it can be assumed that appropriate measures are taken in every control system. It was left in the evaluation as the described design choices for privacy and security will nevertheless judge the quality of a system.

8.2 Cost

The factor cost could only be roughly estimated and is a complex topic for any infrastructure within an electric grid. No reliable cost calculation for communication infrastructure could be found. A factor that is especially important is operational costs. Any maintenance tasks with low economies of scale-effects, will increase the overall system cost for a large scale rollout dramatically. Within the scope of this work, a number of problematic tasks could be identified:

- Decentralized or non-automated parameter input in algorithm
- Non-Automated data processes concerning grid capacities for each feeder.
- Training and maintenance of artificial neural network requires specialized skills. Development of highly-automated systems poses challenge.

8.3 Rating Criteria

Many system attributes were dropped for being redundant with other factors or being meaningless, as each system reaches the same evaluation. One example is the criterion "Development Cost". All systems have a certain expense while being developed within a lab environment. Hardware cost are relatively small compared to roll-out and also personal expenses are assumed to be comparable between each system and could not be accurately determined. Therefore only the roll-out cost was put into the factor "Scale-Up". It was suggested during the expert survey, to change the Point system of the rating criteria, to give a specified number of points for each fulfilled feature. This way an important feature would yield more points than a less important. It was decided against this system, as the fulfillment of a number of secondary features, without fulfillment of the primary function could lead to the same rating as the fulfillment of the primary function without secondary features. If the points for a primary feature would be significantly more valuable than a secondary feature, additional features would not have a significant impact. By making secondary features only valid, if primary functions are fulfilled, a more accurate rating was achieved. It is also possible to rank the importance of secondary functions this way.

8.4 User Impact

One aspect that was considered as a rating factor, was the impact any coordination has on the user experience. Momentarily, grid customers can expect the fastest possible charging speeds once the charging process is started. With a coordination algorithm, an intervention is made in the personal freedom of a customer, which will lead to refusal by some customers, if not managed properly. Within this evaluation, especially the charging speed was of concern. For the highest charging speed, the available grid capacity needs to be utilized maximally. This factor was therefore included into the "Performance and Safety" criterion. If this requirement is fulfilled, there is no difference between the algorithms regarding user impact. What should be additionally considered, is the implemention of an additional algorithm within the wallbox software, to make sure, a minimum state of charge is reached as quickly as possible, to provide a safety margin for emergencies. Else than that, a regulated approach should be developed, to determine minimum and maximum charging capacities and verify their compliance.

8.5 Expert Survey

The expert survey was found to be a very useful tool to determine and answer a number of complex technical questions. An interdisciplinary group has the advantage of giving a wide range of feedback and attention to underappreciated aspects. In the case of this evaluation however, it was determined, that even among experts, there is no definitive opinion about the importance of individual criteria. In Table 6.6 it can be seen, that many of the participants are influenced by the given suggestion and the final result corresponding very closely. It can either be assumed that the suggested distribution was very accurate, or a more profound system understanding and opinion formation is necessary, for a more meaningful evaluation.

8.6 Charging Infrastructure

8.6.1 Public Charging

One point that is frequently being overlooked in electric-vehicle coordination research, is the fact that almost a third of vehicle owners do not own a private parking spot or garage and therefore do not necessarily have the option of an overnight charging station, as seen in Figure 8.4. This effect is especially prominent in cities. Here especially there is a large demand for public and semi-public charging and alternative parking opportunities, should conventional individual traffic be substituted by EVs.

The permission of individual traffic in city areas above a certain population density should be restricted out of several reasons. Although EVs pose a smaller health risk through air pollution and engine noise, tire noise will be equally high. Car traffic has very high accident potential for pedestrians, bicycle riders and other car drivers. Cars require space, not only for driving, but also parking. Streets need to be constructed to withstand high stresses, which results in high amounts of ground sealing, the removal of trees, which roots damage roads, and ultimately the creation of urban heat islands. Only a share of the city population is using individual means of transport, while the consequences have to be shared communally.[13]

Investment in public charging infrastructure should always account for the coordination functions evaluated within this work and especially in the next subsection:

8.6.1.1 Charging during the Day

A completely different strategy to avoid grid congestions, is to promote possibilities for charging at points of destination. In [18] where a large number of user data has been analyzed, it can be seen, that over 70% of vehicle parking locations are either at home, or at work.

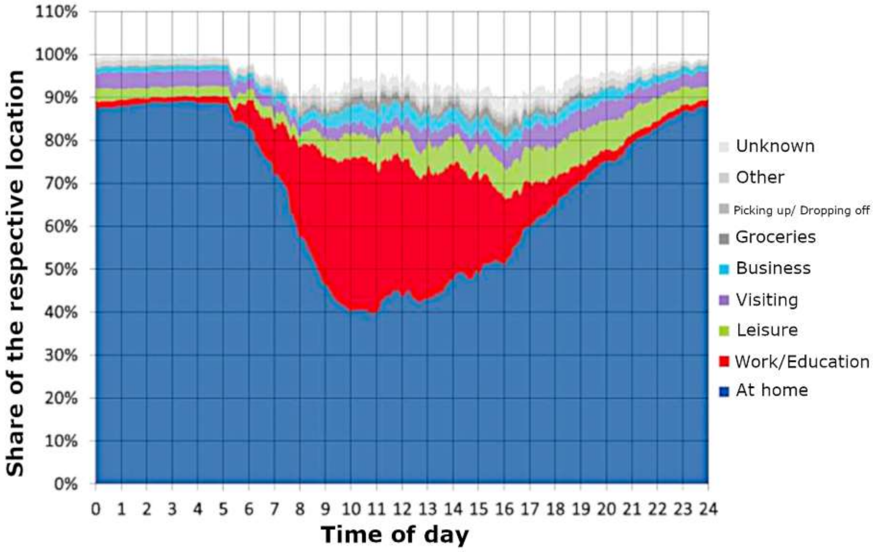


Fig. 8.1: Voltage drop in a typical feeder structure, Adapted from[25]

In 8.1 it can be seen, that especially during noon, a large share of vehicles is parked in a workplace environment. It can be assumed that especially these vehicles will be recharged once returning back home. It can be assumed that photovoltaic will make up an increasing part of future energy production. Therefore, as seen in Figure 8.2, the impact on the electric grid is especially negative without coordination. With the here discussed coordination, EV-charging loads will shift later into the evening(Arrow B). With charging possible during the day (Arrow A in the image), not only the grid situation is relieved but also PV-energy being utilized. Another possibility is to use electric vehicles as distributed charging devices. Assuming, bidirectional charging will be widely available in the future, renewable energy can be stored during the day and discharged in the evening at home. This would require an energy management system at the consumer as well as at the workplace parking location. There is also large potential in combination with citizen energy communities, with prosumers being able to use their own energy by utilizing the grid and a charging station as a service. Another possibility, is the sharing of this stored energy with other members of an energy community. These ideas rely on the existence of spare battery capacity, which can be used economically without significant battery deterioration.

Effort should be made, to lower the implementation threshold for charging stations at the workplace environment, either with subsidies or tax benefits. Also, as electric trucks will become relevant within a short time frame, these should be included in any company energy management concepts. [20]

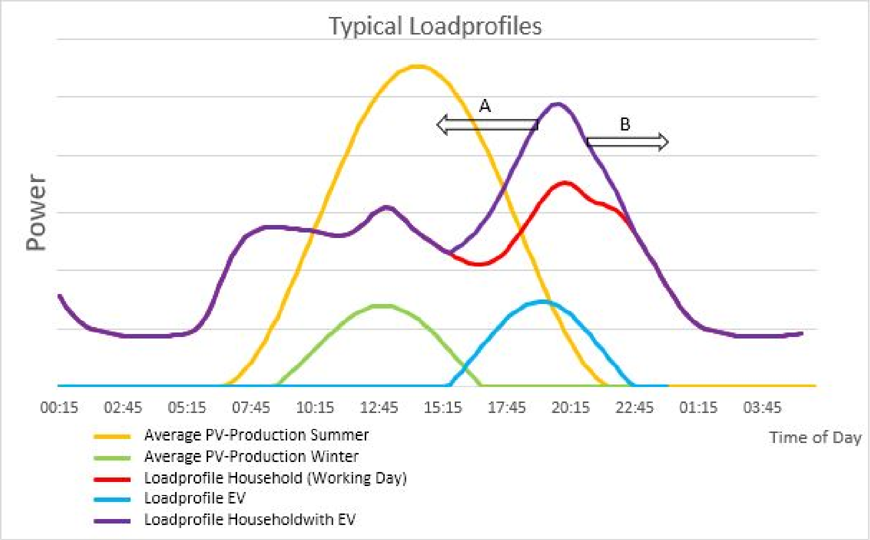


Fig. 8.2: Shifting of EV-charging loads during an average workingday, Adapted from[23]

It can be seen in Figure 8.3 that the described effect is less significant during weekends, but charging possibilities at popular leisure destinations should be considered.

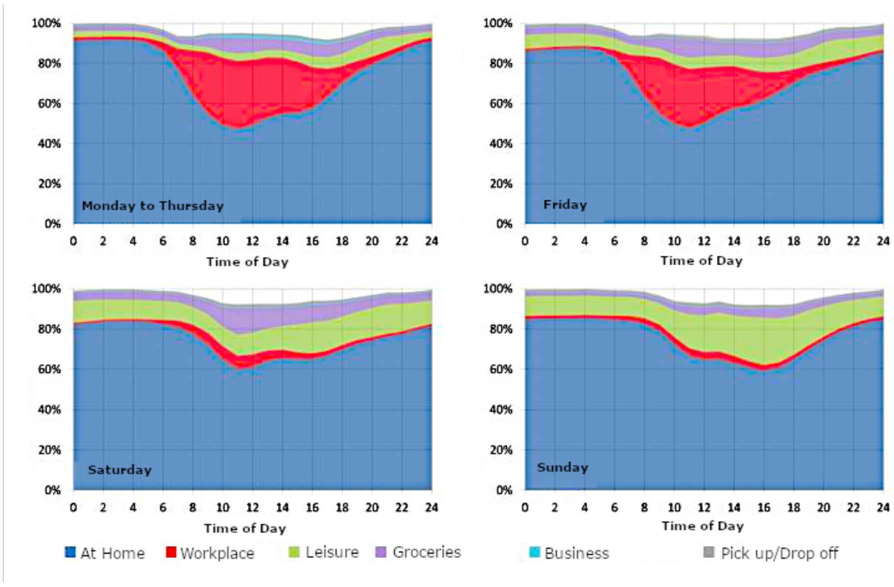


Fig. 8.3: Vehicle parking location in percent and Time of day. Adapted from [18]

8.7 Objectivity

The last issue that needs to be addressed, is the subject of the evaluator being biased towards a certain result from the beginning of the evaluation. This would lead to some aspects being considered more strongly than others which impacts the results. It is the main reason, the expert survey was conducted, as a higher number of perspectives increases the overall accuracy. Nevertheless there will always remain the bias caused by the initially suggested questions, the

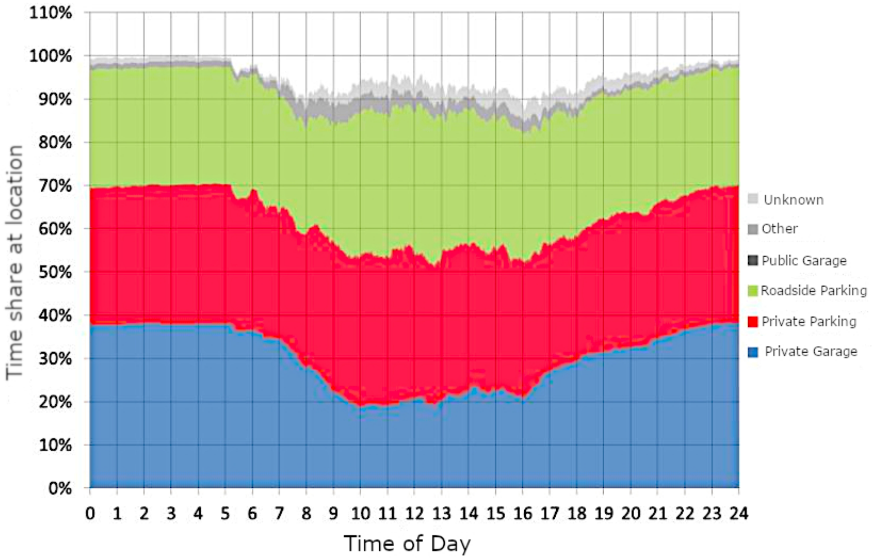


Fig. 8.4: Vehicle Parking Type and hourly progression

occupation of the expert participants and the individual experience. As humans we cannot be conscious about all aspects of a topic but as group size increases, so does reliability as seen in Figure 8.5 .

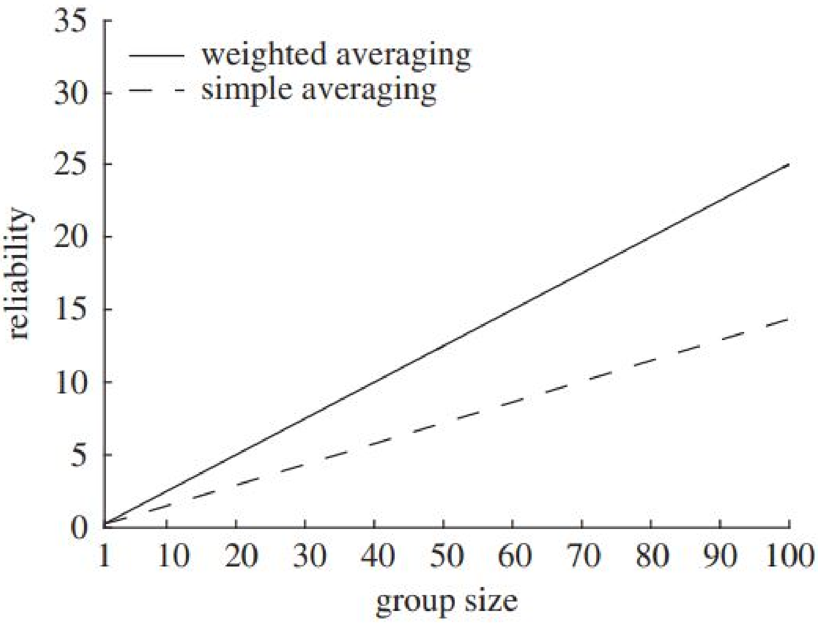


Fig. 8.5: Reliability of a decision rising with group size. Weighting expert opinions higher improves overall reliability [1]

To increase this effect, the opinion of individuals with a higher expected reliability can be weighed more heavily, than the other individuals. How experts are identified is highly situational dependent, but social markers, like experience and confidence in one´s opinion seem to be powerful tools.[1]

It can be seen, that this form of holistic evaluation is a great tool for systematic discussion and decision-making of complex topics. It is a good process, to start from a wide point of view, to narrow down to an essential set of aspects, to describe the desired solution. For the algorithms themselves, an intelligent and highly automated solution seems to be the most promising. Also a high level of adaptability and standardization should be considered, to avoid unnecessary investments and a fast development of these critically necessary grid functionalities.

Chapter 9

Outlook

9.1 Improving Weights

The evaluation technique described in this thesis is applicable for many complex problems and gives good results for relatively little effort. To solve a problem to a high degree of quality, a high diversity of stakeholders is necessary. This way, many viewpoints can be considered. The weighing of the viewpoints on the other hand, is highly subjective and each expert will put emphasis on their respective field. In this evaluation, every opinion of the experts had the same value and the final weights were calculated as the average of all opinions. For better results, a discussion between all the stakeholders should be held on how the weights should be distributed before submitting each opinion. This way all viewpoints can be considered and put into perspective, without loosing the positive quality of disagreement. In the end a compromise is reached, which is representing the informed opinion of a group of people.

9.2 In depth evaluation

For more specific evaluations it is useful to create a point-scheme with higher resolution. This way more quality aspects can be considered. There is also the possibility of creating sub-evaluations, with own rating factors and weights to evaluate the aspects of a criterion which will itself get weighed by another rating scheme. For this to be possible, the subjects which are to be rated have to be very similar, with many overlapping properties. Because the evaluation in this work is very diverse, generalized criteria had to be chosen. The other problem which hindered a more in-depth evaluation, was the lack of reliable data. As an example, it was difficult to estimate the cost for each system to be implemented in a larger scale. If this evaluation was made by a grid-provider company, the costs for each system will be known much more in detail.

9.3 Grid cognification

It seems obvious, that some kind of grid cognification will need to take place in the next few years, to accommodate large fluctuating consumers and producers. This initiative can either come from the grid provider, in form of a centralized coordination, or from the grid users themselves, by reducing their grid impact to operate within the allowed grid range, specified by the grid operator. For optimal grid operation, a mixture of both seems to be most promising. For this to succeed, standards need to be developed, which provide generalized data interfaces between grid-provider and customer, clear responsibilities for each participant and a transparent, cost-by-cause, settlement procedure.

Chapter 10

Conclusion

The developments in energy technologies point to a significant increase of electricity as an energy medium. This shift from conventional sources has significant political and societal support and is happening at a rapid speed. Electricity grids will be faced with fluctuating power situations until certain political and technical problems to avoid them are solved. In many situations increasing grid requirements will be solved traditionally by investing in grid reinforcements with higher maximum loading capacities and margins. However, because grid reinforcement is highly capital intensive and, in many cases, a disproportionate solution, alternative solutions are preferred. The use of intelligent elements within the low voltage grid, has the potential to avoid many problematic situations and has a high potential for additional functionalities regarding the utilization of renewable energy. These systems can either be deployed within existing grid structures but should also be included in newly constructed grids and grid reinforcement projects. There is a large demand for an advanced grid information network, to fulfill functions of a dynamic power grid. As a large number of stakeholders can be identified, ranging from grid operators, energy suppliers, device manufacturers and plant builders to consumers and communities, standards need to be developed to facilitate the participation of all parties. Also, financial incentives and regulatory requirements must be set, to support the additional costs for implementation and operation. The scope of the work is limited to systems which are operated by a grid operator, but coordination responsibilities could also be transferred to another party, e.g., the operator of a renewable energy community. Because the problem is urgent, solutions are needed which can be quickly implemented, also within the existing system. This implicates the requirement for a simple, cheap, effective and adaptive system. The main task in this work was to find a structured methodology, to break down a large set of system requirements to a few representative quality indicators, in order to evaluate a number of different systems. The scope of this evaluation is limited to systems coordinating electric vehicle charging stations, but it seems obvious, that this task is just a first function of an intelligent electric grid. Therefore, the design decisions made for this problem will have an impact on further developments. An emphasis has to be put on the choice of communication systems between the grid participants. A high level of adaptability and many additional functions can be achieved without significant additional investments, if the appropriate topology is chosen. The most potent communication system seems to be a two staged design, with one communication layer between the grid operator and distribution station and a second layer between the distribution station and customers and among the customers. This distributed design allows for low communication needs to peripheral grid sections and low reaction times to changing grid situations. The algorithm with the best rating within this work, relies exclusively on locally measured data to react to grid situations, but can be controlled from a central IT-system if necessary. Additional peripheral measurements can be included, if necessary, to improve grid state estimation. Generally, it has been found, that state estimation using artificial neural networks (ANN), real time power measurements and selected exogenous measurements, is suitable to predict and avoid undesired grid situation effectively. High level computational needs for training and adapting the ANN can be fulfilled centrally within a specialized IT-system. High speed and low latency control is performed in a decentralized manner. The low computational requirements, allow for the accommodation of additional similar functions within the same system. The research for the topic, included many talks with experts working directly or indirectly on smart-grid problems. It was found, that for Austria specifically, barriers regarding government policy, regulation and safety weigh much higher than the identified technical challenges. Energy-specific communication between customers and authorized third parties enables a community-optimized use of the electric grid and efficient use of renewable energy sources without negatively affecting overall grid stability. At the present, grid operators in Austria are hesitant to provide easy access to already existing data and communication capabilities. Explicitly, the smart-meter infrastructure. As grid operators are traditionally highly safety oriented and there is no financial incentive to provide additional services other than legal requirements, these are fulfilled to a minimum extent. It seems plausible, that given a detailed set of technical requirements and regulations, participants within the low-voltage grid and especially large-scale producers, consumers, and energy service companies, can perform grid-supporting functionalities without external interactions. This would not only enable the development of appropriate products, but also the more efficient use of renewable energy, the strengthening of a decentralized energy market, the associated growth of new business opportunities, and a stable basis for investments. The decentralized production and consumption of renewable energy not only has great potential of reducing the climate impact of energy consumption, but also a strong social effect, by distributing energy production among a large number of participant. The investment in PV has the potential to support the largest GDP- increase of all alternative technologies[12], by supporting thousands of jobs through construction and maintenance. Cheap, superfluous energy in summer may create a completely new form of industry, which is focused on energy-demanding products. These possibilities include battery storage, hydrogen production, production of nitrogen fertilizer, cement or synthetic fuels, just to name a few. The future looks bright when it comes to renewable energy. As the electric grid will play an important role in achieving these goals, it is our responsibility to lay down a foundation which future generations can build on.

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