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Impact of Large-Scale Deployment of Energy Communities on Distribution Grids

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Vienna, April 2024

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This thesis would not have been possible without the support, guidance and help of several persons who all contributed in their own ways.

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Abstract

Presented work aims to investigate into the impact of a large-scale deployment of renewable energy communities on distribution grids. To fulfill a large-scale investigation, a twofold approach is followed: First of all, various different wide-range scenarios will be considered and secondly, the large-scale impact will be covered in a geographical sense via the analysis with several low voltage as well as medium voltage grids. In order to do so, several scenarios based on European and Austrian legislature are constructed. These deterministic scenarios then undergo an optimization model with varying objectives. To highlight the impact of one community, a community scenario shall be compared against a no-community scenario thus each defining the optimization objective - individual self-optimization or community-wide optimization. Then, the optimizing frameworks results, that being load time-series data, undergo iterative static load flow calculations and an extensive data analysis is carried out upon these results looking into various aspects. It can be deduced, that the impact of a community increases with the scenarios de-urbanization and further increases with the additional installation of flexibilities such as PV and battery storage systems. However, while the communities trading certainly can affect the grid negatively, this usually is not the case as the economically viable options for large-scale peer-to-peer trading can be viewed as limited. In addition, renewable energy communities are usually capable of marginally reducing the communities residual load by increasing the self-consumption and better utilizing installed flexibilities due to their inherent peer-to-peer trading.

Kurzfassung

Die vorgestellte Arbeit behandelt die Auswirkungen eines großflächigen Einsatzes von Erneuerbaren-Energiegemeinschaften auf elektrische Verteilnetze. Um den erwähnten großflächigen Einsatz zu erforschen, wurde einem zweiseitigen Ansatz nachgegangen: Einerseits beschreibt dies einen weiten Szenarientrichter und andererseits wird mit der großflächigen Verwendung auf den geographisch weitreichenden Einsatz dieser erneuerbaren Energiegemeinschaften eingegangen indem sowohl etliche Niederspannungs- als auch Mittelspannungsnetze betrachtet wurden. Um diesen Ansatz zu verfolgen werden etliche Szenarien basierend auf entweder europäischer oder österreichsischer Gesetzgebung konstruiert. Diese deterministischen Szenarien werden anschließend mittels eines Optimierungsmodells auf Basis verschiedener Optimierungsziele optimiert. Um den Einfluss einer Energiegemeinschaft festzustellen, wird für jedes Szenario der Gemeinschaftsfall mit dem Nicht-Gemeinschaftsfall verglichen wodurch das Optimierungsziel festgelegt wird: Gemeinschaftliche oder individuelle Kostenoptimierung. Die Resultate des Optimierungsmodells, dies sind Zeitreihen der optimierten Lasten, werden in einem nächsten Schritt iterativen, statischen Lastflussberechnungen unterzogen. Abschließend wird eine ausführliche Datenanalyse durchgeführt. Aus diesen Ergebnissen kann geschlossen werden, dass der Einfluss einer Energiegemeinschaft sowohl mit der De-Urbanisierung des Szenarios als auch mit der steigenden Durchdringung von Flexibilitäten, etwa Photovoltaik oder Batteriespeichersysteme, steigt. Obwohl der Stromhandel einer Energiegemeinschaft definitiv negative Netzauswirkungen haben kann, muss festgehalten werden, dass dies in der Regel nicht der Fall ist da aus ökonomischer Sicht lediglich limitierte Optionen für großflächigen Stromhandel bestehen. Außerdem sind erneuerbare Energiegemeinschaften typischerweise in der Lage, aufgrund einer besseren Ausnutzung der installierten Flexibilitäten durch den für Energiegemeinschaften inhärenten Stromhandel die Gemeinschaftsresiduallast geringfügig zu reduzieren.

Contents

Acronyms

CEC Citizen Energy Community
CEP Clean Energy for all Europeans package
CIGRE Conseil International des Grands Réseaux Électriques
EAG Erneuerbaren-Ausbau-Gesetz
ENTSOE European Network of Transmission System Operators
EV Electric Vehicle
EVSE Electric Vehicle Supply Equipment
IEEE Institute of Electrical and Electronics Engineers
KPI Key Performance Indicator
LREC Local Renewable Energy Community
LV Low Voltage
MAPE Mean Absolute Percentage Error
ME Maximum Error
MV Medium Voltage
NPV Net present value
PV Photovoltaic
REC Renewable Energy Community
RREC Regional Renewable Energy Community
SCR Self Consumption Rate
SSR Self Sufficiency Rate
TOTEX Total Expenditures

1. Introduction

1.1. Motivation

„Climate change is a threat to human well-being and planetary health (very high confidence). There is a rapidly closing window of opportunity to secure a liveable and sustainable future for all (very high confidence)" [31].

„Rapid and far-reaching transitions across all sectors and systems are necessary to achieve deep and sustained emissions reductions and secure a liveable and sustainable future for all" [31].

Electric energy accounts for 20 % of the global final energy consumption in 2023 and, in order to fulfill set zero emission targets by 2050, that share needs to increase to 30 % by 2030 [30]. With the electric power sector accounting for 20 % of the global energy demand, it is clearly non-negligible for above mentioned rapid and far-reaching transition towards a more sustainable future.

One key approach to decrease the electricity sector's carbon emission is the installation of sources of renewable energies such as Photovoltaic (PV) and wind power, for example. It is expected, that by 2025 over one third of the global electricity demand is covered by renewable electricity sources [30]. However, despite the immense historic progress regarding the global installation of renewable energy sources, these technologies, sometimes still being considered new, to this day face a manifold of challenges.

A solution to, for example, overcome the issue of acceptance by the broader public as a mature technology are so called Energy communities. Effectively, energy communities can contribute to the energy transition by attracting private investments which results in higher installations of renewables and further increase public acceptance by empowering citizens [22].

Energy communities have been implemented into European legislature through the „Clean Energy for all Europeans package (CEP) " in 2019 [22].

Report [16] and [17] presents the numbers of all registered Renewable Energy Community (REC)s in Austria: While by the end of 2021 only five communities were in operation, that number increased to 51 within half a year, only to further increase to 161 by the end of 2022. Half a year later, that being the middle of 2023, this number increased again to 675. In its essence, within 18 months an increase of 670 communities or 13400 % occurred. It can be concluded, that there is definitely public interest in participating to the energy transition. While this increase is undoubtedly a success on its own, energy communities most likely still have not reached a critical mass when comparing their aggregated loads to the grids total load. Therefore, apart from still being considered new, energy communities have not been accounted for from a grid perspective.

Given the immense increase in communities as presented above and assuming this number will further increase (even at a lower rate), energy communities, at least at some point in time, will become relevant from a grid planning and operation point of view. As a conclusion, it is of absolute necessity to research into the *Impact of Large-Scale Deployment of Energy Communities on Distribution Grids*.

1.2. Research Questions

As the title of this thesis „*Impact of Large-Scale Deployment of Energy Communities on Distribution Grids*“ suggests, the conducted research will attempt to answer questions if and how a large-scale deployment of energy communities affects the grids state for certain scenarios.

To be exact, the following research questions will be addressed:

1. Is there a grid impact of RECs?
2. How to measure and quantify the grid impact?
3. Does a potential grid impact depend on other circumstances such as the grid type or the integration of renewables?
4. Will the grid impact increase or decrease with an increasing penetration of RECs?
5. Can general conclusions regarding the grid impact of energy communities be drawn or does the variance of scenarios outweigh any general outcomes?

In order to address question (1), a delta calculation will be carried out: Here, a comparison between a Community and No Community case will be made with otherwise constant parameters. These delta calculations will be performed on the basis of a great amount of potential scenarios. Those scenarios include different projections for community metadata, that being the number of participants and the geographic category of the community and flexibility penetrations such as photovoltaics, number of electric vehicles, heat pumps and boilers. Hence, question (3) is answered. For answering question (2), a wide range of statistical measures shall be introduced. Further, several scenarios will be showcased in great detail in order to better understand the behaviour.

It is important to state, that the aspect of the „*large-scale deployment*“ can be viewed as twofold: First of all, it refers to a deployment of communities in a vast variety of different scenarios, thus covering the potential impact for a broad field of applications. Secondly, the large-scale aspect correlates to a large-scale deployment in a more literal, geographic sense. Then, the impact will be investigated with several communities being allocated within a medium voltage distribution grid with varying community penetration rates. Therefore, question (4) considering the further penetration of communities can be answered.

Finally, to address question (5), extensive conclusions and discussions will be drawn.

1.3. Structure of Thesis

In order to address the research questions stated in section 1.2, this thesis adheres to the following structure:

In Chapter 2, first and foremost, a closer look will be taken into the European Legislature regarding Energy Communities as well as into the Austrian implementation of these laws (Section 2.1.1). Then, the results of an extensive literature research focusing on the the current state of research on Energy Communities will be presented in Section 2.2. Finally, the gap in the literature in addition to the definition of this thesis contribution shall be introduced in Section 2.3

Chapter 3 will present the underlying methodology necessary to address this thesis contribution. Section 3.1 goes into detail with the definition of the scenarios regarding grid models, community parameters, time horizons as well as penetration rates of renewable energy sources that will be utilized. In an intermediate step, Section 3.2 will dive into how the communities are constructed and provides further explanations for the input data. Then, Section 3.3 will provide a comprehensive overview of the simulation and optimization framework that will be used for the community simulation in this thesis. After presenting the scenarios and the simulation framework, the general workflow for the grid analyses for both low voltage grids as well as medium voltage grids are presented (Section 3.4.1 and 3.4.2, respectively).

In Chapter 4 the obtained results will be displayed. Here, the results of low voltage grid calculations is presented in Section 4.1 whereas the medium voltage results are stated in Section 4.2.

Chapter 5 includes an extensive conclusion and discussion of this thesis output. Section 5.1 displays the conclusion and Section 5.2 the discussion.

Finally, Chapter 6 presents the outlook of this work and potential future research.

2. State of the art and own contribution

This chapter will provide insight into the European and Austrian legislative background of energy communities, as shown in Section 2.1. Then, Section 2.2 will present the outcomes of an extensive literature research regarding energy communities. Finally, Section 2.3 will address the research gap and define the contribution of this thesis as already hinted in Section 1.2.

2.1. Legislative Background

2.1.1. European Legislature

With the introduction of the „CEP“ package in 2019, the European Commission laid the foundation to the legislative implementation of energy communities [14].

The CEP legislative package is split into many various regulations and directives, different kinds of energy community legal forms emerged from different directives, each serving their own purpose [24]. To be exact, the so-called „citizen energy community“ derived from the Electricity Market Directive while the „renewable energy community“ is implemented within the Renewable Energy Directive [24]. European Commissions Renewable Energy Directive [25], for example describes RECs in Article 2(16) as

„'renewable energy community' means a legal entity:

(a) *which, in accordance with the applicable national law, is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity;*
(b) *the shareholders or members of which are natural persons, SMEs or local authorities, including municipalities;*
(c) *the primary purpose of which is to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits;*“ [25]

The European Commissions Electricity Market Directive [26], on the other hand, defines citizen energy communities as

„'citizen energy community' means a legal entity that:

(a) *is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including municipalities, or small enterprises;*
(b) *has for its primary purpose to provide environmental, economic or social community benefits to its members or shareholders or to the local areas where it operates rather than to generate financial profits; and*
(c) *may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders;"* [26]

While these two approaches to energy communities are seemingly similar and also perform similar activities, decisive differences do exist [24]. One key difference is the proximity in which all participants have to be located. While the citizen energy community per se does not define a necessary required proximity of participants, members of a REC *„must be in the vicinity"* [24]. Also, as mentioned in the cited legislation above, the participation in such a community is not allowed to be the members main income or economic pursuit [24]. Apart from that, Citizen Energy Community (CEC) are technology-neutral thus allowing generation from fossil fuels or renewables. REC, as their name suggests, commit exclusively to renewable sources of energy [24]. Article 2(16) of the Renewable Energy Directive provides a clear definition of such renewable sources of energies: *„'energy from renewable sources' or 'renewable energy' means energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas;"* [25].

A big aspect of RECs is the community-internal peer-to-peer trading, defined by the Renewable Energy Directive Article 2(18) [25] as

„'peer-to-peer trading' of renewable energy means the sale of renewable energy between market participants by means of a contract with pre-determined conditions governing the automated execution and settlement of the transaction, either directly between market participants or indirectly through a certified third-party market participant, such as an aggregator. The right to conduct peer-to-peer trading shall be without prejudice to the rights and obligations of the parties involved as final customers, producers, suppliers or aggregators;" [25].

In summary, it can be concluded, that energy communities present a legal entity with the overall goal to increase the installations of renewable energies by attracting private investments and further increasing public acceptance of such technologies. It is important to further note, that (renewable) energy communities must be viewed as de-central entities without economic success being the overall goal.

2.1.2. Austria's Implementation of EU Legislature

In Austria, energy communities have been implemented with the so-called „Erneuerbaren-Ausbau-Gesetz (EAG) " [18]. According to the EAG (6. Teil) [8], RECs have the permission to produce, consume, store or sell energy from renewable sources, perform aggregation as well as other energy services [8]. Also, the participation in a REC cannot be the main economic activity of a business [8].

As mentioned in Section 2.1.1, REC members need to be within a certain, yet undefined proximity. In Austria, that proximity is defined as to be in the same grid area [18] with one further level of detail: Regional Renewable Energy Community (RREC)s need to be within the same medium voltage grid while Local Renewable Energy Community (LREC)s are required to allocate within the same low voltage grid [8]. A clear advantage of that requirement is the reduction of the grid tariff, since all participants are located within the same grid area [8].

2.2. Carried out research regarding Energy Communities

This section presents the results of an extensive literature review regarding research on energy communities.

Journal contribution [29] presents a metastudy of the research on energy communities carried out until 2021. In order to carry out this study, 67 papers were analyzed and further classified by their general topic, keywords and the components of a given community [29]. Paper [29] finds, that, first of all, a big spike in published papers was apparent after the publication of the Renewable Energy Directive II in 2018. Also, it is shown, that the vast majority of published papers focus on the model of the community rather than social aspects or drivers and barriers of communities. Also, most published articles include components such as PV and Storage into the community models. In addition, it is laid out, that peer-to-peer trading is the predominant structure of such an community in research whereas only 20 % of papers utilized an aggregator [29]. To sum it up, paper [29] suggests, that by 2021 the vast majority of published articles considered communities with peer-to-peer trading, PV as production plant and additional storage. Also, the majority of research was model-focused rather than impact or outcome focused.

Fortunately, conference contribution [13] provides clear pathways and scenarios for energy communities in Austria aiming to aid further research. Contribution [13] presents data regarding the spatial distribution, i.e. rural, suburban and urban communities, expected PV, battery and Electric Vehicle (EV) penetrations per community. These numbers are either based on official Austrian installation goals, marked developments or statistics-based. Further, this article suggests expected, typical member sizes and member structures of such communities [13].

The contribution [15] shows the impact of energy communities on the distribution grid in an Italian case study. Here, energy communities are created utilizing a stochastic approach with a Monte-Carlo simulation, varying in their respective size and sources of energy. In detail, the communities loads are defined, then, the communities load profile is determined and then, the portfolio of the communities generation is optimized with two different strategies: The amount of energy is generated as used by the communities members to achieve a net-zero balance. The other strategy is implemented as such, so it minimizes the communities residual load, i.e. the exchanged electricity with the grid. Then, for either scenario, the size-optimized generators are randomly allocated to further comply with legal standards. Then, after reaching convergence, a yearly iterative load flow calculation is calculated [15]. This journal paper does cover a wide range of possible scenarios by utilizing a Monte Carlo simulation, however, the restriction could be seen by the optimization of the generation profile. As previously described, this portfolio is optimized. In reality, distribution generation units appear more often than not in a rather uncontrolled way regarding the sizing and their respective location. Therefore, a so to say „less perfect“ model taking the generation sources as they appear could in fact be more realistic. Apart from that, it would be interesting so observe more scenarios derived from actual projections or installation goals of, for example, PV and also to include other potential flexibilities in the community.

A contribution to „Applied Energy“ [50] investigates into the optimal sizing and grid impact of RECs with PV production and battery storage systems. Here, the optimal sizing of the communities PV and battery systems was carried out by formulating a linear programming optimization problem. In order to do so, five different community compositions were analyzed with three different grid types (rural, suburban and urban) with three different battery storage placements. The components were sized adhering to different objectives: Firstly, a maximization of economical benefit, then a reduction of the power exchange with the grid, and a maximisation of self-sufficiency. As to analyze the grid impact, three Conseil International des Grands Réseaux Électriques (CIGRE) test grids were utilized. Also, as mentioned, five different community configurations are assessed. However, when taking a closer look into the test grids and the geographic allocation of the community, it comes clear, that first of all, the test grids are very generic and second, for most community setups, the vast majority of participants are located directly next to each other being on the same feeder rather than being somewhat spread out within the grid. In other words, in a rural grid, for example, a community would consist of all households of one street but no household from the remaing village. While this setup definitely is not impossible, it could be discarded as an exception with heterogeneously or more randomly spread out communities being more typical. In addition, the utilized test grids can be considered as too idealized when compared to actual grid topologies.

Article [27] aims to investigate into the social arrangements, technical designs as well as the impacts of energy communities by performing a large-scale literature review over previously carried out research regarding energy communities. In detail, paper [27] presents the social arrangements such as the roles and interactions between consumers, energy service providers and initiators, the design and modelling choices together with the impacts of the communities. This study finds, that the overwhelming objective when designing a community is from the economic realm, followed by both, environmental and technical terms. Subsequently, the majority of the analysed papers considered various economic parameters, such as energy bill savings, total cost savings or levelized cost of electricity amongst others as Key Performance Indicator (KPI)s. Regarding the technical impacts, parameters, for example the self-consumption rate, self-sufficiency rate, electricity imports or primary energy have majorly been analyzed. While all these parameters provide great overview about the net performance of a community, only a limited conclusion can be drawn when it comes to the impact of the community on electrical grids state in greater detail.

In journal contribution [33], a grid-oriented peer-to-peer trading strategy is presented following a game-theoretical approach. Here, the emphasis is put mainly on developing a trading strategy with a novel contribution to evolutionary game theory. Thus, great attention is brought to the formulation of the optimization problem and its modelling. This novel approach on trading strategies is then simulation-tested with the Institute of Electrical and Electronics Engineers (IEEE) 15- and 33-bus generic grid topologies considering various performance indicators such as power changes, voltages and price changes always comparing the case with the trading strategy to the absence of introduced trading strategy. While it is expected from the authors that the strategy is effective independent from the provided grid topology, this work still majorly focuses on the development of a model/operating strategy and its following test rather than drawing general conclusions from the impact of communities in various scenarios on electrical distribution grids.

Contribution [4] proposes a novel approach for energy management in energy communities with respect to grid balancing and energy sharing. Here, a mathematical LP and MILP optimization is used to maximise the self-consumption and self-sufficiency by making use of novel forms of energy sharing. In addition, the energy management system is designed so it minimizes potential load fluctuations of grid thus letting the community serve as grid balancing. With this contribution being majorly focused on the community model itself, no impact on an actual grid model per se is researched. Also, only parameters such as active loads are considered for the grid. Additionally, several other parameters fully describing the state of the grid would be beneficial.

Journal article [35] investigates into the techno-economical impact of solar-energy communities through various scenarios depending on community metadata such as community size, prosumer ratio and a production to demand ratio. The impact is determined via three main KPIs: The first one being the profitability of prosumers based on the Net present value (NPV), the communities self-sufficiency rate and also the impact on the grid being measured by transformer overloading. Article [35] focuses merely on the transformer loading when considering the grid impact. While this represents the behaviour of a community fairly well in respect to the outer grid, it fails to first of all describe the reactive power household of the grid and secondly, completely ignores the internal behaviour of the communities grid - both aspects which cannot be ignored when researching into the impact of energy communities on the distribution grid. Also, said article only focuses on urban grids whereas communities could also yield interesting results in non-urban cases. Further, the integration of other flexibilities such as battery storages, heat pumps or Electric Vehicle Supply Equipment (EVSE) could benefit the considerations.

Finally, contribution [12] researches into the performance of a small REC in respect to its energetic and environmental performance. Hence, all considerations are carried out on a very low, detailed component level. As the key objective of this contribution is a buildings environmental and energetic performance with a REC, the grid aspect corresponds only to energy values exchanged with the grid. Therefore, only a fairly limited outcome regarding this communities grid impact can be made.

2.3. Research Gap and own contribution

Contribution [15] mentions, that, despite the high number of published papers that somehow tackle the topic of energy communities, only a handful in fact considers the impact of a community on the (distribution) grid. Further decreasing the number of papers investigating into the grid impact of communities is the fact, that, as explained in Section 2.2, many publications only describe the grid with an active power flow to and from given grid. With the immense complexity of any electrical grid in mind, this approach is, in order to investigate properly into the grid impact, clearly not sufficient. When fully investigating into the grids state with energy communities, it is crucial to also account for voltages and thermal loadings aside from active powers only.

Hence, a research gap appears: Unlike the majority of publications, this work shall not primarily focus on a model describing an energy community but rather utilize an existing, provided and most importantly, reviewed model - thus fully focusing on the impact of a large-scale deployment of such communities on the distribution grid on the basis of a variety of scenarios. In contrast to article [15], the scenarios are built upon actual projections for community metadata and thus a deterministic calculation is performed rather than a Monte Carlo approach. Also, again in contrast to [15], a greater variety of different grid models will be considered. Further, hosting capacity analyses with subsequent optimal placing of generation components are deliberately not carried out as a chaotic, uncoordinated installation of flexibilities presents not the exception but the norm. Therefore, these, most likely, less optimal scenarios might in fact increase the potential for real world application.

The contribution of this work can be divided into three major steps:

1. **Definition of scenarios**: In a first step, the deterministic scenarios underlying the simulations later on shall be defined. It is important to state, as this thesis was part of the project ORANGE [3, 44], some scenarios cohere to the scenarios defined for that project.
2. **Construction of the simulation framework**: An extensive simulation framework was built in `Python` in order to combine the existing optimization framework `Femto.jl` with `DIgSILENT PowerFactory` and the further evaluation of results. Here, great emphasis was put upon automating the simulation process.
3. **Data Analysis and Evaluation**: Detailed, large-scale simulations covering a wide span of potential scenarios yield a great amount of data. Therefore, it was of absolute necessity to carry out an extensive data analysis and evaluation. Hence, the vast majority of this work was in fact this data analysis.

3. Methodology

This chapter will present the methodology of the carried out work in order to reach stated research goals.
Figure 3.1 presents an extensive overview of all carried out steps in the form of a flowchart. All sources of data as well as their data streams are represented as well.

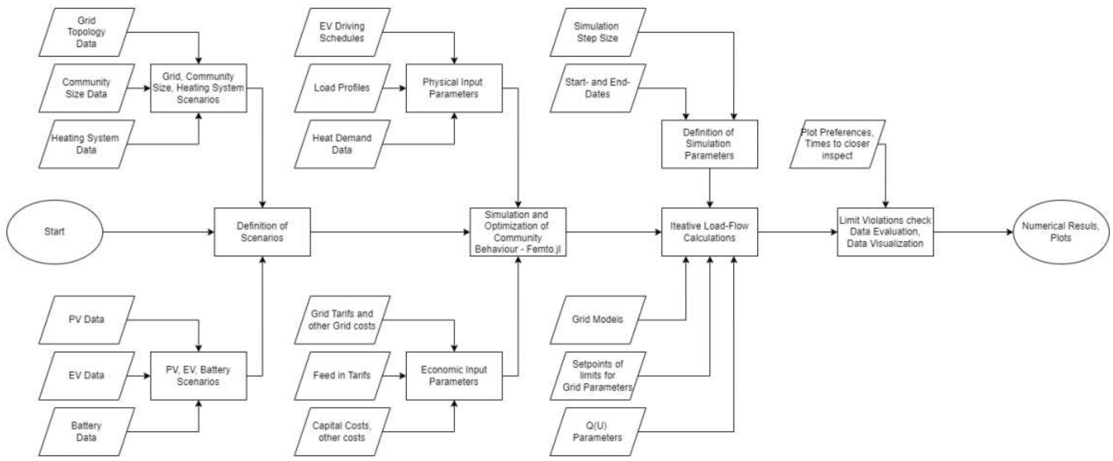

Figure 3.1.: Flowchart visualizing all major steps, data sources as well as data streams

As briefly described in Section 1.3, at first, the scenarios under investigation will be defined. These scenarios include the communities parameters such as number of members, penetration rates of sources of renewable energies, i.e. PV, penetration rates of electric vehicles, heat pumps and battery storages, spatial distribution of the community, i.e. rural, suburban and urban areas, grid topologies and the time horizon of the simulation.

Then, in an intermediary step, the setup of the communities is outlined in Section 3.2. Here, it is explained how the communities are formed upon the scenario data specified previously.

Then, in a second step, the mathematical model responsible for simulating and optimizing the communities internal behaviour as well as its input parameters will be explained in more detail. This model takes - amongst various other sources of data - load profiles and data from the defined scenarios as input, carries out an optimization with objectives varying with the scenario and outputs again load profiles, but with optimized flexibilities and community internal trading.

After the simulation and optimization of the communities internal techno-economic behaviour, these load profiles serve as input parameters for iterative carried out Load Flow Calculations on the previously defined Low Voltage (LV)- and Medium Voltage (MV)-grids. Also, the definition of input parameters, such as simulation step size, Q(U) parameters and grid limits will be justified. The results of this step are Dataframes with data for terminal voltages, loadings amongst many others for all simulated time steps.

As a last step, an extensive data evaluation as well as visualization is carried out in order to cope with this massive amount of data.

The exact methodology of these calculations will be deduced within the following sections.

3.1. Definition of Scenarios

Firstly, before carrying out any simulations, one needs to clearly define the scenarios that shall be taken into consideration. Conference contribution [13] presents, as already mentioned in Section 2.2.

In this work, energy communities based on EU legislature will be inspected. With Austria being a member state of the European Union, the underlying data for each of the scenarios will be taken at the example of Austria, *but with great emphasis on keeping this work as country-neutral as possible in order to allow for a more holistic point of view*. Therefore, the scenarios to be used in this thesis will naturally follow the results of [13].

Also, the scenarios roughly correlate to the investigated scenarios in the project ORANGE, a research project where this thesis was a part of [3, 44].

3.1.1. Overview of obtained scenarios

Section 3.1.2 outlines the spatial classification providing six representative grids, called „**Rural 1**“, „**Rural 2**“, „**Suburban 1**“, „**Suburban 2**“, „**Urban 1**“, „**Urban 2**“, all of which adhere to the community sizes specified in Section 3.1.3. Section 3.1.4 presents the scenarios for PV installations. Together with the Battery System penetration rates as specified in Section 3.1.5, the scenarios „**EAG 2020**", „**EAG 2030**", „**ÖNIP 2020**", „**ÖNIP 2030**", „**ÖNIP 2020+**", „**ÖNIP 2030+**" will be introduced. Additional data regarding Heat pump penetration rates as well as EV penetration rates are declared in Section 3.1.7 and Section 3.1.6, respectively. These PV-Battery-heat pump-EV-Year scenarios shall be multiplied with the Community-Size-Grid scenarios:

$$\begin{bmatrix} \text{Rural} & 1 \\ \text{Rural} & 2 \\ \text{Suburban} & 1 \\ \text{Suburban} & 2 \\ \text{Urban} & 1 \\ \text{Urban} & 2 \end{bmatrix} \times \begin{bmatrix} \text{EAG} & 2020 \\ \text{EAG} & 2030 \\ \text{ÖNIP} & 2020 \\ \text{ÖNIP} & 2030 \\ \text{ÖNIP} & 2020+ \\ \text{ÖNIP} & 2030+ \end{bmatrix}^{T}$$

In order to avoid overly excessive simulation runs as well as redundancy of data, a split has been made with the ÖNIP scenarios: Scenarios with the „+"-Appendix were only computed for the „1"-Grids, while the regular ÖNIP scenarios were only calculated with the „2"-Grids.

The following subsections will go into the synthesis of the scenarios in great detail.

3.1.2. Spatial classification and typical grids

In general, parameters such as PV penetration rates, number of inhabitants amongst many others highly depend not only on the location within Austria but also on the region type. Therefore, as a first assumption, the regions of Austria shall be divided into **rural**, **suburban** as well as **urban** regions. Figure 3.2 presents an overview of the classified regions in Austria.

Quite obviously, the region type dictates the electric grids topology, i.e. rural low voltage grids typically have fewer loads but much longer lines compared to their urban counterparts. In order to carry out study [2], typical Austrian distribution grids were selected by an educated guess from power system researchers as well as grid operators. For each of the above classified region types two exemplary grid models will be used in this thesis, each slightly varying in their respective size. These grids can be viewed in the Appendix A in greater detail. Henceforward, these grids will be referred to as „**Rural 1**", „**Rural 2**", „**Suburban 1**", „**Suburban 2**", „**Urban 1**", „**Urban 2**". It is important to state, that these grid models represent actual grids in Austria. Therefore, all names and other identifiers have been anonymised. The topologies as well as the load types are presented in the Appendix in A in more detail.

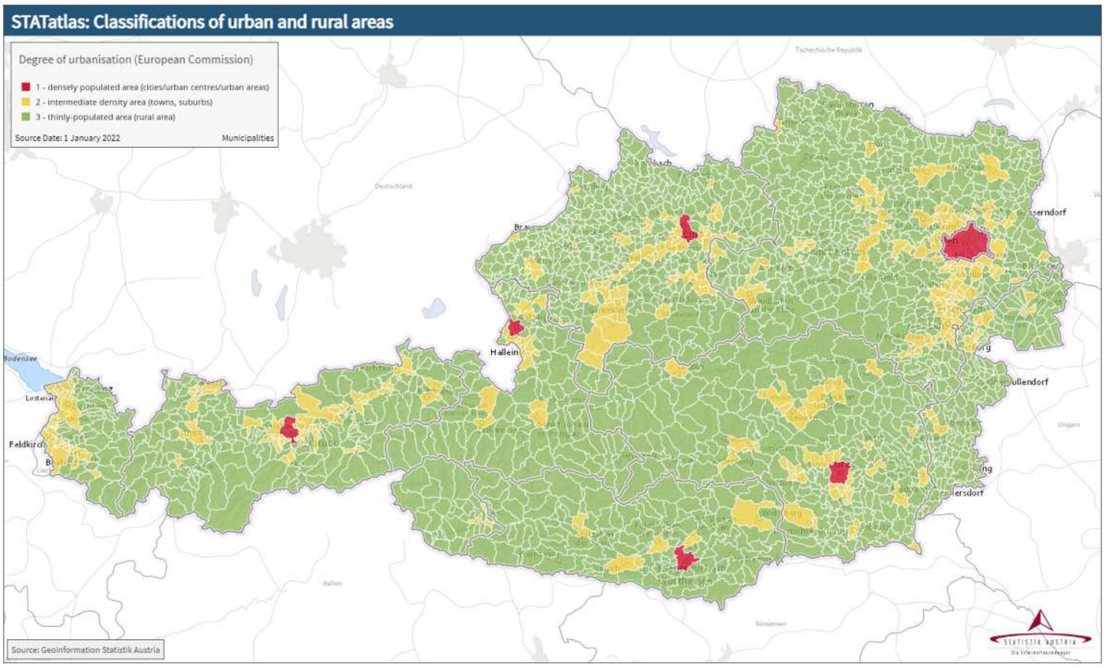

Figure 3.2.: Overview of Austrian municipalities classified either as urban (red), suburban (yellow) or rural (green) areas. Source: [47]

3.1.3. Typical Community sizes

Conference paper [13] presents an statistics-based assumption regarding typical expected sizes of energy communities depending on their respective regional classification as shown in Table 3.1.

Region Type	Inh./HH	Num. HH	Num. Inh.	Num. Businesses
Rural	2.54	20	51	0
Suburban	2.2	50	110	5
Urban	2.05	120	246	3

Table 3.1.: Expected, typical sizes of Energy Communities in dependency of the regional classification. Presented are Inhabitants (Inh.) per Household (HH), Number (Num.) of Households, Number of Inhabitants as well as Number of Businesses, Source: [13]

As the numbers presented in Table 3.1 are derived from theoretical communities in theoretical grids, they do not necessarily match the potential available number of households in the grids specified in Section 3.1.2. Therefore, the actual numbers as well as the load type of members have been slightly altered in order to match the provided grid's topology. The exact numbers are presented in Table 3.2.

	Total num. of part.	Share (%) pot. part.	Num. part. Res. HH	Num. part. Comm.	Num. part. Agr.
Rural 1	20	69	10	0	10
Rural 2	13	68.4	8	0	5
Suburban 1	35	72.9	28	5	2
Suburban 2	55	72.4	48	5	2
Urban 1	98	73.7	95	3	0
Urban 2	123	47.3	120	3	0

Table 3.2.: Number (num.) of the total communities participants (part.), the share of the participants in relation to the overall potential participants and the participants by load type: Residential Households (Res. HH), Commercial loads (Comm.) and Agricultural loads (Agr.)

3.1.4. PV penetration rates

Photovoltaic power generation already does, and will do even more in the future, massively influence the reduction of carbon emissions and further aid tackling the Energy Transition towards a more sustainable Energy system [49]. Therefore, it is of greatest importance to build various scenarios upon the system integration and expected market shares, i.e., penetration rates, of PV systems. In order to outline the current role of PV in Austria, Figure 3.3 displays all funded PV installations in Austria as of 2022.

Figure 3.4 presents the Austrian historic development of the annual new installed PV peak power as well as the representative cumulative installed power. Looking at this clear trend, it is important to investigate into various scenarios regarding PV penetration rates as these numbers might further increase. Therefore, an extensive sensitivity analysis regarding PV penetration rates will be carried out.

Austrian law, the so called „Erneuerbaren-Ausbau-Gesetz" (EAG), requires new PV installations with an energy output of 11 TWh in total until the year 2030 [7]. These goals directly correspond to the PV scenarios that were used here. The year 2020 presents a „base-case " scenario, with the current installments (2021) whereas the 2030 numbers show the projected numbers derived from the EAG. The exact calculation from the goal to the actual scenario was carried out in [13]. Henceforth these scenarios will be called **EAG 2020** and **EAG 2030**.

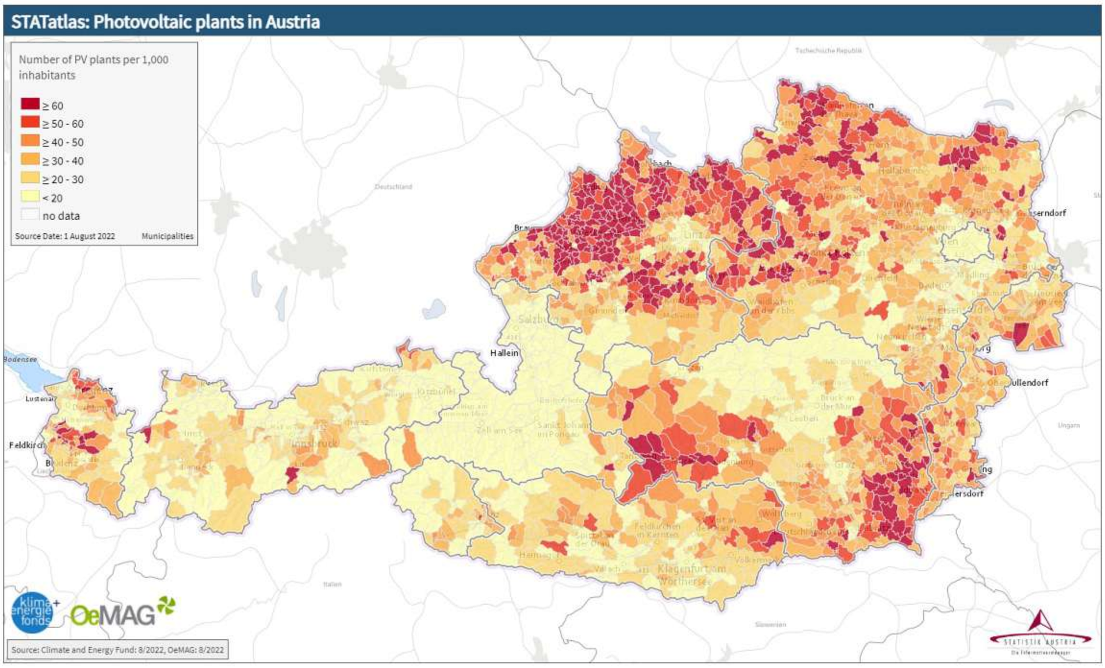

Figure 3.3.: Density Map of the total funded installed PV plants in Austria Source: [47]

In addition to the PV goals from the EAG, the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology proposed further goals within the „Österreichischer Integrierter Netzinfrastrukturplan" (ÖNIP), these goals being significantly higher than those from the EAG following recent market activity [45]. Based on the recent developments, ÖNIP projects an energy output of 21 TWh of the expected PV installations until 2030 [45]. Therefore, two PV scenarios derived from these projections, **ÖNIP 2020** and **ÖNIP 2030**, were inclued as well.

In order to investigate into scenarios, that include even higher PV installations, the scenarios **ÖNIP 2020+** and **ÖNIP 2030+** were introduced. Here, in contrast to the regular ÖNIP scenarios, the amount of installed PV systems was deliberately doubled.

Figure 3.5 presents the parameters for these scenario-year combinations and Table 3.3 and 3.4 display the numeric values for the installed PV capacities for each scenario in the year 2020 and 2030, respectively.

Looking at Tables 3.3 and 3.4 and especially Figure 3.5, the immensly spread out scenario funnel can be observed: Starting with scenarios with almost no to very little PV and Battery integration up to scenarios over exceeding already ambitious projections - thus increasing the accuracy of these simulations.

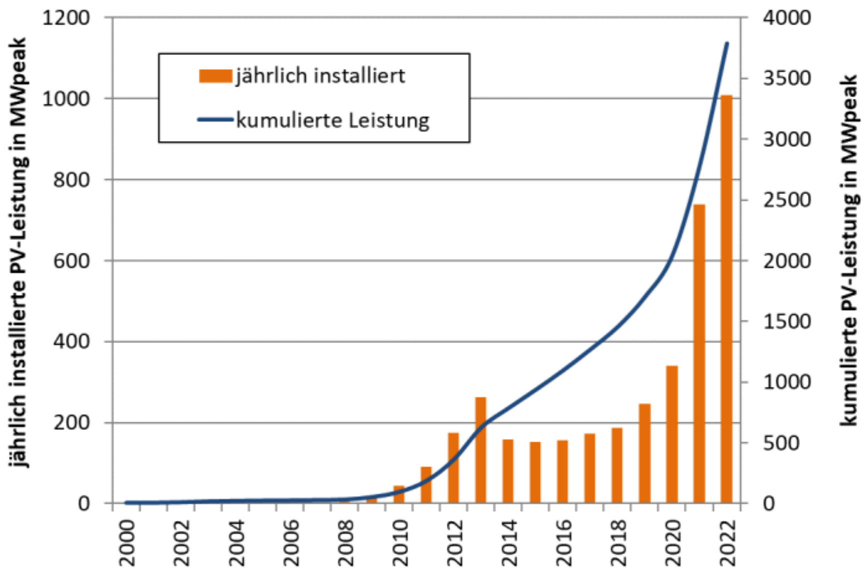

Figure 3.4.: Historic development of installed PV capacity in Austria. The orange bars show the yearly new installed power whereas the blue line displays the cumulative installed power Source: [5]

3.1.5. Battery Storage penetration

According to [13], in the year of 2020, 8.7 % of current PV installations also include a coupled battery storage system. While the storage capacity accounted only for 1.8 % of the PVs peak power in 2014, it accounts for 16.7 % in 2020. It is also expected, that this ratio will further increase [13]. Figure 3.5 displays the total installed PV and battery storage capacities for each of the scenarios that was used for the calculation in this thesis. Table 3.3 and 3.4 show the numerical values for the installed PVs and battery systems as well as the ratio of installed PV peak power to installed Battery capacity.

	EAG 2020			ÖNIP 2020			ÖNIP 2020+		
	PV	Batt.	PV/Batt.	PV	Batt.	PV/Batt.	PV	Batt.	PV/Batt.
	Num. (Power (kWp))	Num. (Cap. (kWh))	Share (%)	Num. (Power (kWp))	Num. (Cap. (kWh))	Share (%)	Num. (Power (kWp))	Num. (Cap. (kWh))	Share (%)
Rural 1	4 (21.9)	1 (5.5)	25.1	x	x	x	4 (56.1)	1 (14)	25
Rural 2	5 (23.9)	1 (5.5)	23	5 (58.1)	0 (0)	0	x	x	x
Suburban 1	5 (23.8)	0 (0)	0	x	x	x	5 (23.2)	1 (4.6)	19.8
Suburban 2	6 (28.8)	0 (0)	0	6 (28.2)	1 (4.6)	16.3	x	x	x
Urban 1	1 (4.2)	1 (4.2)	100	x	x	x	1 (20.9)	0 (0)	0
Urban 2	1 (4.2)	0 (0)	0	1 (20.9)	1 (20.9)	100	x	x	x

Table 3.3.: Numeric values for number of installed PV systems, the total peak power (kWp) per scenario and grid, installed number of batteries as well as total capacity (kWh) and the share of PV to Battery (%) for all **2020** scenarios. „x“ indicates, that this scenario has not been simulated.

	EAG 2030			ÖNIP 2030			ÖNIP 2030+		
	PV	Batt.	PV/Batt.	PV	Batt.	PV/Batt.	PV	Batt.	PV/Batt.
	Num. (Power (kWp))	Num. (Cap. (kWh))	Share (%)	Num. (Power (kWp))	Num. (Cap. (kWh))	Share (%)	Num. (Power (kWp))	Num. (Cap. (kWh))	Share (%)
Rural 1	20 (240.9)	18 (325.2)	135	x	x	x	20 (726.6)	14 (762.93)	105
Rural 2	13 (146.5)	9 (162.6)	111	13 (219.9)	5 (136.2)	61.9	x	x	x
Suburban 1	34 (168.8)	29 (215.9)	127.9	x	x	x	34 (300.6)	17 (225.45)	75
Suburban 2	35 (173.8)	25 (186.2)	107.1	35 (155.3)	18 (119.4)	76.9	x	x	x
Urban 1	15 (75.3)	11 (82.8)	110	x	x	x	15 (245.8)	9 (221.2)	90
Urban 2	15 (75.3)	12 (90.4)	120.1	15 (122.9)	7 (86)	70	x	x	x

Table 3.4.: Numeric values for number of installed PV systems, the total peak power (kWp) per scenario and grid, installed number of batteries as well as total capacity (kWh) and the share of PV to Battery (%) for all **2030** scenarios. „x“ indicates, that this scenario has not been simulated.

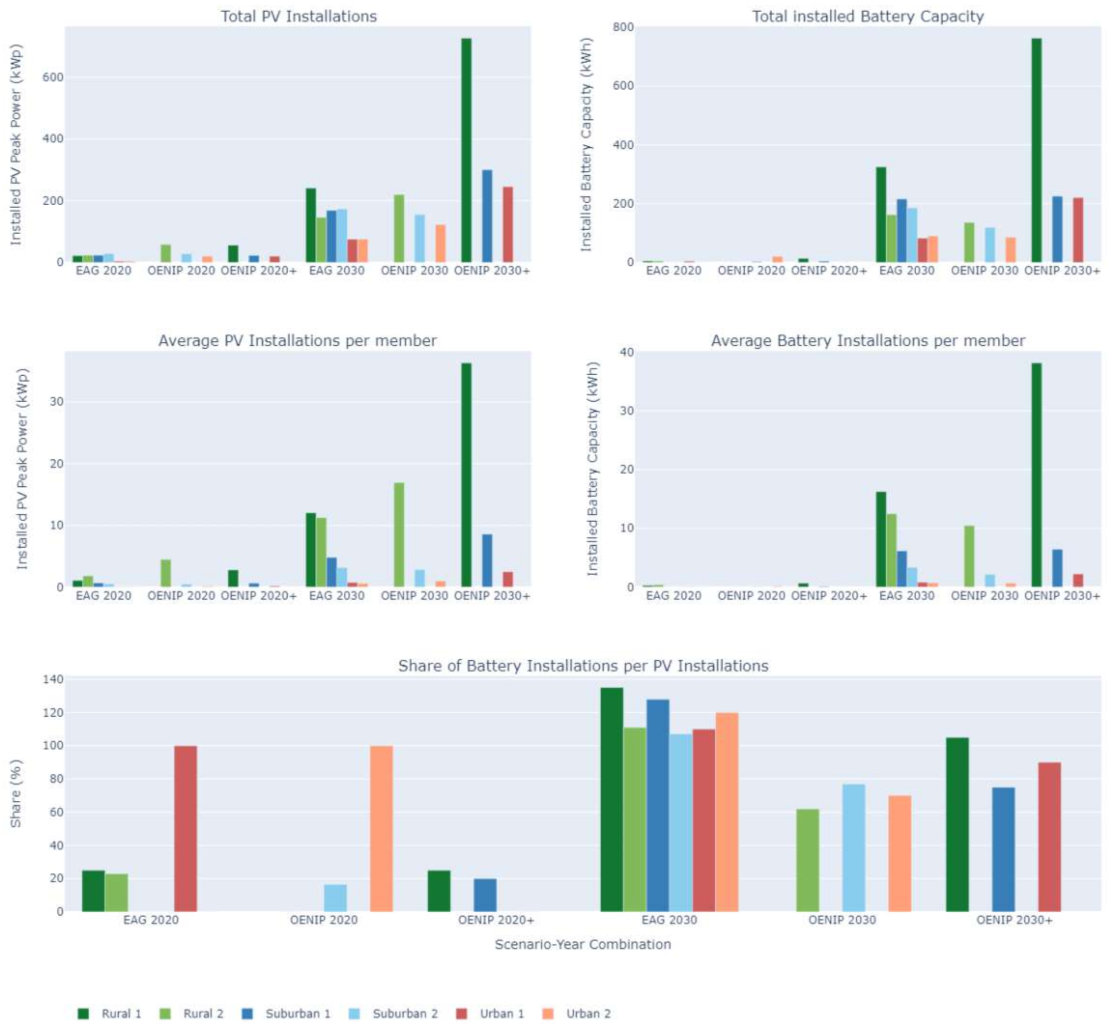

Figure 3.5.: Total installed PV peak power (kWp) and total installed battery capacity (kWh), average installed PV peak power (kWp) per member, average installed Battery capacity (kWh) and share of battery storage of PV installations (%) for each of the scenario-year combinations. Note, that the ÖNIP scenarios were separated into ÖNIP and ÖNIP+, the latter featuring an even higher penetration of flexibilities. Since not every scenario-year combination was simulated, some bars are missing

3.1.6. EV penetration rates

Traffic accounts for 32.4 % of the total final energy consumption in Austria (EU-27 average: 29.2 %) [11]. This sector being, in order to reach climate goals, clearly non-negligible, it is important to include the current penetration rates as well as their projections of electric vehicles - even if, at least at the moment, EVs do not account for much of the gross energy usage caused by transport with the current market share being 2.13 % [46].

Figure 3.6 displays the density of motorized vehicles per county. Comparing this Graph to Fig. 3.2, a correlation between rural areas and high vehicle density is clearly visible.

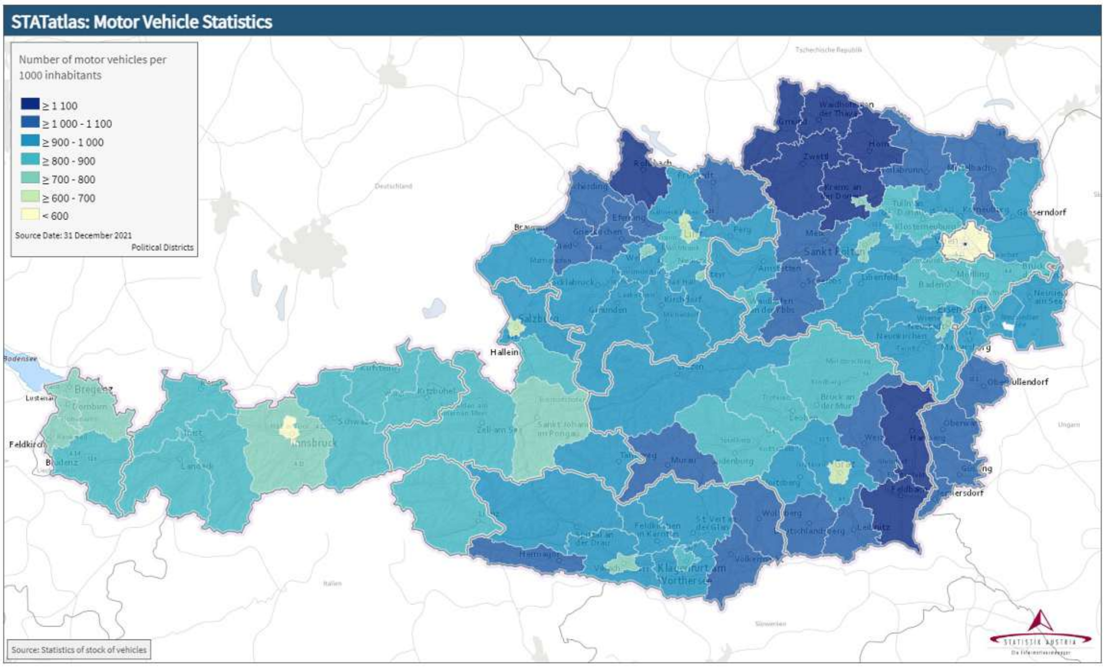

Figure 3.6.: Density of motorized vehicles in Austria by counties. Source: [47]

Conference contribution [13] presents the current numbers as well as future projections of EVs in correlation to the regional classification and projected EVs per typical community. Table 3.5 shows the data from above mentioned publication [13] while Table 3.6 presents the data that was actually used in this thesis simulations (Again, the numbers from the publication only refer to theoretical grids and communities, hence the data has been matched to grids available here). As clearly visible, the scenarios adhere to the PV scenarios specified in Section 3.1.4. Also, the scenario **ÖNIP 2030+** deliberately has a significant higher amount of installed EVs in order to investigate into scenarios with very high flexibility shares.

Region Type	EVs / 1k Inh. 2020	EVs / 1k Inh. 2030	EVs / Comm. 2020	EVs / Comm. 2030
Rural	4.9	96.3	0 (0.24)	5 (4.9)
Suburban	8.5	168.8	1 (0.9)	19 (18.5)
Urban	5.2	109.7	1 (1.2)	27 (26.9)

Table 3.5.: Number of EVs per 1000 inhabitants (Inh.) per region type for 2020 based on statistical data and 2030 based on projections as well as Number of EVs per typical Community (Comm.), again, for 2020 and 2030 (rounded numbers), Source: [13]

	EAG 2020	ÖNIP 2020	ÖNIP 2020+	EAG 2030	ÖNIP 2030	ÖNIP 2030+
Rural 1	0	x	0	5	x	10
Rural 2	0	0	x	5	5	x
Suburban 1	1	x	1	19	x	35
Suburban 2	1	1	x	19	19	x
Urban 1	1	x	1	27	x	54
Urban 2	1	1	x	27	27	x

Table 3.6.: Number of electric vehicles (EV) per scenario-grid combination. The penetration rates adhere to the numbers presented in [13]. „x" indicates, that this scenario-grid combination has not been simulated

3.1.7. Penetration Rates of Heat pumps and electric hot water boilers

Study [23] outlines, that about 51 % of the European final energy demand (EU-28, study published in 2016) was required for the Heating and Cooling sector. Within this very sector, again, about 52 % were consumed by space heating. That again, accounting for roughly a quarter of the European final energy demand, renders this sector non-negligible in order to reach climate goals. Study [32] outlines that, in order to reduce the carbon emissions from the space heating sector, an electrification of the space heating sector needs to take place. A prominent technology realising this transition are heat pumps [32].

Table 3.7 presents the numbers of installed heat pumps, electric hot water boilers as well as their representative yearly consumption of electric energy. The current and expected amount of heat pumps was deduced from the market development report of heat pumps in Austria [6]. It is important to state, that the electric hot water boilers were already existing in the utilized grid models. Therefore, they shall be included to the simulations as well.

While electric hot water boilers were assumed to be constant over time, a sensitivity analysis was carried out regarding the penetration rate of heat pumps, also adhering to the PV scenarios specified in Section 3.1.4. Table 3.7 presents the numbers for the respective scenario-grid combinations.

Section 3.2.1 will go more into detail regarding the synthesis of the heat demand.

	EAG 2020	ÖNIP 2020	ÖNIP 2020+	EAG 2030	ÖNIP 2030	ÖNIP 2030+	All Scenarios
	Num. Heat pumps	Num. Heat pumps	Num. Heat pumps	Num. Heat pumps	Num. Heat pumps	Num. Heat pumps	Num. Boilers
Rural 1	0	x	0	5	x	10	13
Rural 2	0	0	x	5	5	x	8
Suburban 1	2	x	2	22	x	35	29
Suburban 2	15	15	x	35	35	x	66
Urban 1	0	x	0	3	x	6	94
Urban 2	1	1	x	4	4	x	177

Table 3.7.: Numbers (Num.) of installed heat pumps (HP) for the selected scenario-grid combinations as well as the number of electric hot water boilers. Note, that the electric boilers are not subject to the scenario development. „x" indicates, that this scenario has not been simulated

3.2. Community Setup

After defining the scenarios, the input parameters of a community, so to say, a brief explanation on the communities setup will be given.

First and foremost, the size of the community adheres to the data specified in Section 3.1.3. Whether a potential member is part of the community or not gets randomly assigned. After that selection they are referred to as „Member“ or „Nonmember“. Then, the known amount of PV systems, batteries, heat pumps and EVs - the future flexibilities - will get randomly allocated as well. A key logic here is, that community members are more likely to possess one or more of the flexibilities and owners of, for example, a PV system are more likely to also own a EV and Battery system. Essentially, a strong correlation between participating in a community and owning a PV system, Battery, heat pump and EV is deliberately implemented.

Just as the scenarios, the instantiated communities also cohere partly to the scenarios determined for the ORANGE project [3, 44].

3.2.1. Assessing the heat demand

As already mentioned in Section 3.1.7, the heating sector is responsible for a vast amount of the gross energy demand and the electrification via heat pumps can contribute to this sectors decarbonization [32]. As clearly visible in Table 3.7, the amount of heat pumps increases with time. As these heat pumps will be modeled with great sophistication in `Femto.jl` (see Section 3.3), it is important to asses the necessary heat demand.

As already mentioned, the electricity demand of all loads is known (see Table A.1). From this known electricity demand the footprint of the house was deduced. The building type was assumed by the spatial properties of the grid, i.e. rural areas having mostly Single-Family homes whereas urban areas majorly consist of flats and apartments. Then, based on data from the Hotmaps project [36] the heat demand per square meter was deduced based on a typical distribution of the building quality classes.

3.2.2. Electricity and Heating Load Profiles

To investigate into the *Impact of Large-Scale Deployment of Energy Communities on Distribution Grids*, using appropriate and especially rather realistic time-series data as load profiles is crucial as the behaviour is observed at a very low level, i.e. LV- (and later MV-) level. Therefore, very little aggregation is taking place - following this, the behaviour of single loads matter. Hence, an aggregated standard load profile is not sufficient.

The agent-based `LoadProfileGenerator` [37] was utilized to generate the load profiles for households corresponding to the known yearly electricity consumption, assumed heat demand and assumed type of house based on the spatial distribution. `LoadProfileGenerator` does not feature the generation of commercial and agricultural loads, hence the standard load profiles from [1] are used for these non-household loads. Since the APCS standard load profiles feature various load-subcategories for the various different categories of commercial loads, for example, the standard load profiles are assumed to be sufficiently accurate for non-household loads. Apart from that, non-household loads only exist in small numbers in each community (see Table 3.2), that resulting in a fairly limited influence of those loads. Therefore, the utilization of standard load profiles can be justified as sufficient.

These electric load profiles will serve as input parameter for `Femto.jl`, as better explained in Section 3.3. The thermal load profiles, however, are derived from publications [38, 39, 40].

3.2.3. Computation of EV driving schedules

In Section 3.1.6 the expected penetration rates of EVs are presented based on conference contribution [13]. Table 3.6 shows that the amount of EVs is expected to increase with time. As the electricity demand of electric vehicles highly depends on the respective driving schedule, those schedules were modeled with great attention to detail within the project ORANGE [3, 44]

Report [48] presents the results of a large-scale survey carried out to investigate into the mobility behaviour of Austrian citizens. From that typical mobility behaviour, the expected mobility and thus EV driving patterns for the communities members was deduced, assuming, the behaviour does not change with EVs as the survey for report [48] focuses mostly on internal combustion engine cars as it was carried out in 2013. Then, with those driving patterns, typical charging patterns are computed and subsequently result in load profiles for EV charging. In general, EV charging will serve as a flexibility.

3.2.4. PV Profiles

Section 3.1.4 states the amount of PV systems to be installed. The production profiles for the PV systems were generated using the `PVlib` framework [51]. Since the PV production depends on the geographical location on great extent, several locations within Austria were chosen:

- Urban: Vienna
- Suburban: South Viennese Suburbs (Lower Austria)
- Rural: Salzburg (State)

These generated PV profiles were then scaled in a next step to match the installed peak power ratings. Figure 3.7 shows a PV profile for a 5.4 kWp plant typical for central Europe.

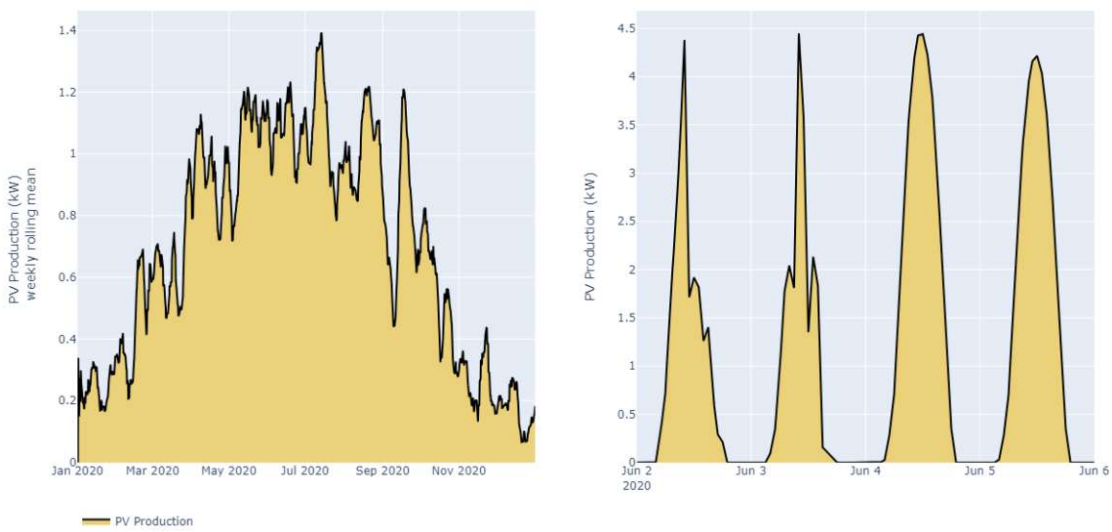

Figure 3.7.: Exemplary Curve for PV prodcution of a 5.4 kWp plant in a rural Austrain location for a) the yearly production with a rolling average of one week and b) some exemplary summer days

3.3. Simulation and Optimization Framework - `Femto.jl`

After having outlined and established the scenarios and communities, the provided mathematical simulation and optimization framework will be briefly explained as well as its economical input parameters. As mentioned in the introductory part, this model performs optimizations with varying objectives, depending on the scenario.

Here, the scenarios obtain their last dimension: the optimization goal. This last dimension proves to be a very crucial point since the calculation of an energy communities grid impact is determined by the underlying optimization goal. To be exact, the impact of one energy community is always determined by performing a delta calculation against the same scenario, but without a community. The objectives are

1. Community-wide overall minimization of all Total Expenditures (TOTEX)
2. Household-wide TOTEX minimization.

These two objectives will from now on be called „**Community**" and „**No Community**". So, in its essence, a energy community is implemented by utilizing a different objective as well as a reduced grid tariff, as outlined in Section 3.3.1. In order to yet again underline this important step, Figure 3.8 and 3.9 display an exemplary, simplified low voltage grid with households and their flexibilities with an energy community and without, respectively.

As clearly visible in Table 3.2 as well as in Figure 3.8, not every load is a member of a community. These so called „Non-Members" are always simulated with the objective of individual self-optimization.

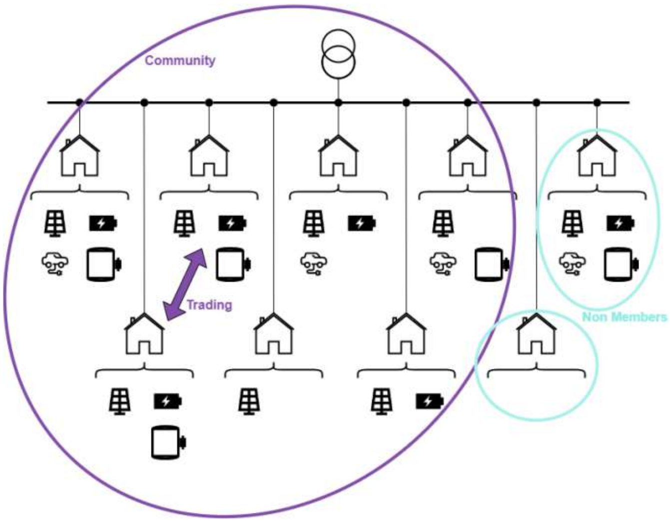

Figure 3.8.: „**Community**“ case: Pictogram of an exemplary low voltage grid with several households with their attached flexibilities (PV, Battery systems, EVSE and a thermal storage are shown here). The ellipses point out the area of optimization. The purple ellipse, marked as community, presents the energy community with its internal trading and community-wide minimization of TOTEX. The turquoise ellipses shows the remaining non-members carrying out their individual self-optimization. Furthermore, the previously mentioned positive correlation between owning flexibilities and community membership is outlined.

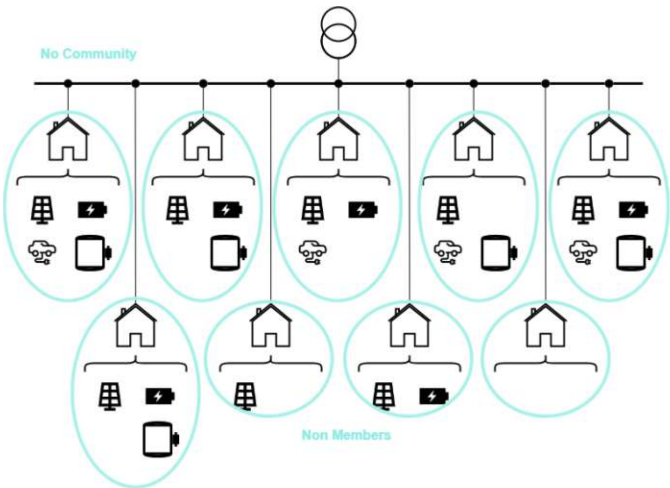

Figure 3.9.: „**No Community**“ case: Pictogram of an exemplary low voltage grid with several households with their attached flexibilities (PV, Battery systems, EVSE and a thermal storage are shown here). The ellipses point out the area of optimization. The turquoise ellipses presents the non-members carrying out their individual self-optimization.

3.3.1. Definition of Economic Input Data

Here, the economic input data underlying the optimization framework is presented.

At First, each of the loads gets either a dynamic or constant electricity supply tariff randomly assigned with a set share so that the vast majority of tariffs are still constant electricity supply tariffs. The underlying logic is, that prosumers, so consumers with a PV and Battery system, are more likely to have a dynamic tariff. The constant supply tariffs for all 2020 scenarios are calculated based on historic price data from [19] and the production data from [21] for Austria. The dynamic tariffs, however, include the dynamic load data in addition to the price and production data specified, again, in [19, 21]. In order to predict the expected electricity supply tariffs for all scenarios occurring in year of 2030, the price data from paper [34] is used. All prices for the PV production are directly taken from the European Network of Transmission System Operators (ENTSOE) Transparency Platform [21] via a module from [41]. Then, the data for the grid tariffs is defined.

Legislation [10] provides information on the annual grid usage charge, an annual constant cost set to 36 EUR, the volumetric grid usage charge and the volumetric grid loss charge, as seen in Table 3.8. Then, the „Elektrizitätsabgabegesetz“ sets the

	Burgenland	Carinthia	Lower Austria	Upper Austria	Salzburg	Styria	Tyrol	Vorarlberg	Vienna
Vol. Grid. Usage Charge (EUR/MWh)	58.3	70.3	53.7	51.2	52.9	61.3	50.2	36.8	50.0
Vol. Grid. Loss Charge (EUR/MWh)	24.74	25.19	22.25	25.21	17.24	23.28	26.9	20.8	29.14

Table 3.8.: Volumetric Grid Usage Charge for the Austrian States. Source: [10]

price for electricity surcharge to 15 EUR/MWh [9]. As clearly visible in Table 3.8, the charges depend on the state in Austria. Therefore, states have been selected to match the location of the grid models and geographical properties. To comply with the necessary anonymisation of real grid model data, the exact locations are under concealment.

3.3.2. Brief Introduction to the model

The provided framework is called `Femto.jl` (*Flexibility and **E**nergy **M**anagement **To**olbox for Julia*) and allows the optimization of flexible consumption, storage and production in multiple electricity markets whilst adhering to both technical and economic constraints [42, 43]. The source-code itself is available from [41]. The optimization problem is formulated as an Mixed Integer Linear Problem [43]. As already hinted in the previous sections, the following technologies are implemented as flexible components [42]:

- PV systems
- Batteries
- EV charging stations
- Electric boilers
- Heat pumps

All of these mentioned components are used as flexibilities while adhering to both technical and economic constraints. Obviously, technologies such as PV systems are highly dependent on the availability of solar irradiation. Nevertheless, assuming the availability of such irradiation, the production can be used as flexibility, i.e., a certain amount can be curtailed if economically viable.

The model presented in [43] offers a so called „Generic Component Interface“ which is used to model said components as they share key characteristics [43]. These modular components both adhere to technical constraints, such as power consumption and state-of-charge limits, as well as market constraints, such as reserves [43]. Apart from that, this component interface features a so called „Component Specific Cost“ that accounts for deviations from an expected schedule, for example unexpected balancing activations, and represents extra fees, grid costs and the associated degradation of components [43].

The model as presented refers to its usage in multiple electricity markets to day-ahead markets, intraday markets or balancing markets [43]. Here, for the project ORANGE, the multi-market design has been adapted to reproduce both Energy communities internal markets as well as the external market(s).

The model outputs time-series data with the active power of each load (household, commercial, PV, etc; member as well as non-member) as well as the power per load by component type. Also, another output is data regarding the communities residual load and internally traded energy. These time-series will be inputted into the power system analysis software as seen in the next step.

3.4. Iterative Load-Flow calculations

In order to assess the grid impact of various community behaviours, various iterative load flow calculations have been carried out. These calculations are performed in `DIgSILENT PowerFactory`, a power system analysis software, with the so called „Quasi-Dynamic-Simulation" Toolbox. It is important to state that, despite the name implicating a dynamic calculation, the carried out calculations were all steady-state iterative load flow calculations. So to say, a load flow calculation with load profiles [28].

`PowerFactory` offers a `Python` API. In order to ease the workflow and automate essential tasks, all computations were performed via this API.

The results from the previous step are, as mentioned in more detail in Section 3.3, load profiles for each load and each PV plant. Here, each load profile gets allocated to its corresponding load by its unique name. Since most grid models have, if at all, very few installed PV plants, the existing PVs will be erased from the existing grid model and the new PVs are added as new objects, connected to their dedicated terminals and assigned their generation profile. A clear advantage of including PV plants separately, is the ability of implementing a Q(U) control on the PV object. Therefore, each PV generation features a full Q(U) model where the characteristic curve follows [20] and is parameterized as following: It is important to state, that despite the existence of a Q(U)

$\cos(\phi)_{max}$	$U_{Q,0,min}$	$U_{Q,0,max}$	$U_{Q,max}$	$U_{Q,min}$
0.9	0.9	0.93	1.07	1.1

Table 3.9.: Numerical values for the parameters for the Q(U) control applicable to all PV systems

control mechanism, a state-of-the-art P(U) control to limit PV feed-in to avoid grid code violations was deliberately not implemented. Here, in this research work, the focus is upon investigating into the potential impact rather than operating a grid per se thus violations are of no concern and only present interesting behaviours.

Also, as clearly visible in Table A.1, many grids include electric hot water boilers as separate loads. Here, these boilers are included within the household load profile. Therefore, all original hot water boiler loads will be erased from the grid model as well.

After this refinement and adaptation of the provided grid models, the iterative load flow calculations are performed with a simulation step size of 15 minutes to comply with EN 50-160.

In order to assess the impact of energy communities on the grid, the following KPIs have been selected:

- Terminal Voltages (p.u.)
- Line Loadings (%)
- Transformer Loadings (%)

3.4.1. Low Voltage Grid calculations

In a first step, the impact of one Energy community on one low voltage feeder shall be investigated. Consequently, the grid models from Appendix A will be utilized. Start- and End-time of all simulations are the first and last time step of the given year and all scenarios specified in Section 3.1 are simulated.

The detailled topologies as well as further information regarding the grid models can be viewed in the Appendix A.

3.4.2. Medium Voltage Grid calculations

Here, in order to investigate the impact of the large(r)-scale deployment, several communities shall be placed within a MV branch, with one or many communities per Low Voltage Feeder. Appendix B presents these grids in more detail.

The definition of scenarios works just as described in Section 3.1 and the building of the community works as in Section 3.2. As seen in Table B.1, one subgrid can occur multiple times within a MV grid. In addition to a slight alteration regarding line length as described in Section B, the community members have been allocated by their unique name only for the first occurrence of a LV grid. For every following occurrence, the loads of community members as well as their appended PV systems have been shuffled with other loads of the same load type and similar yearly consumption to avoid exact duplicates of LV subgrids.

In contrast to the yearly calculation carried out for the LV grids, only a handful of weeks per year have been calculated. The reason for that is the avoidance of excessive computation and memory effort. Since the MV grids are based on the previously presented LV grids on great extent and the underlying simulation data is identical, only the times where either critical or interesting occurrences happened in the analysis of LV grids have been simulated here. Also, not each scenario was inspected here. Again, only scenarios that yielded interesting results for the LV calculation was considered. It is important to define the such interesting scenarios. Essentially, only scenarios and times have been selected that already yielded significant deviations in the LV calculations. In other words, times and scenarios with identical behaviour between the Community and No Community case are of no concern.

Here, with several possible energy communities within a given MV feeder, a sensitivity analysis regarding the penetration rate of communities is performed. Upon a defined energy community penetration rate, it is randomly chosen which LV subgrid will become a community. Therefore, several penetration rates have been considered, such as:

- 0% (which correlates to the previously named „**No community**" scenario)
- 25%
- 50%
- 75%
- 100% (that representing the „**Community**" scenario)

Again, the exact synthesis as well as further details regarding the MV grid topologies are presented in the Appendix B.

4. Results

This chapter presents the obtained results from carried out simulations. In general, a distinction is made between the results of Low voltage grids and medium voltage grids. Section 4.1 and Section 4.2 present those results, respectively.

The simulations yielded excessive amounts of data: At the example of the LV grids, 4 scenarios were investigated each for 6 grids, each with either a community or no community with a time step of 15 minutes for one whole year. To cope with this massive amount of data, a „Data to showcase " approach was chosen. In its essence, that implies the following (rough) steps:

1. Calculation of deviation and other statistical measures
2. Presentation of the results of the modelling and optimization framework
3. Showcasing the results of the load flow calculations

To better understand this approach, a brief explanation is given:

Calculation of deviation and further statistical measures As already mentioned in Section 3.3, the impact of a community is always determined by performing the same simulation once with (referred to as „**Community**") and once without a community (called „**No Community**"), a delta calculation so to say. These error measures refer to the deviation of the Grid KPIs for those two scenarios. It is important to state, that, despite the name, it is not an error per se, rather a deviation. In addition to these deviation measures, several other statistical measures such as correlation coefficients and community performance indicators have been introduced.

Presentation of the results of the modelling and optimization framework In this second step, the results from the modelling and optimization framework `Femto.jl` (see Section 3.3) are presented. Results are the trading behaviour of the community, the communities residual load as well as the sources and sinks of the various types of loads and flexibilities. This already allows for a better understanding and provides a good overview, when critical situations for the grid might occur.

Showcasing the results of the load flow calculations In the previous steps, potential critical times can be filtered - especially with the deviation measures from the first step. Here, various examples of these occurrences will be showcased.

4.1. Low Voltage Distribution Grids

In this section, the results for the low voltage grids will be presented. As outlined in the introductory part of this chapter, first of all, in order to fulfill the „data to showcase“ approach, the deviation calculation will be presented at first followed by further statistical analysis.

In order to carry out these mentioned steps, the following mathematical formulation shall be introduced:

Let $\underline{A}$ be the matrix of all results of one KPI, terminal voltages for example

$$\underline{A} = \begin{pmatrix} \vec{a}_1 & \vec{a}_2 & \dots & \vec{a}_n \end{pmatrix} \tag{4.1}$$

where:

$\vec{a}_i$ = Vector of time series result data of one element (= terminal, line or transformer)
n = number of elements in the result matrix

Further, it is assumed that only the maxima as well as minima for each timestep of one KPI are relevant hence defining the envelopes as

$$\vec{E}^{A}_{lower} = \begin{pmatrix} \min \vec{a}_{1,1\dots n} \\ \min \vec{a}_{2,1\dots n} \\ \vdots \\ \min \vec{a}_{m,1\dots n} \end{pmatrix} \tag{4.2}$$

where:

$\min \vec{a}_{j,1\dots n}$ = Minimum value of all elements for one timestep
m = number of timesteps

and

$$\vec{E}^{A}_{upper} = \begin{pmatrix} \max \vec{a}_{1,1\dots n} \\ \max \vec{a}_{2,1\dots n} \\ \vdots \\ \max \vec{a}_{m,1\dots n} \end{pmatrix} \tag{4.3}$$

where:

$\max \vec{a}_{j,1\dots n}$ = Maximum value of all elements for one timestep
m = number of timesteps

As already mentioned in Section 3.4, selected KPIs are terminal voltages as well as thermal line and transformer loadings. It is crucial to note, that only for the terminal voltages the upper as well as the lower envelope is considered as only one transformer exists in a grid and the lower envelope of line loadings yields always zero (several lines are constantly deactivated). Also, the slack node is excluded from the result matrix. Further, these envelopes will be calculated for every Community and No Community case. Hence, the following envelopes are remaining:

$\vec{E}_{upper}^{TV,Comm.}$ = upper envelope of all terminal voltages (TV) for the Community case ($Comm.$)
$\vec{E}_{lower}^{TV,Comm.}$ = lower envelope of all terminal voltages (TV) for the Community case ($Comm.$)
$\vec{E}_{upper}^{LL,Comm.}$ = upper envelope of all line loadings (LL) for the Community case ($Comm.$)
$\vec{E}_{upper}^{TL,Comm.}$ = upper envelope of all transformer loadings (TL) for the Community case ($Comm.$)
$\vec{E}_{upper}^{TV,NC}$ = upper envelope of all terminal voltages (TV) for the No Community case (NC)
$\vec{E}_{lower}^{TV,NC}$ = lower envelope of all terminal voltages (TV) for the No Community case (NC)
$\vec{E}_{upper}^{LL,NC}$ = upper envelope of all line loadings (LL) for the No Community case (NC)
$\vec{E}_{upper}^{TL,NC}$ = upper envelope of all transformer loadings (TL) for the No Community case (NC)

In addition, the nomenclature for the sources and sinks of power must be defined:

$$\vec{P}_T^C = \sum_{i=1}^{n} \vec{P}_{i,T}^C \tag{4.4}$$

where:

$\vec{P}_T^C$ = Aggregated Power of Technology T and Community Case C (time series)
$\vec{P}_{i,T}^C$ = Time series consumption or production of a single component of Technology T and Community Case C
$T \in [\text{PV}, \text{Batt.}, \text{HP}, \text{Boil.}, \text{EVSE}]$ = Types of Flexibilities
$C \in [\text{Comm.}, \text{NC}]$ = Community case
n = number of available systems of one technology

Furthermore, the communities residual load is defined as

$$\vec{P}^C_{Res} = \vec{P}^C_{LP} + \vec{P}^C_{Batt.} + \vec{P}^C_{PV} + \vec{P}^C_{HP} + \vec{P}^C_{EVSE} + \vec{P}^C_{Boil.} \tag{4.5}$$

where:

$\vec{P}^C_{LP}$ = Power of the non-flexible load profile of all community members

Then, the communities internal trading shall be formulated:

$$\vec{P}_{Trade} = \sum_{i=1}^{n} \vec{P}_{i,Trade}[\vec{P}_{i,Trade} \geq 0] \tag{4.6}$$

where:

n = number of potential trading participants
$\vec{P}_{i,Trade}[\vec{P}_{i,Trade} \geq 0]$ = Trading of each participant that is greater or equal than zero (internal trading sum would be constantly zero otherwise)

4.1.1. Statistical overview of obtained data

Computation of deviation measures for all scenarios

Here, in a first step, an overview of the deviations between every „Community“ and „No Community“ case shall be given across all scenarios. Regarding the deviation measures, two metrics are presented:

First, the Mean Absolute Percentage Error (MAPE) is calculated as

$$\text{MAPE} = \frac{1}{m} \sum_{t=1}^{n} \left| \frac{\vec{E}^{NC} - \vec{E}^{Comm.}}{\vec{E}^{NC}} \right| \tag{4.7}$$

where:

$\vec{E}^{NC} \in [\vec{E}^{TV,NC}_{upper}, \vec{E}^{TV,NC}_{lower}, \vec{E}^{LL,NC}_{upper}, \vec{E}^{TL,NC}_{upper}]$ = Envelopes of the No Community cases
$\vec{E}^{Comm.} \in [\vec{E}^{TV,Comm.}_{upper}, \vec{E}^{TV,Comm.}_{lower}, \vec{E}^{LL,Comm.}_{upper}, \vec{E}^{TL,Comm.}_{upper}]$ = Envelopes of the No Community cases
m = number of timesteps

Then, the Maximum Error (ME) is calculated as well

$$\mathrm{ME} = \max |\, \vec{E}^{NC} - \vec{E}^{Comm.} \,| \tag{4.8}$$

where:

$\vec{E}^{NC} \in [\vec{E}^{TV,NC}_{upper}, \vec{E}^{TV,NC}_{lower}, \vec{E}^{LL,NC}_{upper}, \vec{E}^{TL,NC}_{upper}]$ = Envelopes of the No Community cases

$\vec{E}^{Comm.} \in [\vec{E}^{TV,Comm.}_{upper}, \vec{E}^{TV,Comm.}_{lower}, \vec{E}^{LL,Comm.}_{upper}, \vec{E}^{TL,Comm.}_{upper}]$ = Envelopes of the No Community cases

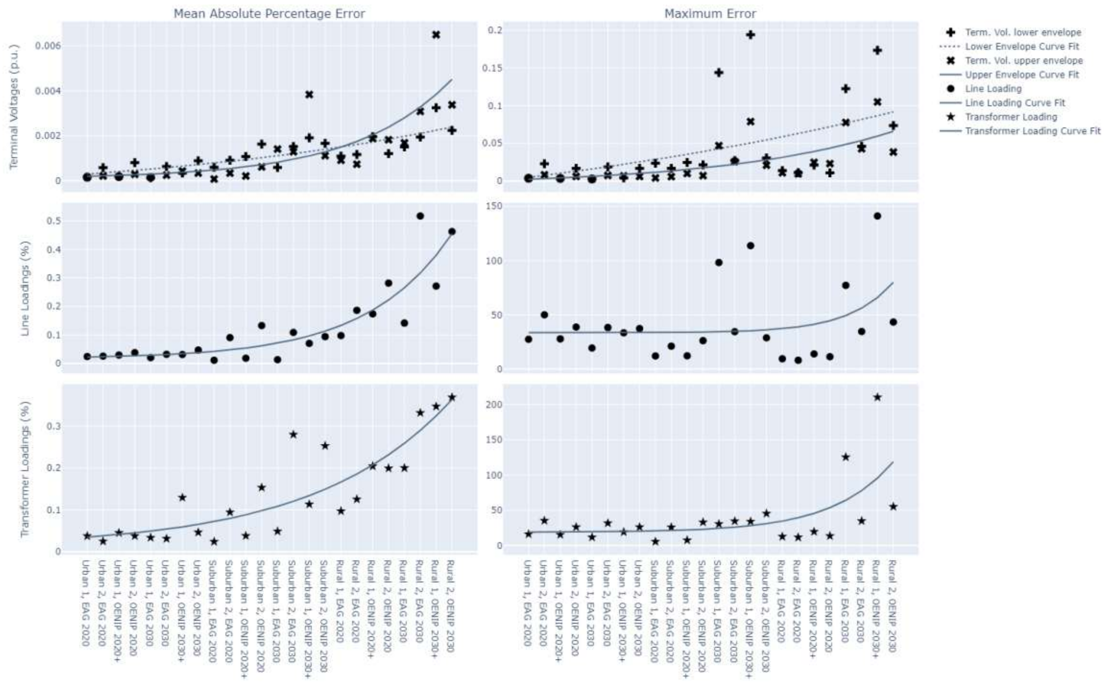

Figure 4.1.: Deviation measures (Mean Absolute Percentage Error (MAPE) in (a) and the maximum absolute error in (b)) for all scenario-grid combinations (sorted by region type and the respective PV and flexibility penetrations) for terminal voltages, line loadings and transformer loadings. Terminal Voltages are considered by their respective upper and lower envelope while for transformer and line loading only the upper envelope is taken into consideration. Also, a curve fit is shown.

Looking at Figure 4.1, a clear trend is visible: Apart from some outliers, the deviation between „**Community**“ and „**No Community**“ increases with the „de-urbanization“ and the increased installation of flexibilities. So in essence, the biggest deviations and subsequently the most interesting occurrences can most likely be found in rural scenarios with a high integration of flexibilities.

A first look at the aggregated production and consumption data

In order to better understand the differences between the Community and No Community cases as presented above, a first look at the aggregated production and generation data analog to Equation 4.4 will be taken so that $P_T^C = \sum_m \vec{P}_T^C$ with m being the number of timesteps. Figure 4.2 presents the yearly sum of all flexible sources and sinks of power each for the Community and No Community case for each scenario. It is important to state, that the non flexible load profiles are not displayed on purpose, as they remain the same between the Community and No Community case.

Looking at Figure 4.2, it becomes clear that, first of all, the difference when considering the yearly aggregation of the sources and sinks of power remains limited. Typically, the Community case offers higher PV production and also, the remaining flexibilities get dispatched more often. However, the magnitude of this effect is limited as some scenarios such as the Urban and Rural ÖNIP 2030+ scenarios show the opposing behaviour. Nevertheless, it can be concluded, that the existence of a community does marginally benefit the aggregated usage of PV and flexibilities.

Figure 4.2.: Yearly sum of the aggregated sources and sinks of power for all scenarios, each for the Community and No Community case - the latter is marked with the dashed colorbars.

A first look at the communities internal trading

Figure 4.3 presents the total amount of the community-internal trading per year for each scenario-grid combination so that $P^C_{Trade} = \sum_m \vec{P}^C_{Trade}$ with m being the number of timesteps. As the size of the community varies quite with the region and grid size, the total average community-internal trading per member is calculated as well for each scenario-grid combination. Here, it is visible, that the average total internal trading does not significantly increase with the additional installation of flexibilitites for rural scenarios. This number only increases significantly for urban scenarios, with suburban being somewhat in the middle (see the flexibility installations in Figure 3.5 for reference). Therefore, it is expected, that with an increasing amount of flexibility installations, a certain saturation effect, limiting the economic viability of community-internal trading, takes place.

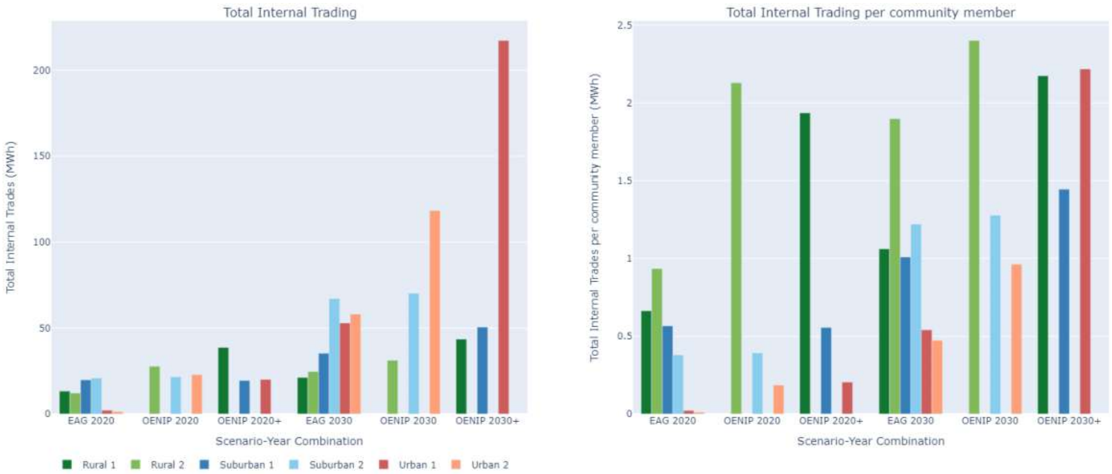

Figure 4.3.: (a) Total (yearly sum) of the internal trading per scenario-grid combination and (b) total average internal trading per community member for each scenario-grid combination

As Figure 4.3 only represents the yearly sum, it is crucial to investigate further into whether a seasonality is taking place in the bigger picture. Figure 4.4 presents the community-internal trading in the time domain with the trading $\vec{P}_{Trade}$ averaged by the number of community members, averaged by the region-grid combinations and further computed with a 2-Week rolling average. In other words, all scenarios are condensed to their respective year and region type.

Unmistakably, looking at Figure 4.4, for urban and suburban scenarios, the scenarios for the year 2030 always yield higher internal trading with the peak occurring some time during summer. This behaviour correlates quite well with a typical yearly feed-in

Figure 4.4.: Community-internal trading, averaged per community member, averaged per region-year combination and displayed with a 1-Week rolling average

curve of a PV plant - more installations result in higher overall output with the peak taking place during summer. In contrary, the rural grids show a different behaviour: While the 2020 scenario follows this typical pattern, the 2030 scenario shows the lowest values of internal trading (if the start of the rolling average is not accounted for as the minimal periods are set to one) during summer time and rather has its peaks in between summer and winter. This interesting behaviour will be further inspected.

Correlating the behavioural patterns of all scenarios

Nearly all results as well as input data are available in a time-series format. In addition to the deviation measures presented above, the correlation coefficients for various curves shall be calculated adhering to the Pearson method such as

$$\rho_{X,Y} = \frac{\text{cov}(X,Y)}{\sigma_X \sigma_Y} \tag{4.9}$$

where:

$$\begin{aligned} \text{cov}(X,Y) &= \text{covariance of sample } \vec{X} \text{ and } \vec{Y} \\ \sigma_X &= \text{standard deviation of sample } \vec{X} \\ \sigma_Y &= \text{standard deviation of sample } \vec{Y} \end{aligned}$$

The samples, i.e., time-series vectors can be defined as the following in addition to previously defined equations (4.2 - 4.6):

$$\vec{\text{Flex}} = \vec{P}^{Comm.}_{Batt.} + \vec{P}^{Comm.}_{HP} + \vec{P}^{Comm.}_{EVSE} + \vec{P}^{Comm.}_{Boil.} \tag{4.10}$$

$$\vec{D}_{env}^{KPI} = \mid \vec{E}_{env}^{KPI,Comm.} - \vec{E}_{env}^{KPI,NC} \mid \quad (4.11)$$

where:

$\vec{D}_{env}^{KPI}$	= absolute deviation for a given KPI between Community and No Community case
$env \in [upper, lower]$	= upper or lower envelope
$KPI \in [TV, LL, TL]$	= given grid KPI

Thus, D_{lower}^{TV}, for example, refers to the terminal voltages lower envelope deviation time series.

Figure 4.5 shows the obtained correlation coefficients for the whole year and for each scenario-grid combination. So, „Flex. - TV upper env. dev", for example, describes the correlation between the curve of all combined flexibilities and the terminal voltage upper envelope deviation between the community and no-community case.

As visible from Figure 4.5, PV generally positively correlates well with the communities internal trading with less correlation for the rural scenarios with high PV integration. Opposing to that, the scenarios with a weak or weak negative correlation between PV and trading have a high positive correlation between trading and the communities residual load. That implies, that in scenarios with very high PV penetration, grid electricity is used for trading. Also, as seen in the third row, trading generally boosts the usage of flexibilities (without PV, so only batteries, heat pumps, EVSE and boilers).

In general, the usage of flexibilities per se has little to no significant influence on the deviation of the grids parameters as seen in the second category of rows. Obviously, PV production has an impact on the grids parameters. However, in general, there is little correlation between its production and the absolute deviation between the community and no-community case. Only within selected scenarios (mostly rural EAG scenarios), the deviation of the terminal voltage upper envelope and transformer loading correlates with PV production. From this, it can be deduced, that the increasing implementation of PV does not create too much of a deviation between the community and no-community case.

Finally, a closer look is taken at the relationship between the community-internal trading and the grid parameters deviations. Here, trading has no significant impact on any urban scenario. For suburban scenarios, trading has a positive correlation to the deviation of terminal voltages upper envelopes as well as the transformer loading deviation for some cases and a weak positive correlation in most cases. For rural scenarios, the results are two-folded with the separation being between 2020 and 2030 scenarios. All rural 2020 scenarios have a strong correlation between the deviation of the upper terminal voltage envelope and the transformer loading deviation while 2030 scenarios appear more indifferent. That implies, that only certain scenarios depending on the flexibility and PV installations are affected by the trading in general. Therefore, a closer look has to be taken into more specific results.

In order to investigate further into these correlations, a seasonal split (according to calendrical dates) has been made: Figure 4.6 presents the same results only for spring while Figure 4.7 shows the results for winter exclusively. With that distinction, the seasonality first described in Figure 4.4 is better presented. Apart from several minor changes between the yearly correlation coefficients and its subparts, the biggest difference is the influence of PV. In times of high PV production, that typically being spring and summer, PV has a strong negative correlation to the communities internal trading. Also, the correlation between trading and the usage of flexibilities is, generally, more positive during times of high PV production. Apart from that, during spring (and summer as well although not shown here), the correlation coefficients between trading and grid parameters deviations is typically more pronounced. Therefore, it can be summed up, that times of high PV production typically induce greater grid KPI deviations via the community-internal trading when compared to times of lower PV production.

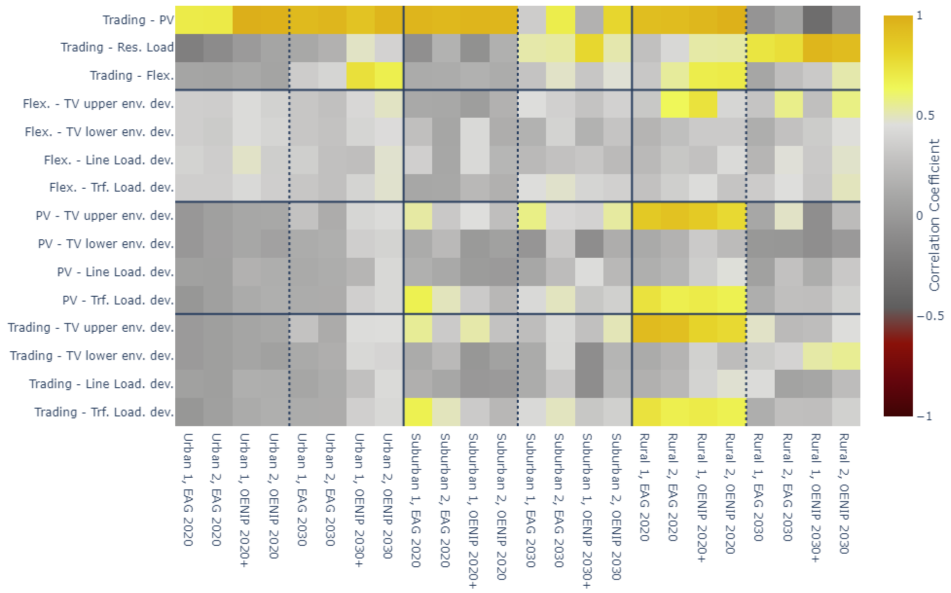

Figure 4.5.: Calculation of various correlation coefficients for the **whole year**: On the y-axis the correlations are marked while the scenario-grid combinations are assigned to the x-axis. For the grid parameters, the absolute deviation between the community and no community case is calculated, called „dev." „Res. Load" refers to the grids residual load, „Flex." to the grids combined flexibilities without PV (heat pump, EVSE, Batteries and Boilers), „Load." to the loading of the respective equipment and „Trf." to the transformer.

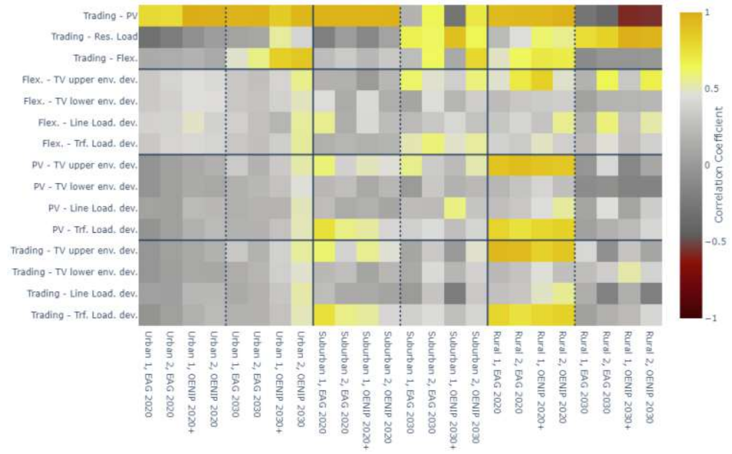

Figure 4.6.: Calculation of various correlation coefficients for **spring**: On the y-axis the correlations are marked while the scenario-grid combinations are assigned to the x-axis. For the grid parameters, the absolute deviation between the community and no community case is calculated, called „dev." „Res. Load" refers to the grids residual load, „Flex." to the grids combined flexibilities without PV (heat pump, EVSE, Batteries and Boilers), „Load." to the loading of the respective equipment and „Trf." to the transformer.

Figure 4.7.: Calculation of various correlation coefficients for **winter**: On the y-axis the correlations are marked while the scenario-grid combinations are assigned to the x-axis. For the grid parameters, the absolute deviation between the community and no community case is calculated, called „dev." „Res. Load" refers to the grids residual load, „Flex." to the grids combined flexibilities without PV (heat pump, EVSE, Batteries and Boilers), „Load." to the loading of the respective equipment and „Trf." to the transformer.

Assessing the communities performance in respect to the grid impact

As already mentioned in the literature review, the techno-economical performance of an energy community is measured by its Self Sufficiency Rate (SSR) as well as its Self Consumption Rate (SCR) - as contributions [35, 27] express in more detail.

Following the definitions from Equation (4.2 - 4.6), an energy communities SSR can be calculated such as

$$\begin{aligned} \text{SSR} &:= \frac{\text{Total Consumption} - \text{Total Imports}}{\text{Total Consumption}} \\ &= \frac{\left(\sum_m \vec{P}_{LP}^{Comm} + \sum_m \vec{P}_{HP}^{Comm} + \sum_m \vec{P}_{Boil}^{Comm} + \sum_m \vec{P}_{EVSE}^{Comm}\right) - \sum_m \vec{P}_{Res}^{Comm.}[\vec{P, m}_{Res}^{Comm.} \geq 0]}{\left(\sum_m \vec{P}_{LP}^{Comm} + \sum_m \vec{P}_{HP}^{Comm} + \sum_m \vec{P}_{Boil}^{Comm} + \sum_m \vec{P}_{EVSE}^{Comm}\right)} \end{aligned} \tag{4.12}$$

while the SCR can be computed as

$$\begin{aligned} \text{SSR} &:= \frac{\text{Total Production} - \text{Total Exports}}{\text{Total Production}} \\ &= \frac{\sum_m \vec{P}_{PV}^{Comm} - \sum_m \vec{P}_{Res}^{Comm.}[\vec{P, m}_{Res}^{Comm.} \leq 0]}{\sum_m \vec{P}_{PV}^{Comm}} \end{aligned} \tag{4.13}$$

with m being the number of timesteps. Also, the consumption as well as production from battery storage systems is not considered here. Clearly, as all vectors are summed up, the coincidence factor ist lost.

Figure 4.8 presents the MAPE of the terminal voltages upper envelopes for each scenario-grid combination in relation to the scenarios SSR and SCR. In general, urban scenarios with low PV and flexibility penetration yield a low self sufficiency rate with a high self consumption rate. That induces, that a low percentage of this communities energy consumption can be covered by its own production while the vast majority of that production gets used locally within the community. With smaller communities and increasing PV and flexibility penetrations, i.e. trajecting towards suburban and rural scenarios with high(er) installations of such technologies, the SSR increases while the SCR decreases. „**Rural 1, ÖNIP 2030+**" marks an extreme case scenario: Here, with the highest PV and flexibility installations per member, the SSR peaks while the SCR has its low. This means, that a high percentage of its energy consumption comes from local sources but only a small fraction of these sources can be used locally.

Again, in regard to the grid impact, Figure 4.8 shows a good correlation between SSR, SCR and the terminal voltages upper envelope MAPE: The MAPE decreases with the self consumption rate and increases with the self sufficiency rate.

Figure 4.9, on the other hand, presents the same parameters only with the terminal voltages lower envelope in mind. The behaviour in general is similar to the upper envelopes behaviour as displayed in Figure 4.8. The only major difference is the magnitude of the MAPE values, the terminal voltages upper envelope experiences a significantly higher MAPE. This can easily explained with the high PV production and subsequent rise of all terminal voltages.

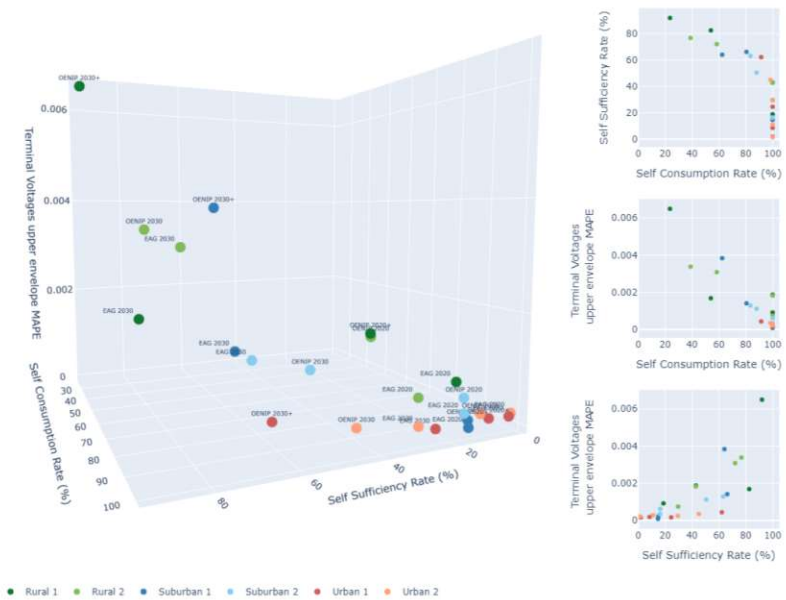

Figure 4.8.: Self Sufficiency Rate (SSR), Self Consumption Rate (SCR) and the terminal voltages upper envelope MAPE both in a three-dimensional figure as well with the respective projections for all scenario-grid combinations

Finally, Figure 4.10 and 4.11 present the data for the line loadings upper envelope and the transformer loading respective MAPE. Again, an increase in the SCR results in a decrease in the respective MAPE values while an increase in SSR results in an increase of the MAPE values.

Therefore, it can be said, that the individual MAPE values of the previously defined KPIs correlate well and further, these results only strengthen already drawn conclusions: Scenarios with very little PV and flexibility integration (in respect to the nonflexible load) yield a high SCR, low SSR and low deviations of grid parameters when compared to the respective no community baseline scenario. The vast majority of urban scenarios and some suburban scenarios are part of this group. Then, a handful of scenarios (majorly rural scenarios in 2030, i.e., with PV overproduction) result in a high SSR, low SCR and the highest overall grid KPI deviations.

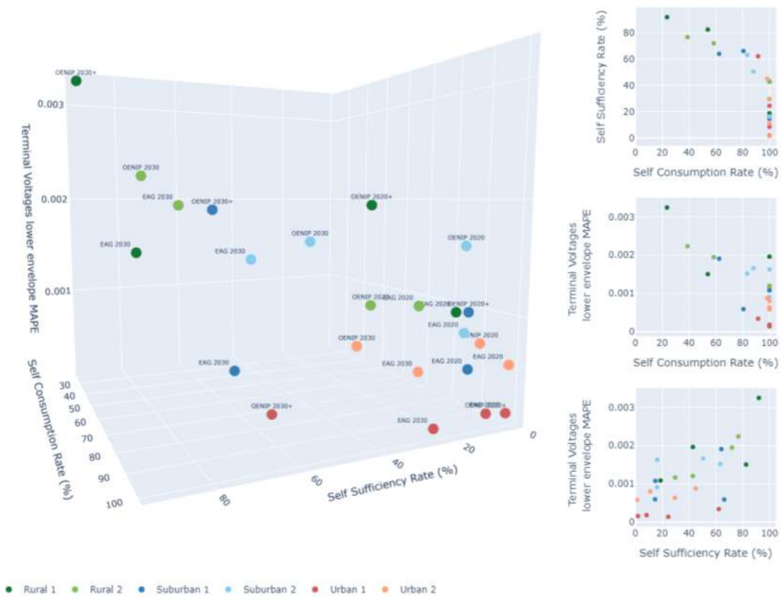

Figure 4.9.: Self Sufficiency Rate (SSR), Self Consumption Rate (SCR) and the terminal voltages lower envelope MAPE both in a three-dimensional figure as well with the respective projections for all scenario-grid combinations

As Figures 4.8, 4.9, 4.10 and 4.11 clearly show when plotting the SSR against the SCR, a curve similar to a pareto front can be observed. Therefore, a handful of scenarios can be derived as optimal solutions in regard to the SSR and SCR. These scenarios are mostly suburban 2030 and urban 2020 scenarios such as „**Suburban 1, ÖNIP 2030+**“, „**Suburban 1, EAg 2030**“, „**Urban 1, ÖNIP 2030+**“ or „**Rural 1, ÖNIP 2020+**“. Also, these optimal scenarios have moderately low MAPE values in respect to their overall efficacy and gain. In other words, mentioned scenarios have a higher deviation of grid KPIs when compared to the no community counterpart but at the same time yield significant benefits in terms of local utilization of local production of renewable energy and a reduced reliance of energy imports.

After having established a handful of statistical observations in addition to investigating into the communities performance with the grid impact in mind, it is of absolute necessity to further take closer looks into exact „non-statistical“ results in order to observe the detailed behaviour at a very low level.

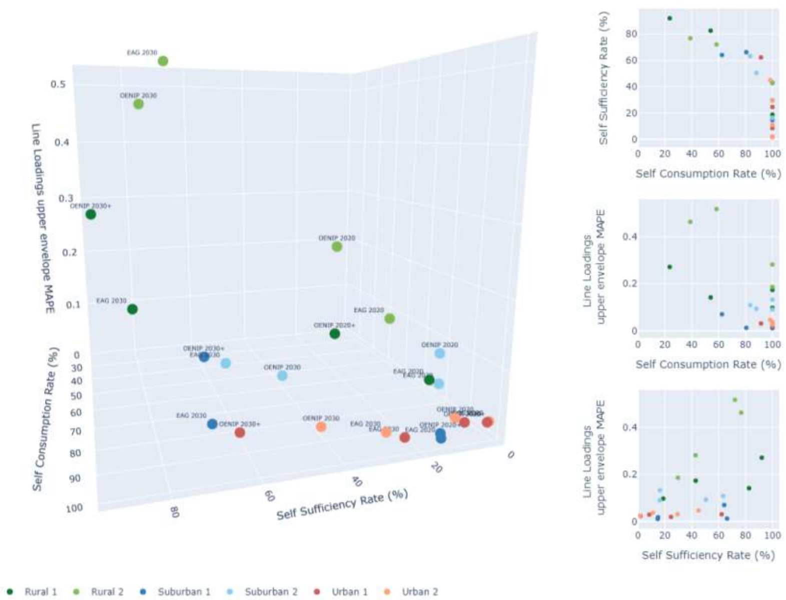

Figure 4.10.: Self Sufficiency Rate (SSR), Self Consumption Rate (SCR) and the line loadings upper envelope MAPE both in a three-dimensional figure as well with the respective projections for all scenario-grid combinations

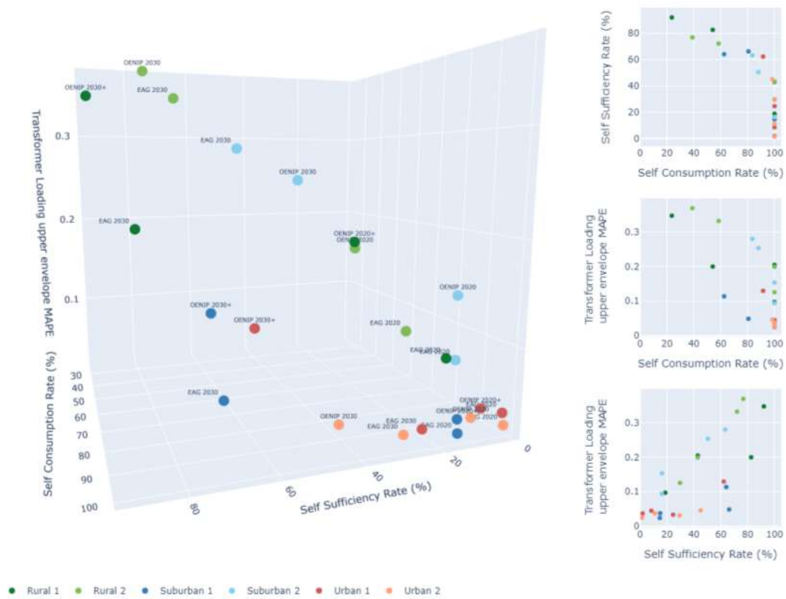

Figure 4.11.: Self Sufficiency Rate (SSR), Self Consumption Rate (SCR) and the transformer loading MAPE both in a three-dimensional figure as well with the respective projections for all scenario-grid combinations

4.1.2. Detailed Results

After having taken an overview of the results comparing all scenarios by the deviation measures as well as various statistical measures, a closer insight into a handful of occasions shall be given.

Results from the Modelling and Optimization Framework

In a first step, the results of the modelling and optimization framework will be presented. The focus shall lay on the community-internal trading, the residual load as well as the sources and sinks of power for the various types. In other words, the communities intrinsic behaviour will be explored. Therefore, only the „**Community**“ case will be investigated. In detail, the impact of the previously carried out sensitivity analysis regarding flexibility integration on the community behaviour will be shown.

Rural Grids Figure 4.12 presents for all „**Rural 1**“ scenarios the weekly rolling average of the aggregated internal trading alongside the times (in Hour of the Day) of the daily peak trading with the dots being sized by the peak tradings magnitude and colored by the number of participants of this peak trade. The goal is to identify times of high trading shared amongst few participants as this results in a high average traded power per trading participant and subsequently a potential grid impact. Additionally, this figure also presents the aggregated sources and sinks of power including the residual load (again, with a weekly rolling average) in order to determine potential correlations between the trading and the communities energy mix.

As clearly visible in Figure 4.12, the increased installation of flexibilities results in a significant reduction of the communities residual load. For 2030 scenarios, the rolling average of the residual load is almost always negative, that making the community a strong energy exporter. It is important to state, that the load profiles do not change with the scenario. Also, the impact of the increased amount of installed flexibilities is obvious. Taking a look at the community-internal trading behaviour, interesting patterns can be observed: While the total traded energy increases (see Figure 4.3 for reference) and its peaks increase as well (apart from one outlier in the EAG 2030 scenario), a bi-seasonal behaviour can be observed for the 2030 scenarios. Especially in the ÖNIP 2030+ scenario, the trading has its lowest value at times of the highest PV productions. Also, as the dots for the daily peak trading time point out, the trading pattern changes from several participants during midday, to only a few participants quite well distributed during the day. In addition, during summer, a very limited amount of energy gets almost exclusively traded in the evening.

Suburban Grids The same plot is displayed for the „**Suburban 1**" scenarios as well as seen in Figure 4.13. Here, the result is similar to the outcomes presented for the rural grid (as shown in Figure 4.12), but essentially with all stated impacts being reduced in their respective significance. In other words, the bi-seasonal and bi-daily trading pattern occurs for the 2030 scenarios as well, just not as extreme as for the shown rural grid. Therefore, less impact of the community on the grids KPIs is expected.

Urban Grids Just as for the rural and suburban scenario, the same plot shall be presented for the „**Urban 2**" scenario as well. Figure 4.14 presents this outcome. For this scenario, due to the lack of installed flexibilities and therefore economically viable trading possibilites, almost no trading with almost no participants takes places for the EAG 2020 scenario. With the increasing installation of flexibilities, first of all, the residual load gets drastically reduced and, secondly, the community-internal trading effectively increases with each further flexibility installation. In contrast to the outcomes from the urban and suburban grids as seen in Figure 4.12 and 4.13, the internal trading peaks during the summer, so has a strong correlation with the yearly PV production, and typically has its peaks midday, again, strongly correlating the typical daily PV production pattern.

When comparing the outcomes from the rural, suburban and urban grid, it is visible that the community-internal trading correlates to the yearly PV production up until a certain point quite well. That implies, that, up until that point, the excess energy from PV production typically gets traded within the community before getting sold to the grid. The reason for that is, that it is in fact more economically viable to internally trade energy rather than selling it to the grid. The turning point, or saturation point, of this effect occurs when the installed PV capacity is so high, that no real demand appears during times of high PV production and the electricity exclusively gets exported to the grid. In other words, no trading occurs due to the PV overproduction as most potential trading partners already face a vast surplus of PV production. This lack of buyers most certainly limits the community-internal trading.

As visible when comparing the EAG 2030 and ÖNIP 2030+ scenarios for both „**Rural 1**" and „**Suburban 1**", the utilization of the battery storage in fact decreases with the PV and Battery installations. Even with these very high flexibility installations (see Figure 3.5 for the installations), the PV system appears to completely overpower the battery system - the batteries are most likely almost always at full charge and therefore do not get dispatched a lot.

In addition to recently mentioned outcomes, the time of the daily peak trading is influenced by above stated turning point. Up until that point, the peak trading typically arises at midday - the typical time with the highest PV power. After that point, these peak-trades happen more distributed during the day for non-summer times and late in the evening in summer.

Mentioned turning point occurs for „**Rural 1**“ and „**Suburban 1**“scenarios before the EAG 2030 scenario. The „**Urban 1**“ happens to not be affected by this as the sheer volume of not-so-flexible loads outweigh the increased PV production.

For the sake of completeness, these plots for the remaining grids not shown here are displayed in the Appendix C.1.1. Figure C.1 shows „**Rural 2**“, Figure C.2 displays „**Suburban 2**“ and Figure C.3 presents „**Urban 1**“.

The following paragraphs will go more into detail regarding the grid impact of the mentioned outcomes.

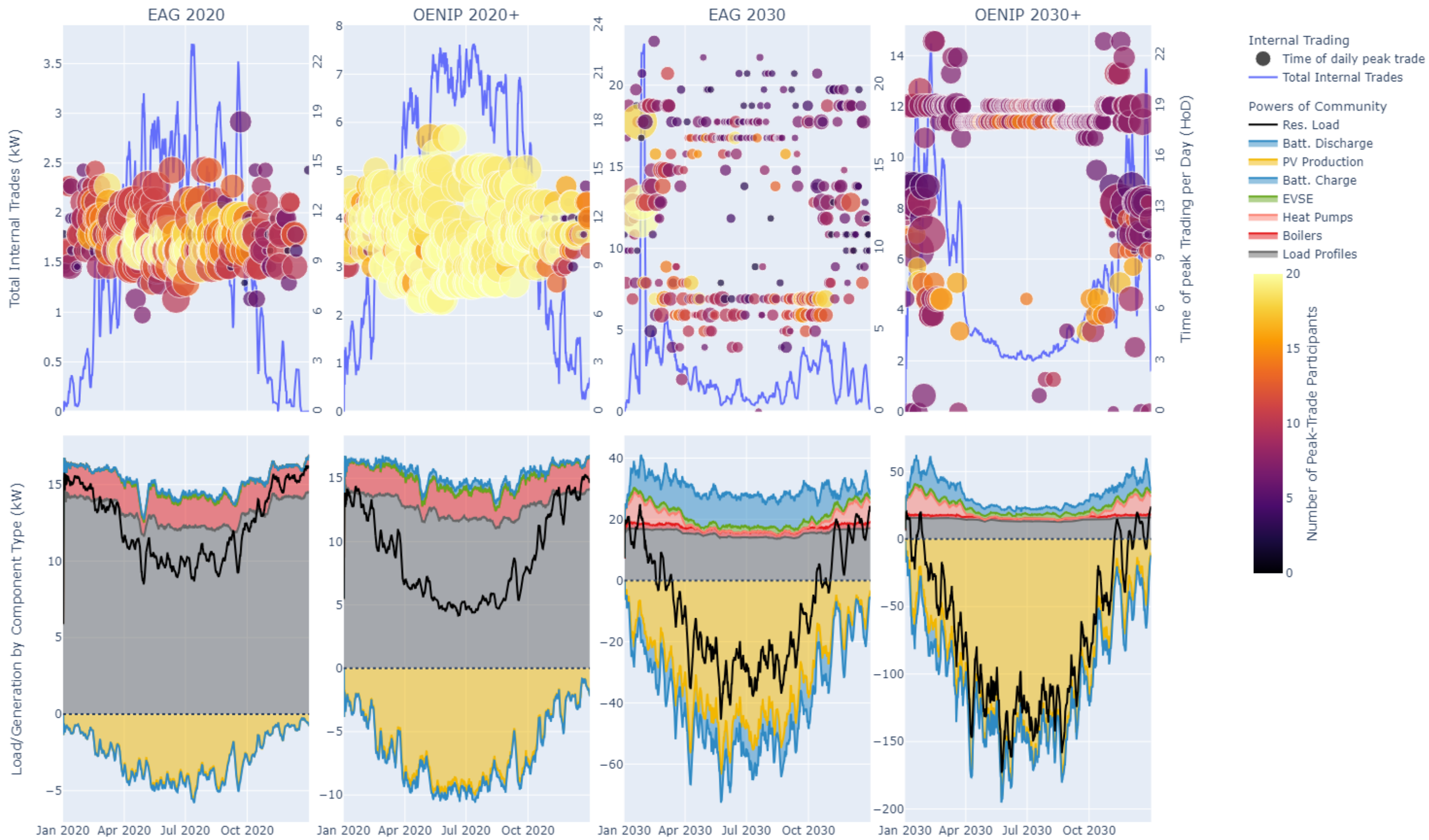

Figure 4.12.: „**Rural 1**“: Yearly aggregated community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

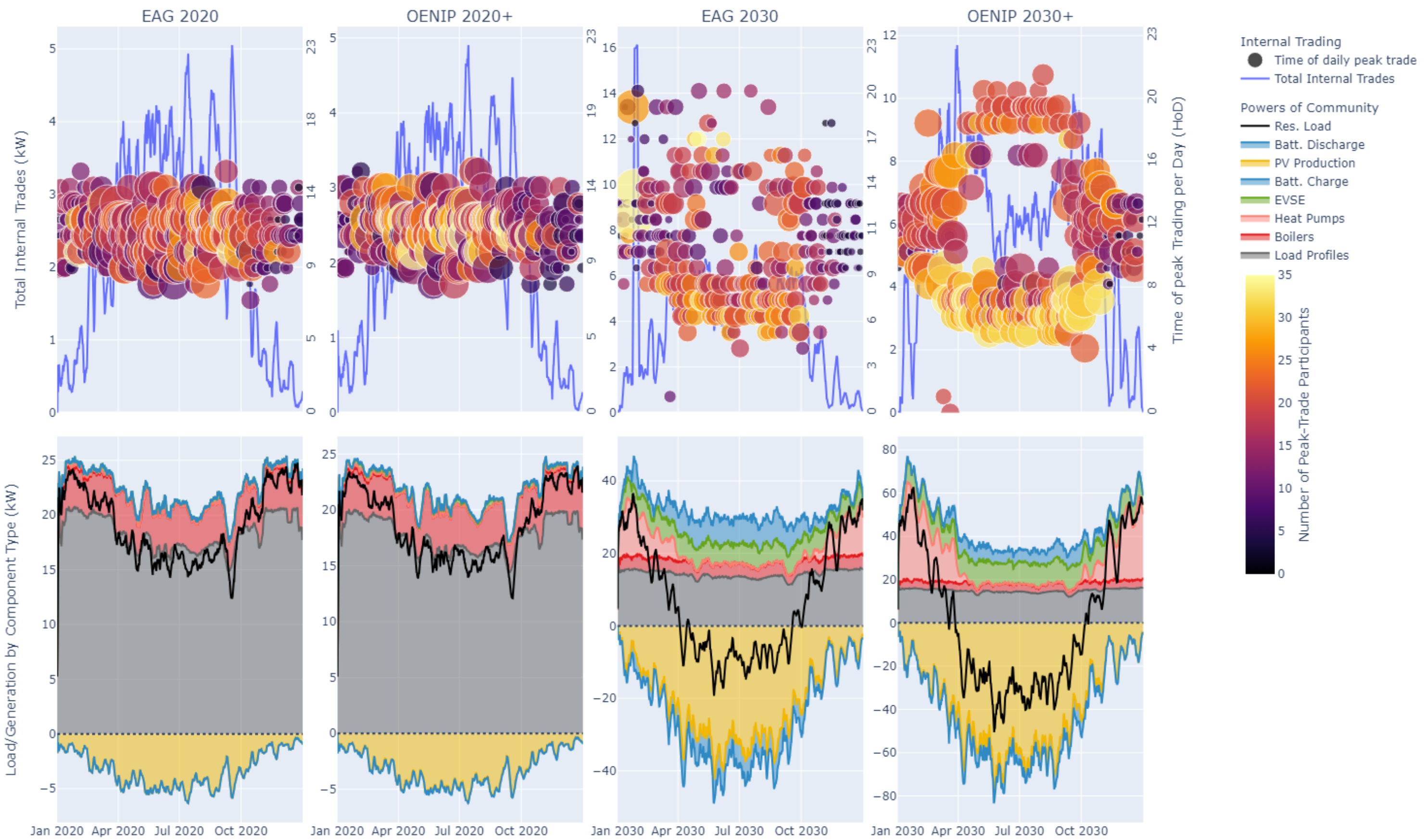

Figure 4.13.: „**Suburban 1**": Yearly aggregated community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

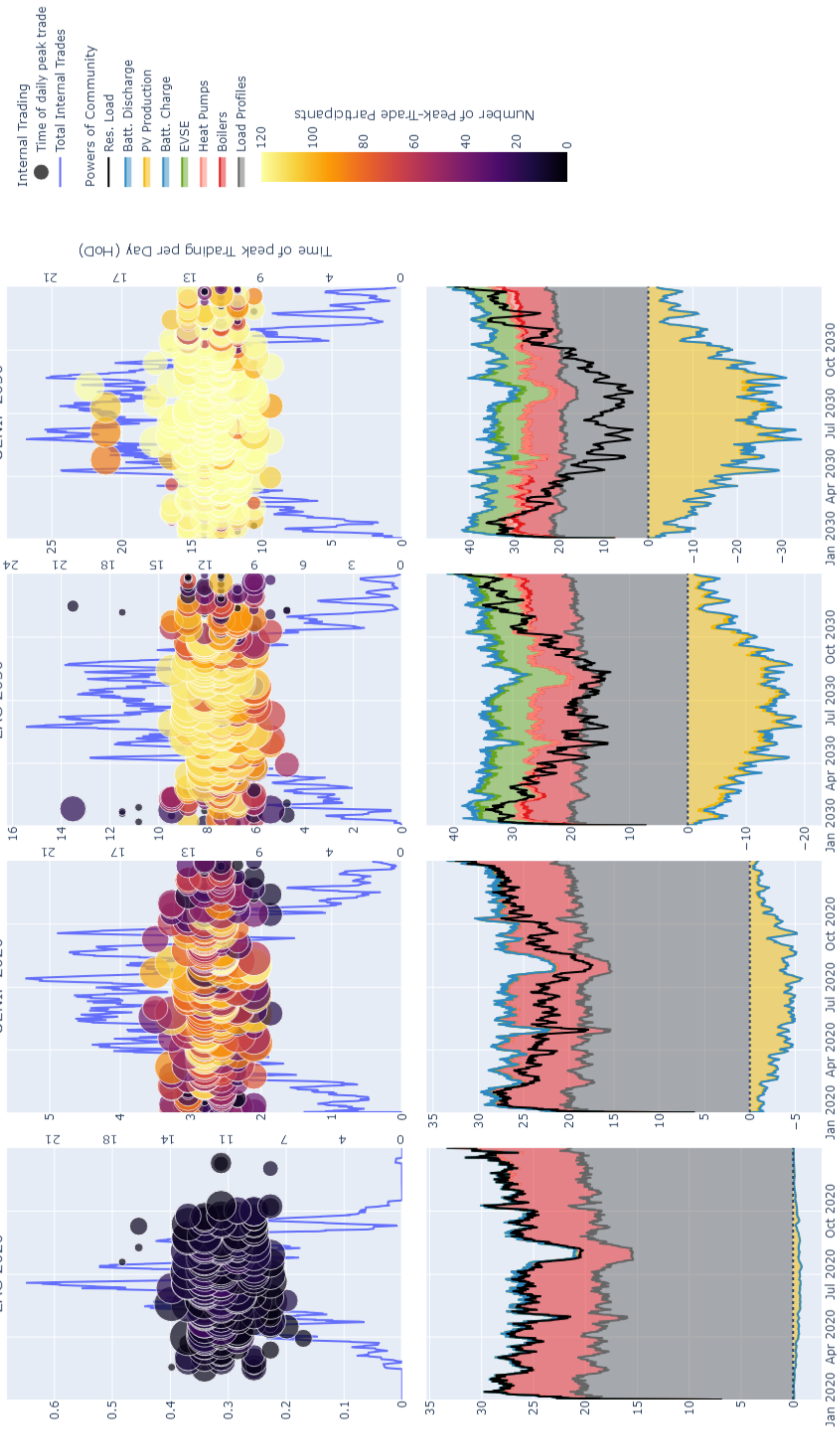

Figure 4.14.: „**Urban 2**": Yearly aggregated community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

Detailed Load Flow Calculation Results

Here, the results from the load flow calculations will be presented. As mentioned in Section 3.4, the simulations yield outputs such as Terminal Voltages, Transformer Loadings and Line Loadings amongst many others. Also, the results will be separated into their respective geographical category and selected showcases of interesting behaviours will be shown each.

Rural Grids Figure 4.15 presents the results for the scenario „**Rural 1, EAG 2020**“ for given summer days with a high PV potential. As clearly visible, the internal trading, as marked with the orange color, results in lower residual load, higher grid parameters within the LV grid (such as terminal voltages and line loadings), less curtailed PV production and a better utilizaiton of flexibilities. The increase in the grids line loadings and terminal voltages is, however, not to be concerned about as the increase is just fractional.

In Figure 4.16, the same parameters are shown for several winter days during and after a „Dunkelflaute“ (dark doldrums) for the scenario „**Rural 1, EAG 2030**“. This „Dunkelflaute“ was represented in the provided electricity price data from [34] and results in high electricity prices within the trading zone and subsequently, due to flexible supply tariffs, in a very high community-internal trading. In other words, the high cost of importing electricity from the outer market increases the internal tradings economic feasibility. Here, the trading vastly exceeds the typical loads from this community (if the spikes from battery charging and discharging are not accounted for). Therefore, with the trading being very high in relation to the communities typical loads, the grid KPIs are substantially higher and also fluctuate more. Here, it can be deduced, that trading can indeed result in a worse grid state.

Finally, Figure 4.17 displays, again, the same parameters, only for the scenario „**Rural 1, ÖNIP 2030+**“ for some summer days. As clearly visible from Figure 3.5, this scenario presents the highest overall PV installations - per capita as well as in sum. Figure 4.17 shows a clear negative correlation between the internal trading and PV production. Furthermore, the internal trading can be seen as negligible compared to the community loads at this time. This behaviour matches very well with the explanations given in paragraph 4.1.2: With increasing PV and flexibility installations, the internal trading follows a bi-seasonal and bi-daily behaviour. As already mentioned, the installed PV and flexibilities are already overly saturated thus not allowing for higher economically viable trading. Here, the trading and subsequently the community has very little impact on the grid’s state. Only, the batteries behaviour is slightly different, resulting in a lower residual load during night time and higher fed-in electric energy due to PV generation for the communities case.

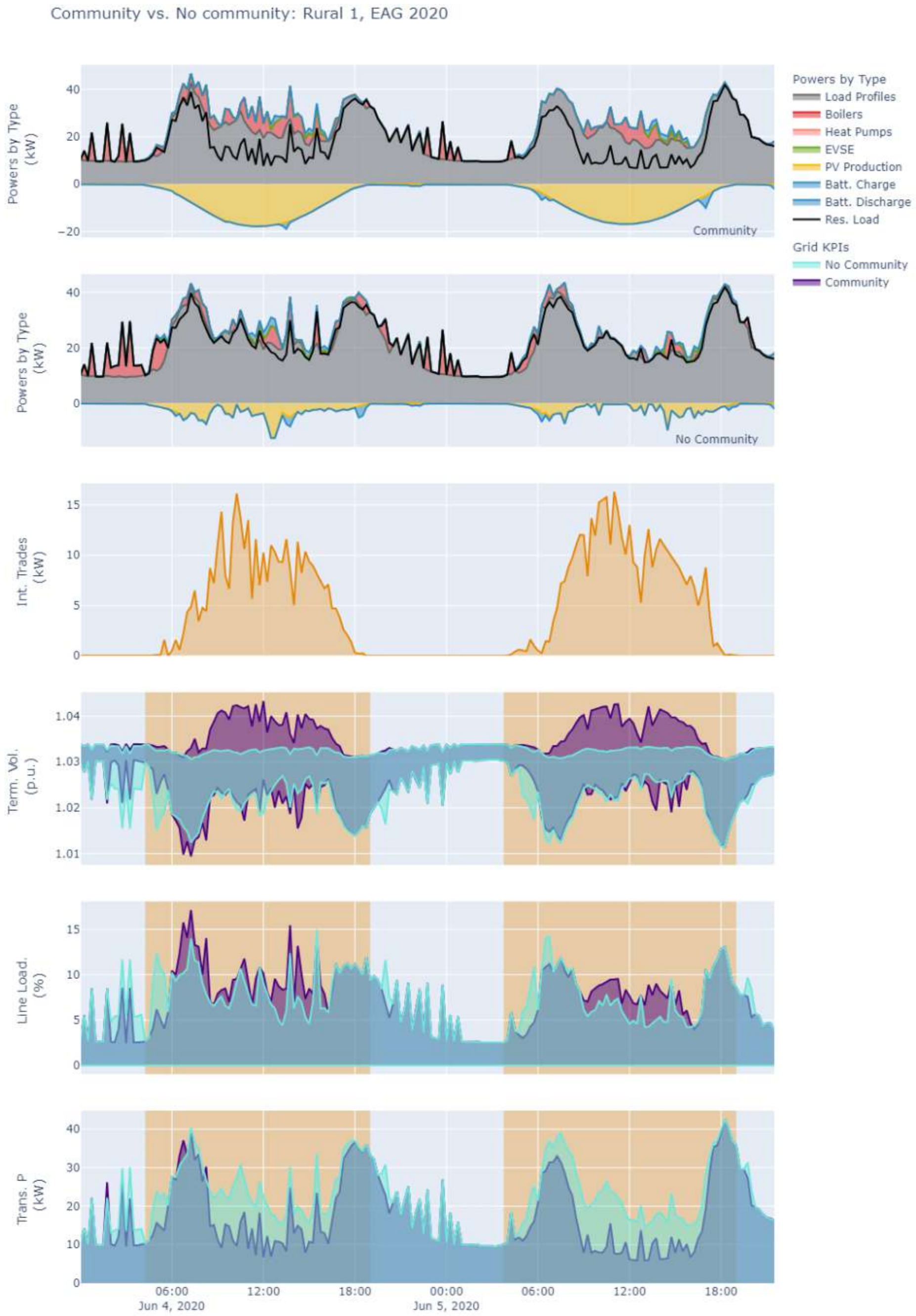

Figure 4.15.: „**Rural 1, EAG 2020**": Aggregated sources and sinks of power both for the „Community" and the „No community" case, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the community and no-community case for given summer days. The orange marked areas represent the times of trading.

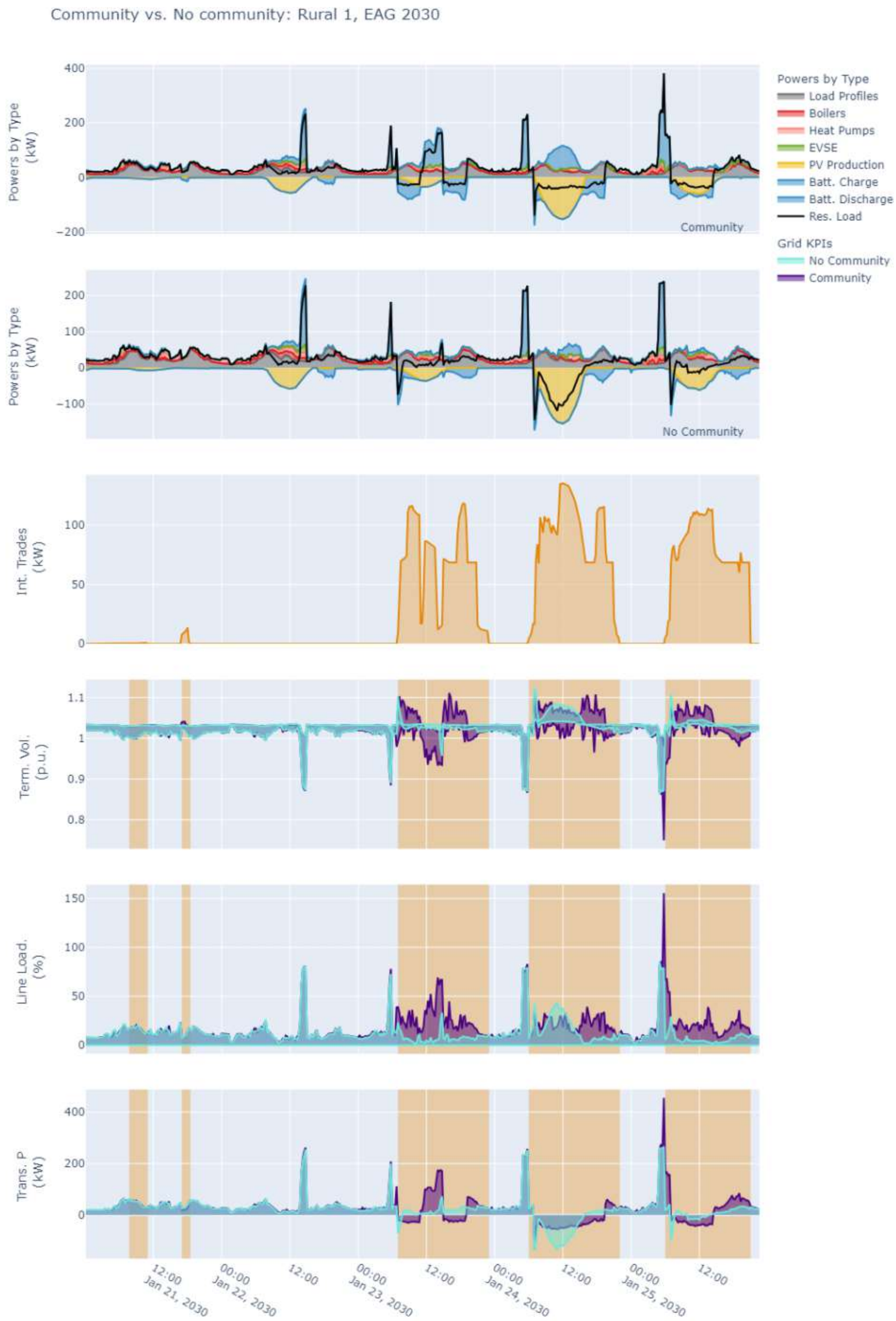

Figure 4.16.: „**Rural 1, EAG 2030**": Aggregated sources and sinks of power both for the „Community" and the „No community" case, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the community and no-community case for several winter days during/after a „Dunkelflaute". Due to the „Dunkelflaute", the electricity price was significantly higher, again, resulting in very high internal trading. The orange marked areas represent the times of trading.

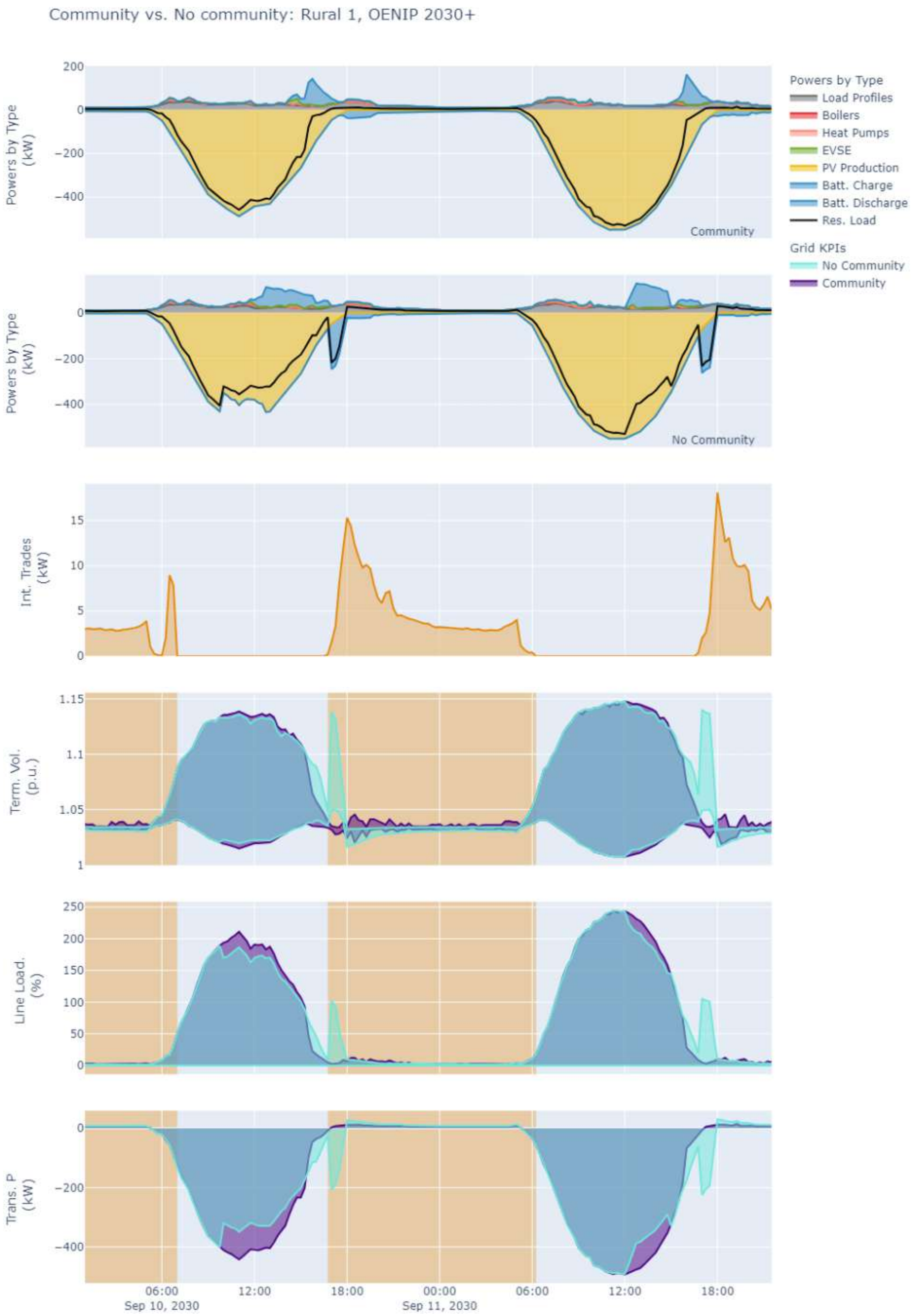

Figure 4.17.: „**Rural 1, ÖNIP 2030+**“: Aggregated sources and sinks of power both for the „Community“ and the „No community“ case, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the community and no-community case for several summer days showing the saturation of PV and thus the limited options for trading and the resulting little impact on the grid. The orange marked areas represent the times of trading.

Suburban Grids Figure 4.18 displays the same parameters as already discussed for the rural grids but nor for the „**Suburban 2, EAG 2020**" scenario. The behaviour is fairly similar to the outcomes from the „**Rural 1, EAG 2020**" scenario (see Figure 4.15 for reference): The community is responsible for slightly higher internal grid parameters (terminal voltages and line loadings) and typically lowers the residual load by curtailing the PV production less. The main difference between this result and its rural counterpart is, that the impact is less pronounced here. This is due to higher share of non-flexible load profiles and the lower trading in respect to all loads.

In Figure 4.16 the detailed results are shown for some winter days for „**Suburban 2, EAG 2030**". Similar to the results presented for its rural counterpart shown in Figure 4.16, the outcomes present the first days after a „Dunkelflaute" resulting, again, in high electricity prices and subsequently high internal trading. Therefore, grid parameters are stressed more in the communities case. However, in contrast to its rural counterpart, the impact is diminished again, due to the smaller share of the tradings maximum power in relation to the overall power of community and non-community loads.

In addition to the EAG scenarios, the outcomes of the „**Suburban 1, ÖNIP 2030+** scenario are shown as well for given summer days with high PV production as seen in Figure 4.20. Looking at Figure 4.13, displaying a sensitivity analysis regarding the installed flexibilites on suburban grids, the bi-seasonal and bi-daily trading pattern can be observes just as in the rural scenarios - less pronounced though. This pattern shows here in Figure 4.20 in more detail. Here, the internal trading is mostly shifted into the night, keeping the grids parameters fairly similar compared to no community. Only the residual load has a more stable shape. Comparing this graph to the results obtained from Figure 4.17, the observed behaviour is similar, yet less extreme in the suburban case. As mentioned above, this is due to the higher share of non-flexible loads and therefore less trading per capita.

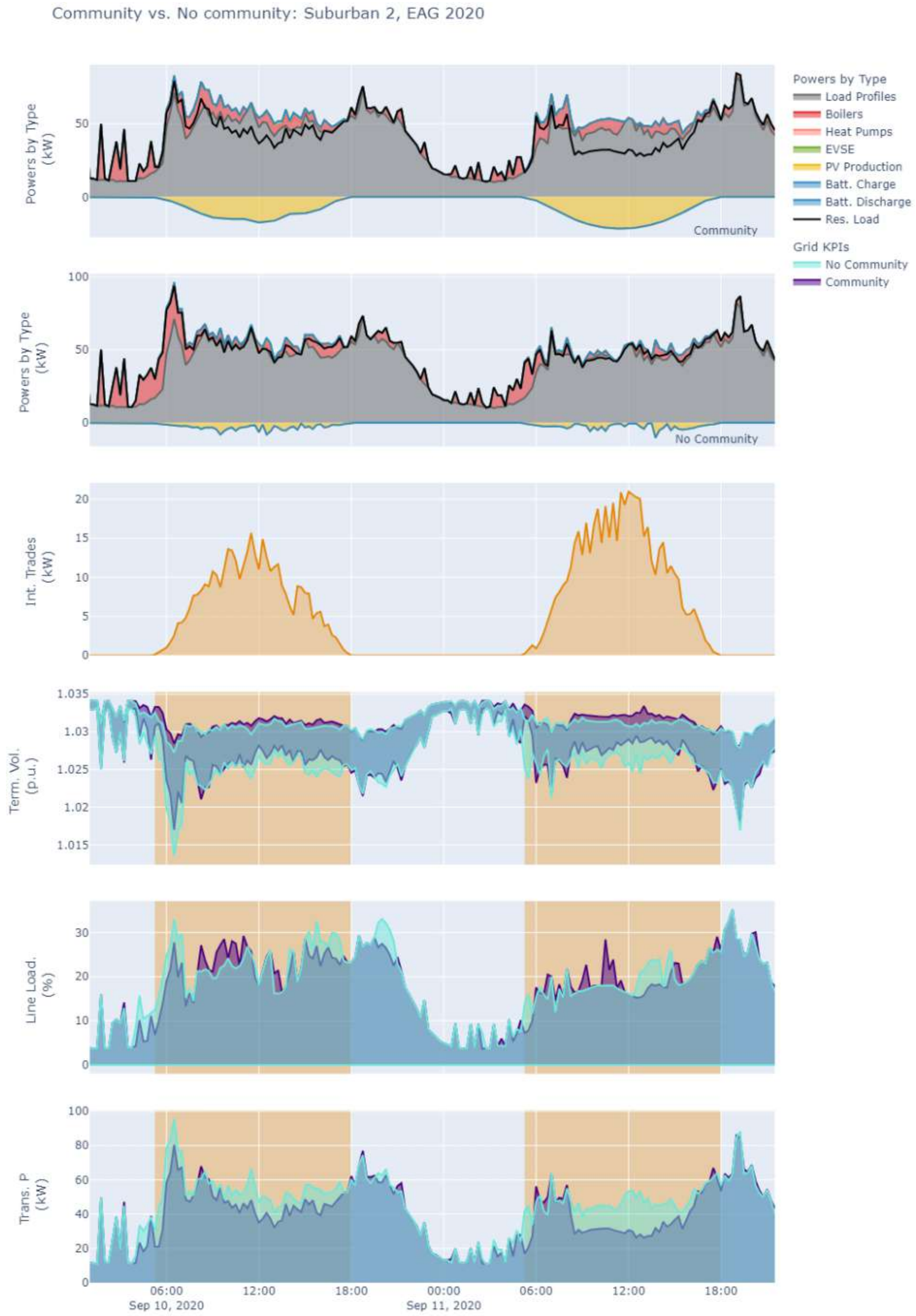

Figure 4.18.: „**Suburban 2, EAG 2020**“: Aggregated sources and sinks of power both for the „Community“ and the „No community“ case, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the community and no-community case for given (late) summer days. The orange marked areas represent the times of trading.

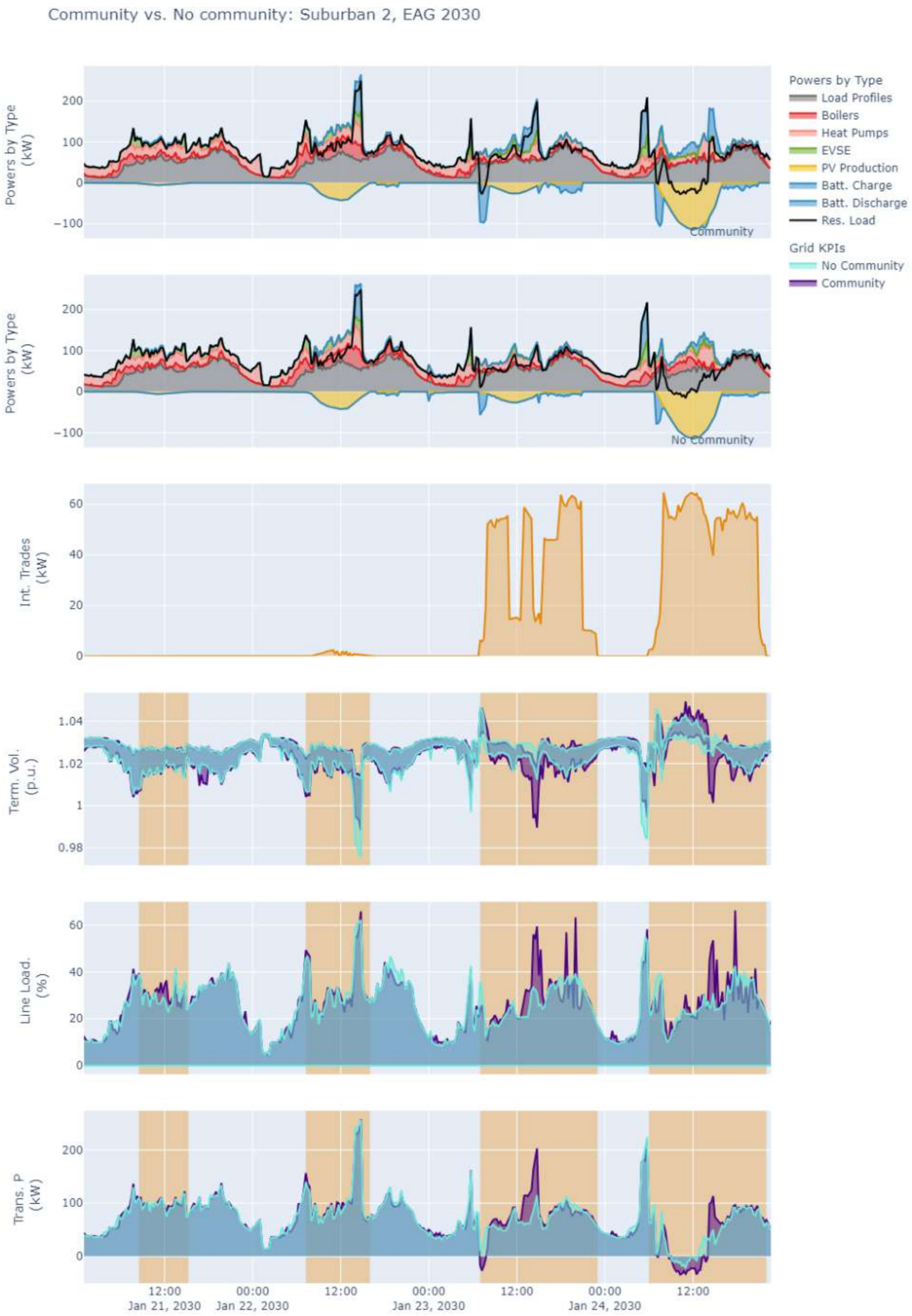

Figure 4.19.: „**Suburban 2, EAG 2030**“: Aggregated sources and sinks of power both for the „Community“ and the „No community“ case, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the community and no-community case for several winter days during/after a „Dunkelflaute“. Due to the „Dunkelflaute“, the electricity price was significantly higher, again, resulting in very high internal trading. The orange marked areas represent the times of trading.

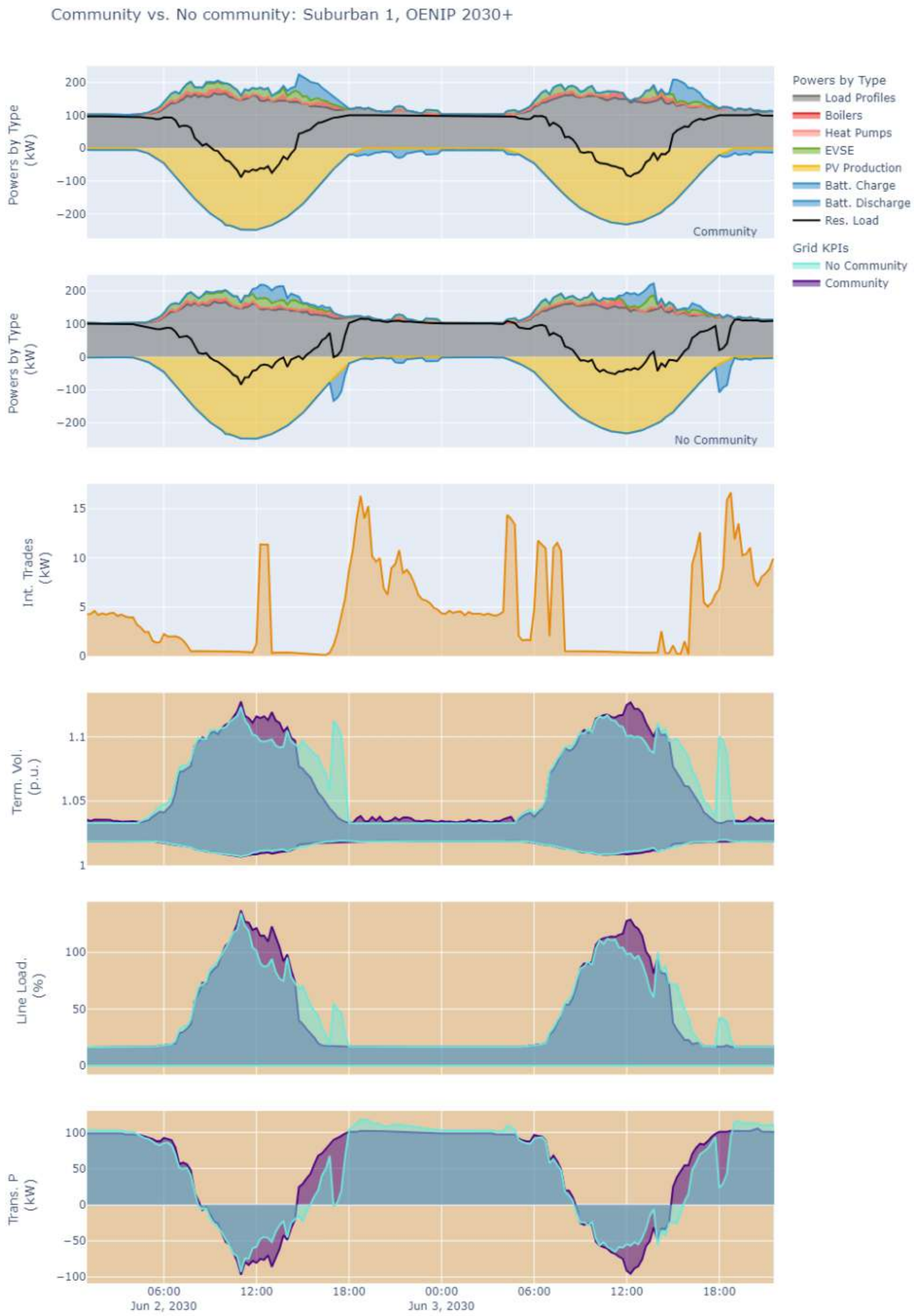

Figure 4.20.: „**Suburban 1, ÖNIP 2030+**“: Aggregated sources and sinks of power both for the „Community“ and the „No community“ case, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the community and no-community case for several summer days showing the saturation of PV and thus the limited options for trading and the resulting limited impact on the grid. The orange marked areas represent the times of trading.

Urban Grids For reference, Figure 4.21 displays the results for the „**Urban 1, EAG 2020**“ scenario with hardly any utilized flexibilites. As clearly visible, without flexibilites and therefore without economic viable trading, the community itself has almost no influence on the grids state, yet again proving the point of excessively looking into the behaviour of the installed flexibilities as well as the communities internal trading.

After showing a reference case scenario, Figure 4.22 and Figure 4.23 both present the results for the scenario „**Urban 1, ÖNIP 2030+**“ for several winter and summer days, respectively. This scenario marks the scenario with the highest flexibility installations for all the urban scenarios. As visible in Figure 4.22, the community allows due to the community-internal trading for a better utilization of the flexibilities and thus keeping the residual load more stable. The Powers by Type subplot shows, that in the communities case the local PV production can directly be used for EV charging as well as thermal use rather than charging and de-charging the battery system. Therefore, the community-internal trading and subsequently the community itself definitely aids the grid by reducing the fluctuation of the residual load.

Similarly, Figure 4.23 displays the behaviour for two days in early summer with both high PV production. Again, the community allows for a better use of the locally installed flexibilities and thus keeping the residual load more stable. Unlike the outcomes from the rural and suburban grids, the communities internal grid parameters (such as terminal voltages and line loadings) do not change much with the trading as the occurring trading can be considered small in relation to the inspected grid.

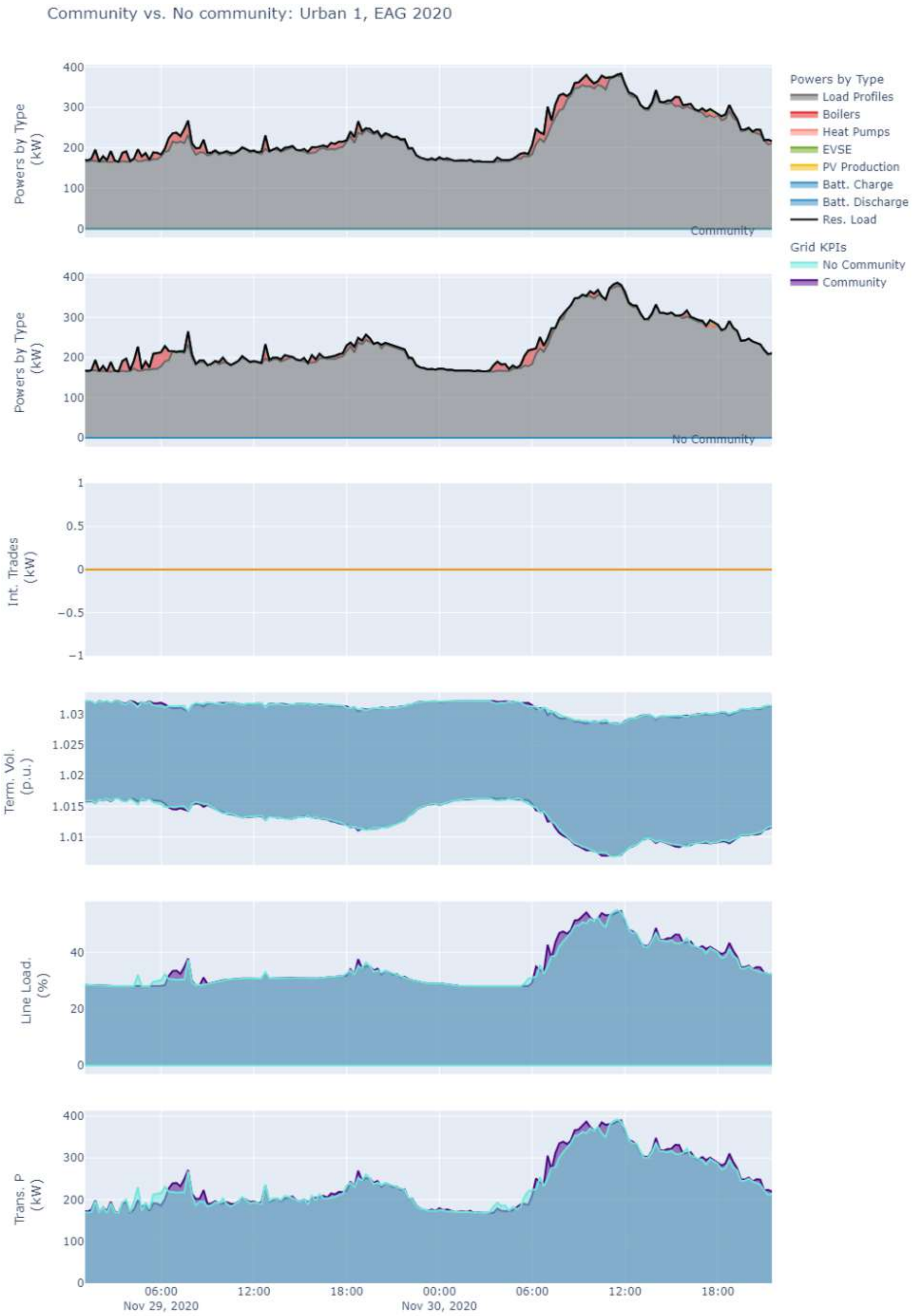

Figure 4.21.: „**Urban 1, EAG 2020**“: Aggregated sources and sinks of power both for the „Community“ and the „No community“ case, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the community and no-community case for several winter days. The orange marked areas represent the times of trading.

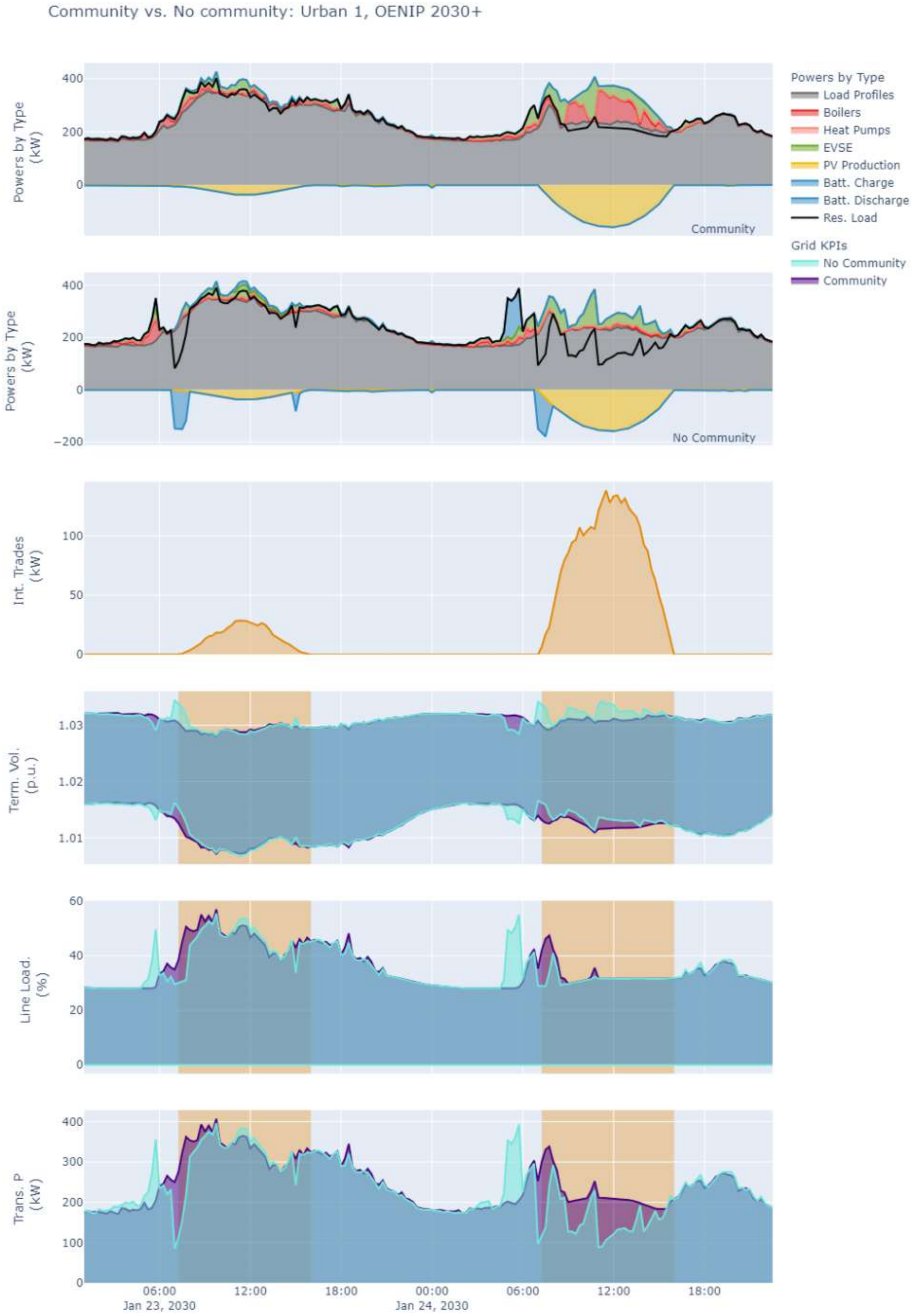

Figure 4.22.: „**Urban 1, ÖNIP 2030+**“: Aggregated sources and sinks of power both for the „Community“ and the „No community“ case, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the community and no-community case for several winter days. The orange marked areas represent the times of trading.

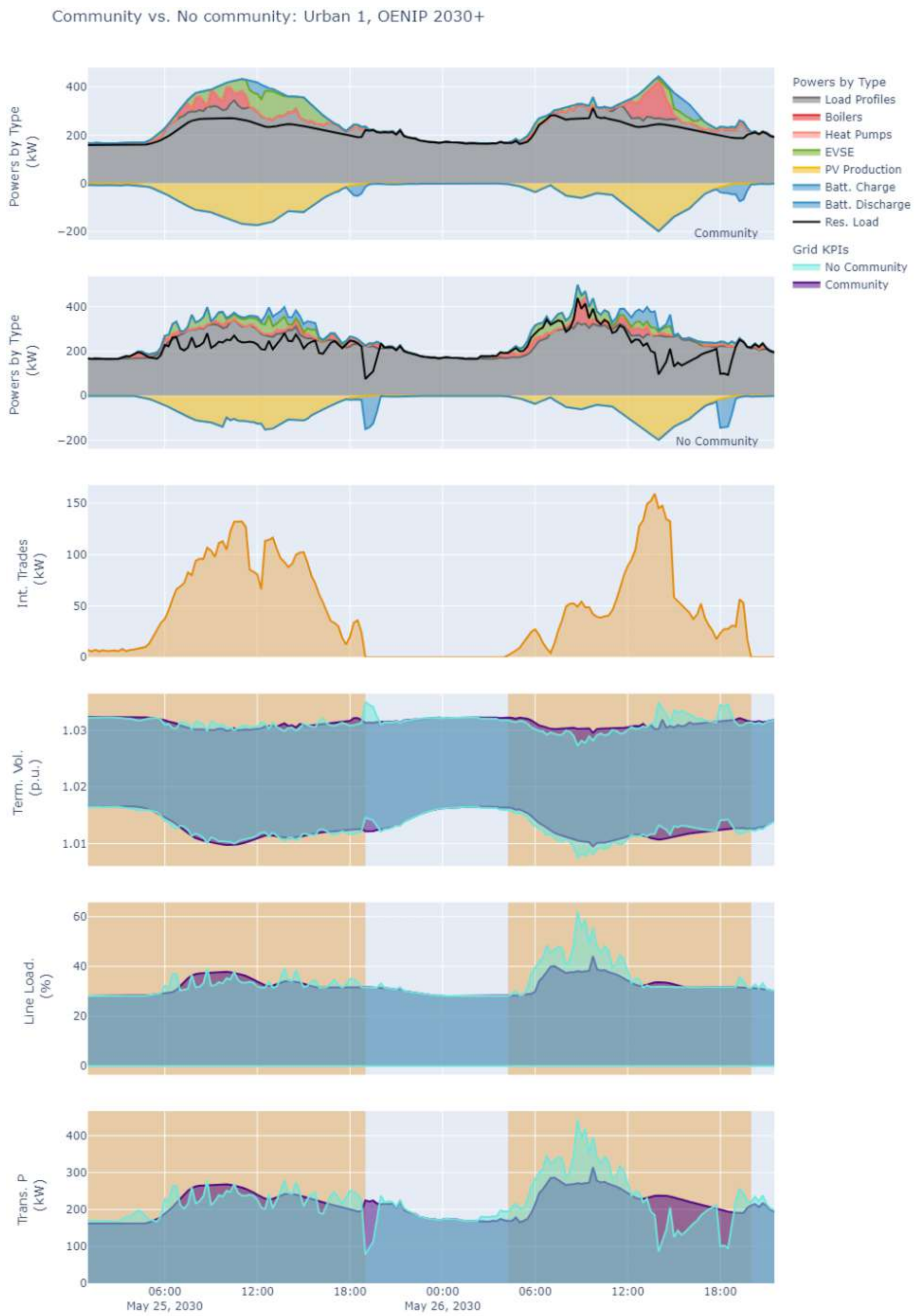

Figure 4.23.: „**Urban 1, ÖNIP 2030+**“: Aggregated sources and sinks of power both for the „Community“ and the „No community“ case, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the community and no-community case for several summer days. The orange marked areas represent the times of trading.

4.1.3. Conclusion of LV considerations

Combining the recently obtained qualitative results from Section 4.1.2 with the previously defined quantitative outcomes from Section 4.1.1, several important conclusions can be drawn.

In general, the impact of an energy community when compared to the exact same scenario without a community remains limited as the economic viable options for a large-scale community internal trading is limited.

A clear trend regarding the spatial category can be observed: Under the assumption of the realistic deterministic scenarios defined in Section 3.1 the influence of a community decreases with the scenarios ubanization both due to the reduced share of flexibilities compared to the non-flexible load profiles and also due to the nature of the grid topology.

Generally speaking, scenarios with little flexibility installations (high SCR, low SSR scenarios) result in little to no impact of energy communities. Here, the communities internal grid, i.e., the low voltage grid behind the transformer typically shows slightly increased local parameters such as line loadings and terminal voltages coupled with a slightly decreased residual load that also offers a more steady curve shape.

On the other hand, the grid impact of scenarios with a very high integration of PV and flexibility installations (high SSR, medium to low SCR) depend highly on the circumstances and the past behaviour: During summer times with constantly high PV production and little to no heating demand, the flexibilities quite often cannot be used as such thus limiting trading and furthermore rendering the grid impact of one community to nearly zero. However, due to certain circumstances such as high electricity market prices (as shown in Figure 4.16 and 4.19) or no prior PV production in combination with high heat demand thus a high potential for flexibilities, a clear impact of the community can be observed. Here, the communities internal trading is comparably high, hence resulting in a negative grid impact. This negative grid impact can be seen as an increase in rather spontaneous load spikes, a broader voltage band or increased transformer loading.

4.2. Medium Voltage Distribution Grids

Section 4.1 goes into extensive detail regarding the calculations specified in Section 3.4.1. However, as to fulfill mentioned research goals of investigating into the *Impact of Large-Scale Deployment of Energy Communities on Distribution Grids*, that not only referring to focusing on various wide-range scenarios but also on a large-scale deployment in terms of investigating into the impact on medium voltage grids, these MV results are shown here.

While both the workflow in general as well as the mathematical notation specified in Equations (4.2 - 4.6) is fairly similar to Section 4.1, the „data to showcase“ approach is not adhered to with the same discipline as in Section 4.1. As mentioned in Section 3.4.2, in order to avoid overly excessive simulation runs, first of all, not each and every scenario and secondly, not every timestep of a given year went through the load flow calculations. Calculating the deviation measures and correlation coefficients on this incomplete dataset would most likely result in heavily corrupted results.

With that in mind, firstly the results from the modelling and optimization framework `Femto.jl` and then, the results from the MV load flow calculations are shown.

4.2.1. Results from the modelling and optimization framework

Similarly to Section 4.1.2, the results of the modelling and optimization framework are presented here. However, unlike in previous results, the sensitivity analysis per se is not carried out upon the scenarios of PV and flexibilities integration but rather on the so called community penetration rate, as already stated in Section 3.4.2. Also, it is important to remind, that many independent communities are located within a MV grid and following figures present the aggregated results of all attached communities.

Figure 4.24 presents this penetration rate sensitivity analysis for the scenario „**Rural, EAG 2020**“, Figure 4.25 for „**Rural, ÖNIP 2030**, Figure 4.26 for „**Suburban, ÖNIP 2020** and Figure 4.27 for the scenario „**Urban, ÖNIP 2030** (For the sake of completeness, further results can be found in the Appendix C.2). Looking at those figures, independent of the grid type and the scenario, no major trend can be observed. While, obviously, with a penetration rate of 0 % the trading always being zero, the aggregated community-internal trading as well as the number of participating households generally increases. Despite the drastic increase of overall traded energy, the aggregated sources and sinks of power remain fairly unchanged for the better part of the presented scenarios. With these outcomes in mind, no direct conclusion can be drawn. Therefore, it is important to look at detailed, local aspects.

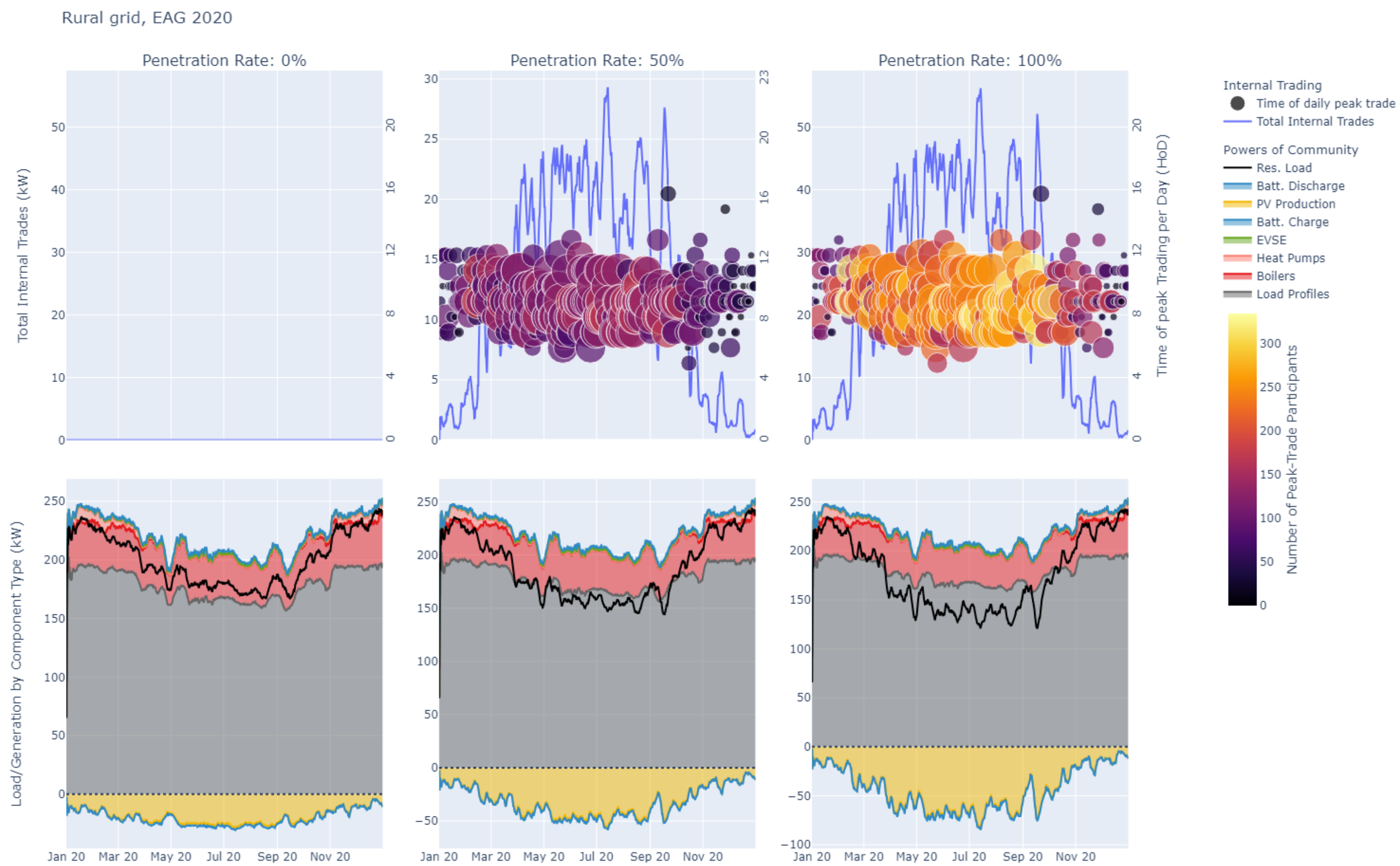

Figure 4.24.: „**Rural, EAG 2020**“: Community penetration rate sensitivity analysis with the aggregated yearly community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

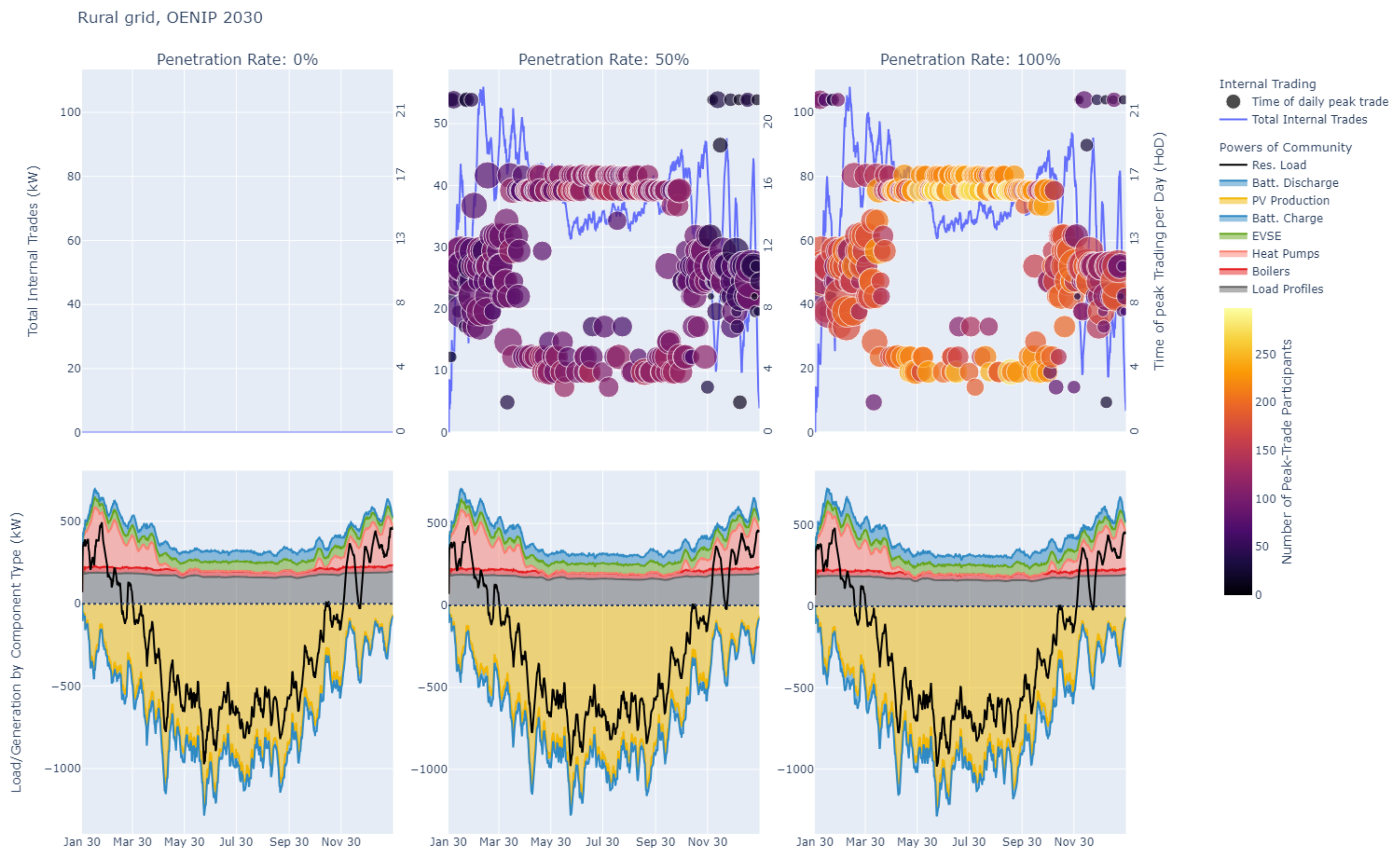

Figure 4.25.: „**Rural, ÖNIP 2030**": Community penetration rate sensitivity analysis with the aggregated yearly community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

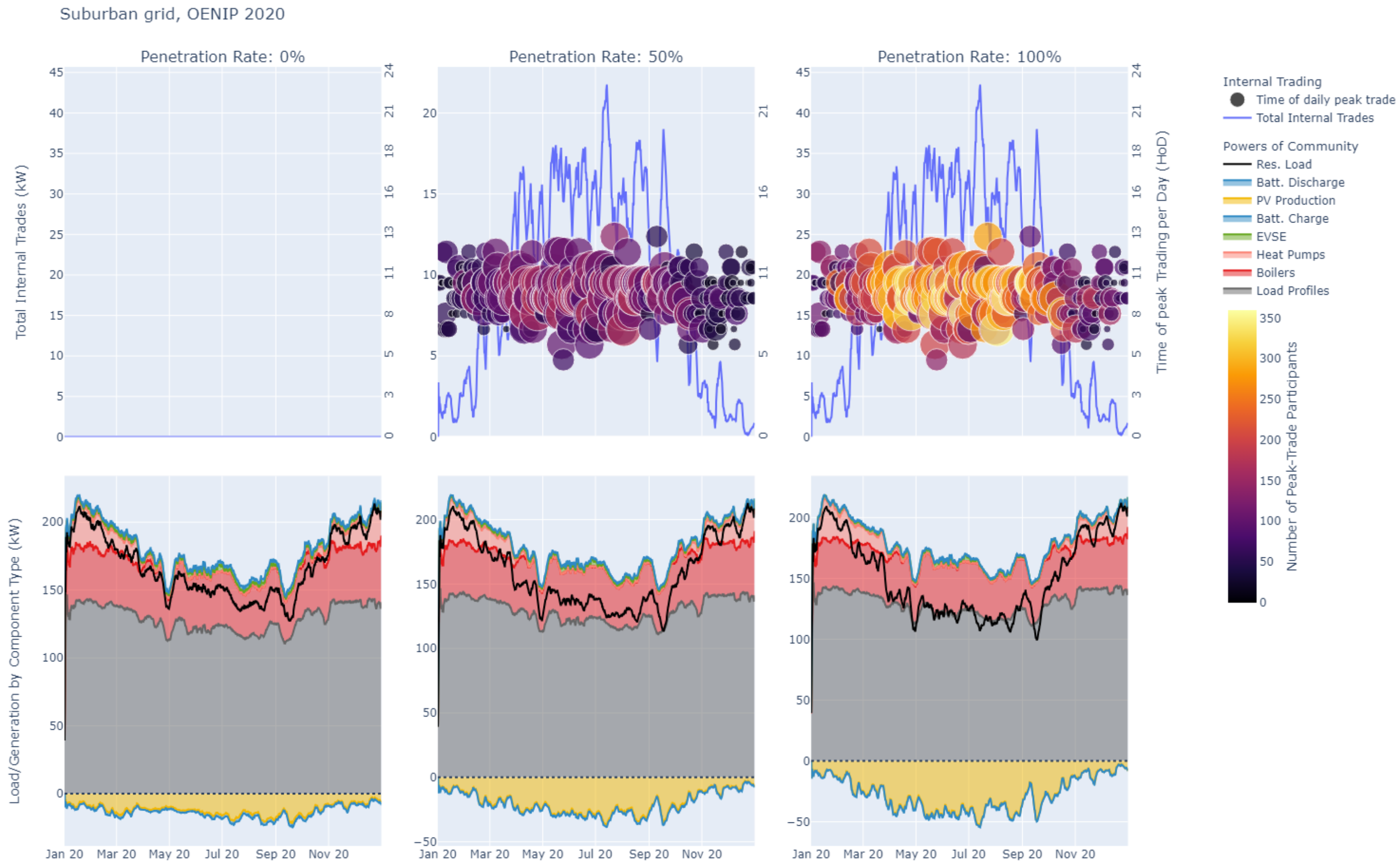

Figure 4.26.: „**Suburban, ÖNIP 2020**“: Community penetration rate sensitivity analysis with the aggregated yearly community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

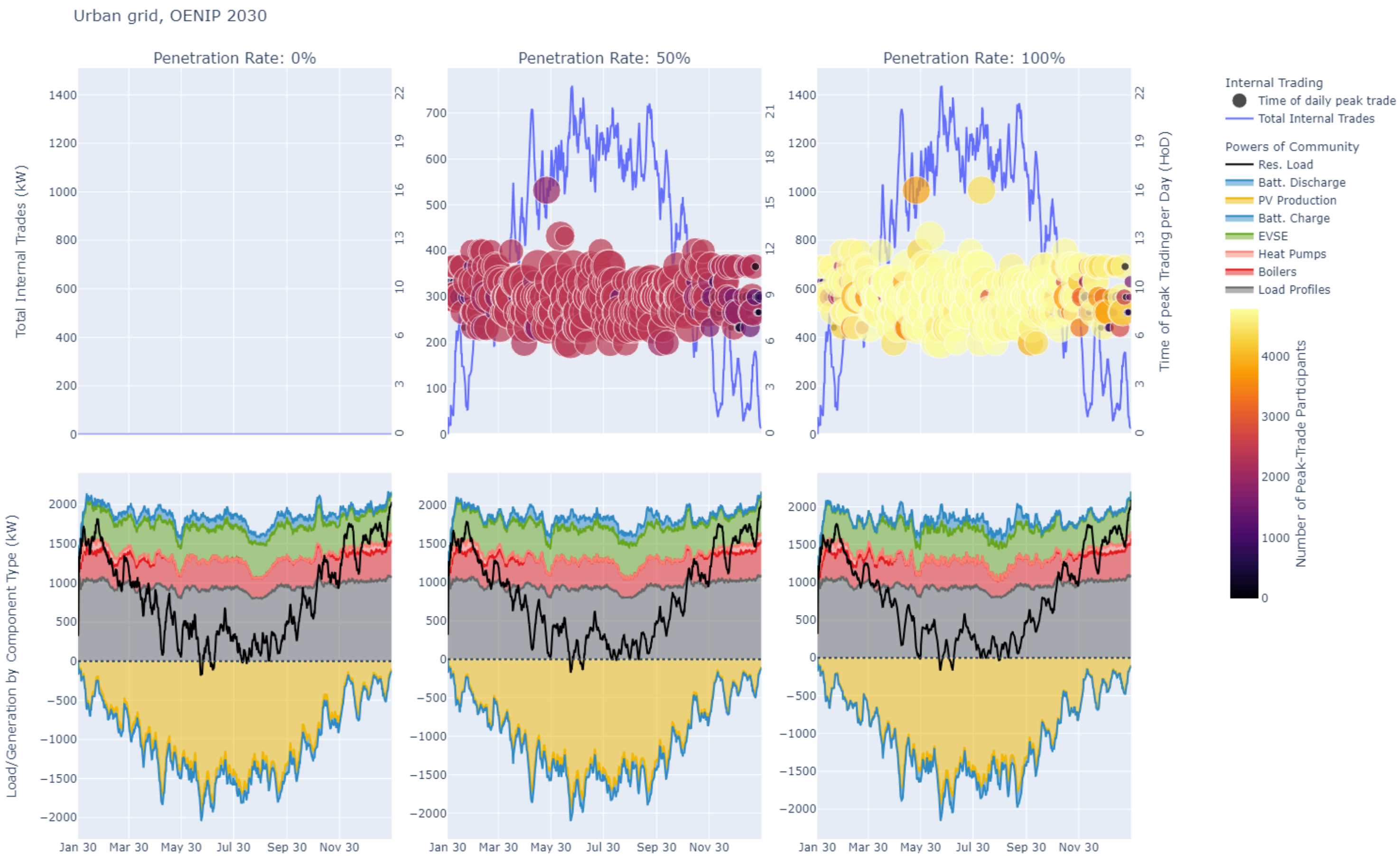

Figure 4.27.: „**Urban, ÖNIP 2030**“: Community penetration rate sensitivity analysis with the aggregated yearly community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

4.2.2. Load Flow Calculation Results

As mentioned in Section 4.2.1, no direct conclusion can be drawn from the aggregated results of the modelling and optimization framework results. Therefore, it is crucial to further investigate into the impact of the community penetration rates on the grid KPIs. These KPIs are, again, terminal voltages, line loadings and transformer loadings. Also, just as in previous considerations, only the envelopes of these parameters will be looked at as they provide the most relevant information while still enabling an easy comparison of scenarios due to their simplicity.

Also, as already mentioned in the Appendix B when describing the synthesis of the MV grids, not each and every LV subgrid was taken into consideration for these calculations. Hence, the grid loading parameters are seemingly too low. With that in mind, it is important to further stress, that the calculations serve better as a comparison of scenarios rather than taking absolute values for guaranteed.

Rural MV Grid Figure 4.28 presents the grids parameters with the sources and sinks of powers alongside the communities internal trading for the scenario „**Rural, EAG 2020**" for two summer days. The grids KPIs have been calculated for penetration rates such as 0 %, 25 %, 50 %, 75 % and 100 % with the 0 % and the 100 % case being displayed in more detail by also showing the sources and sinks of electricity. Here, in the rural scenario with the least PV and flexibility integration, it is visible, that an increasing penetration rate of communities is capable of drastically reducing the communities residual load by first of all allowing for more economically viable PV production and subsequently a better utilization of flexibilities in times of high production. Apart from that, the remainder of grid KPIs are also changed for the better: reduced line loadings as well as a narrower voltage band.

Figure 4.29 on the other hand, displays the same results for the scenario „**Rural, ÖNIP 2030**" during winter. The data shown here presents the first sunny days with high PV production after several days without any notable PV production. Here, looking at the 100 % community penetration case in the scenario with the highest PV and flexibility installations, is is clear, that grid as well as traded electricity is used to charge the battery systems. Therefore, the residual load increased with the increase in community penetration during times of trading. However, despite that increase, the residual load (as well as the other grid KPIs) can be viewed as being more stable.

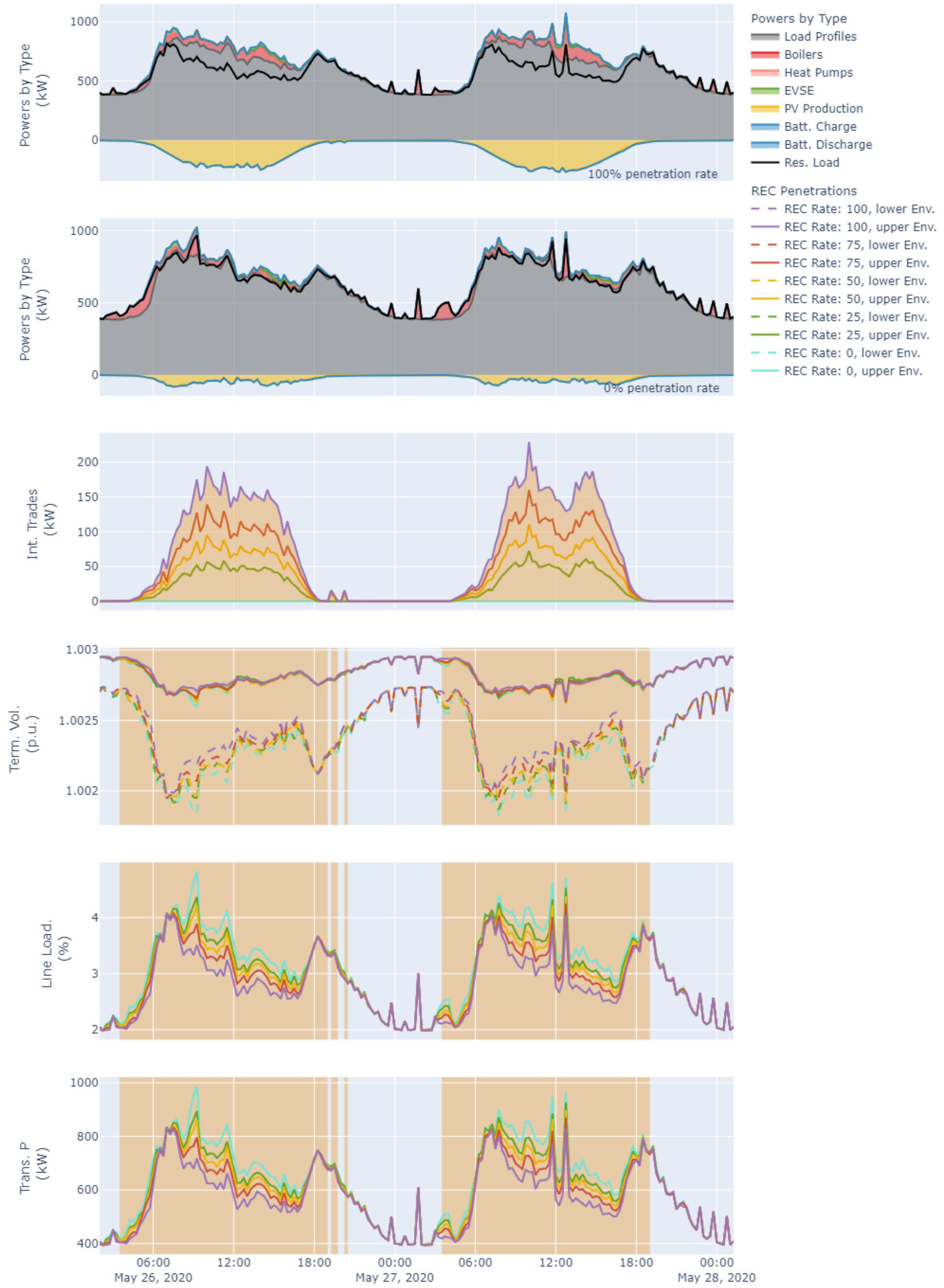

Figure 4.28.: „**Rural, EAG 2020**“: Aggregated sources and sinks of power, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the penetration rates of communities with the 0 % and the 100 % case under closer inspection. The orange marked areas represent the times of trading.

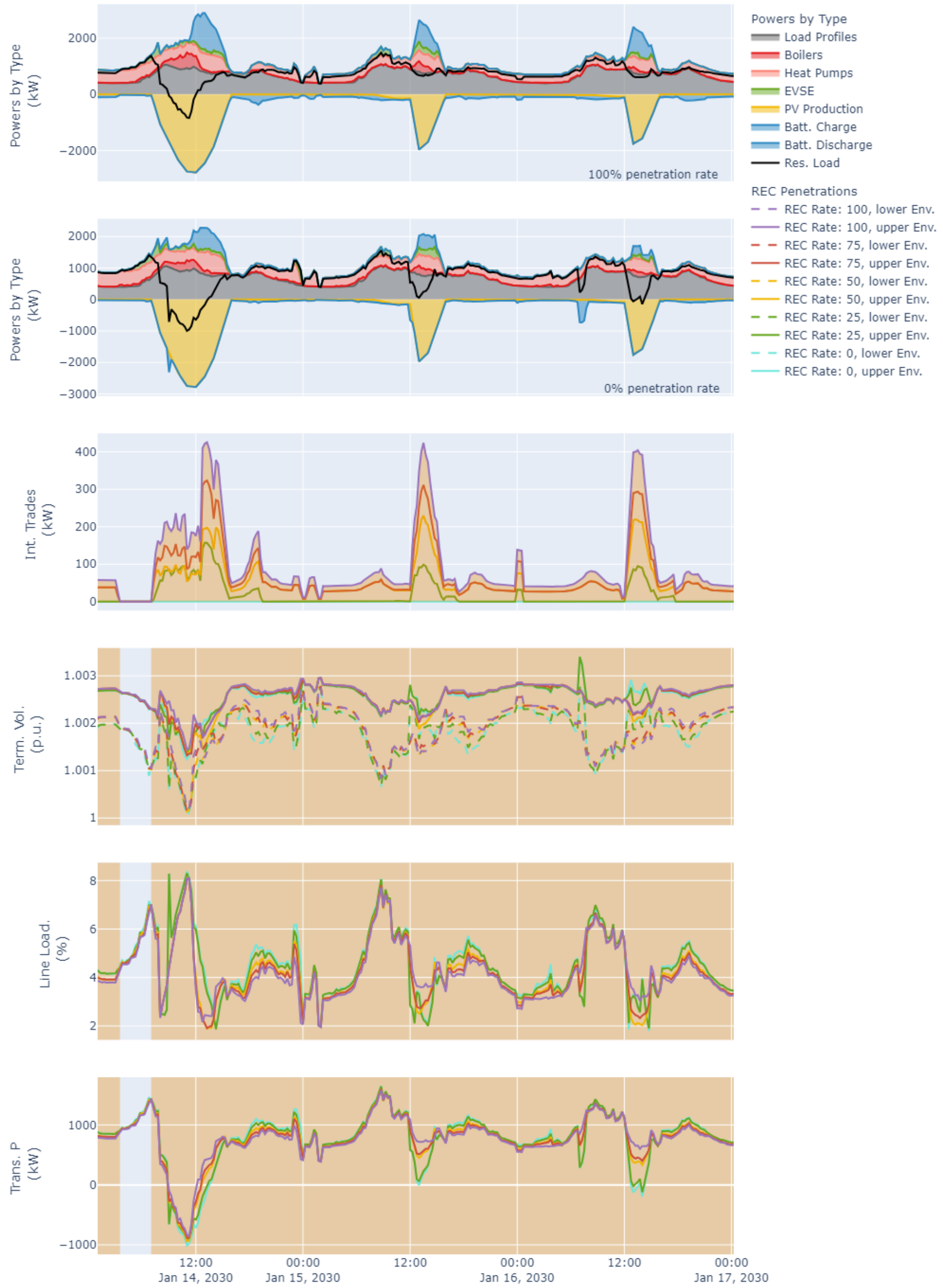

Figure 4.29.: „**Rural, ÖNIP 2030**“: Aggregated sources and sinks of power, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the penetration rates of communities with the 0 % and the 100 % case under closer inspection. The orange marked areas represent the times of trading.

Suburban MV Grid In Figure 4.30, the same parameters are shown for scenario „**Suburban, EAG 2020**. Similarly to its rural counterpart (see Fig. 4.28), trading reduces the residual load alongside other grid parameters. Also, the reduction increases with the penetration rate.

Figure 4.31 on the other hand, displays the days after the occurred „Dunkelflaute" resulting in high economically viable trading due to high electricity prices. This behaviour was already described in more detail for the analysis of LV results in Section 4.1.2 and 4.1.2. While an increasing penetration of communities slightly results in an increase in the grids loading parameters and a lowered lower terminal voltage envelope, the impact remains fairly limited. Unlike the drastic impact of trading presented for the LV grids in Figure 4.16 and 4.19, this drastic change cannot be observed again at MV level. While the aggregated internal trading is especially high, very little direct consequences can be observed on the MV grid level. That implies, that the MV grid serves due to its sheer size as kind of buffer reducing local fluctuations occurring within the low voltage level.

Finally, Figure 4.32 shows the outcomes for „**Suburban, ÖNIP 2030**". Similarly to the previously shown MV results, an increasing community penetration correlates to a not necessarily reduced grid load but much rather to much more stable grid parameters. Line loadings and the residual load, for example, undergo far less fluctuations.

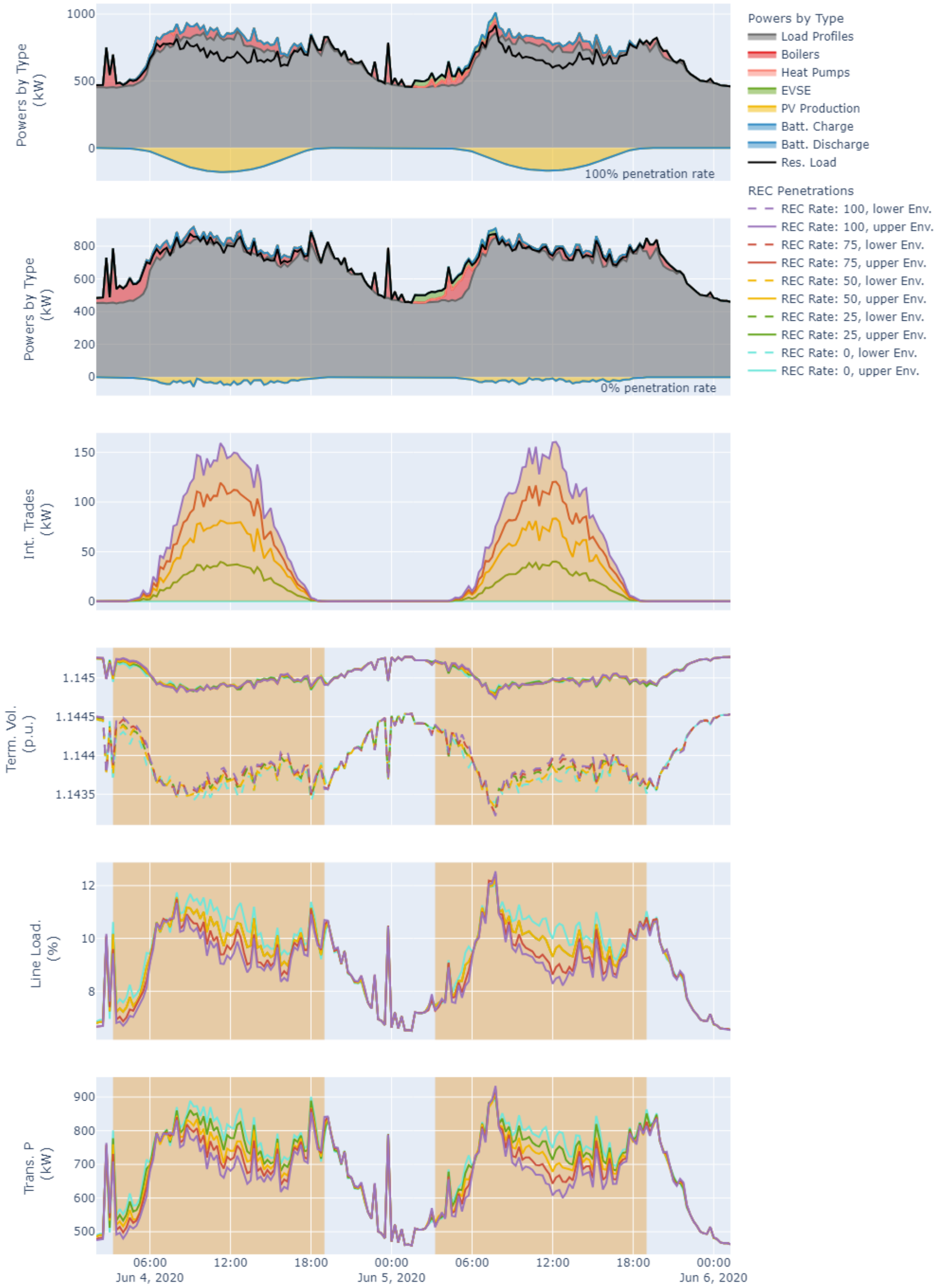

Figure 4.30.: „**Suburban, EAG 2020**“: Aggregated sources and sinks of power, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the penetration rates of communities with the 0 % and the 100 % case under closer inspection. The orange marked areas represent the times of trading.

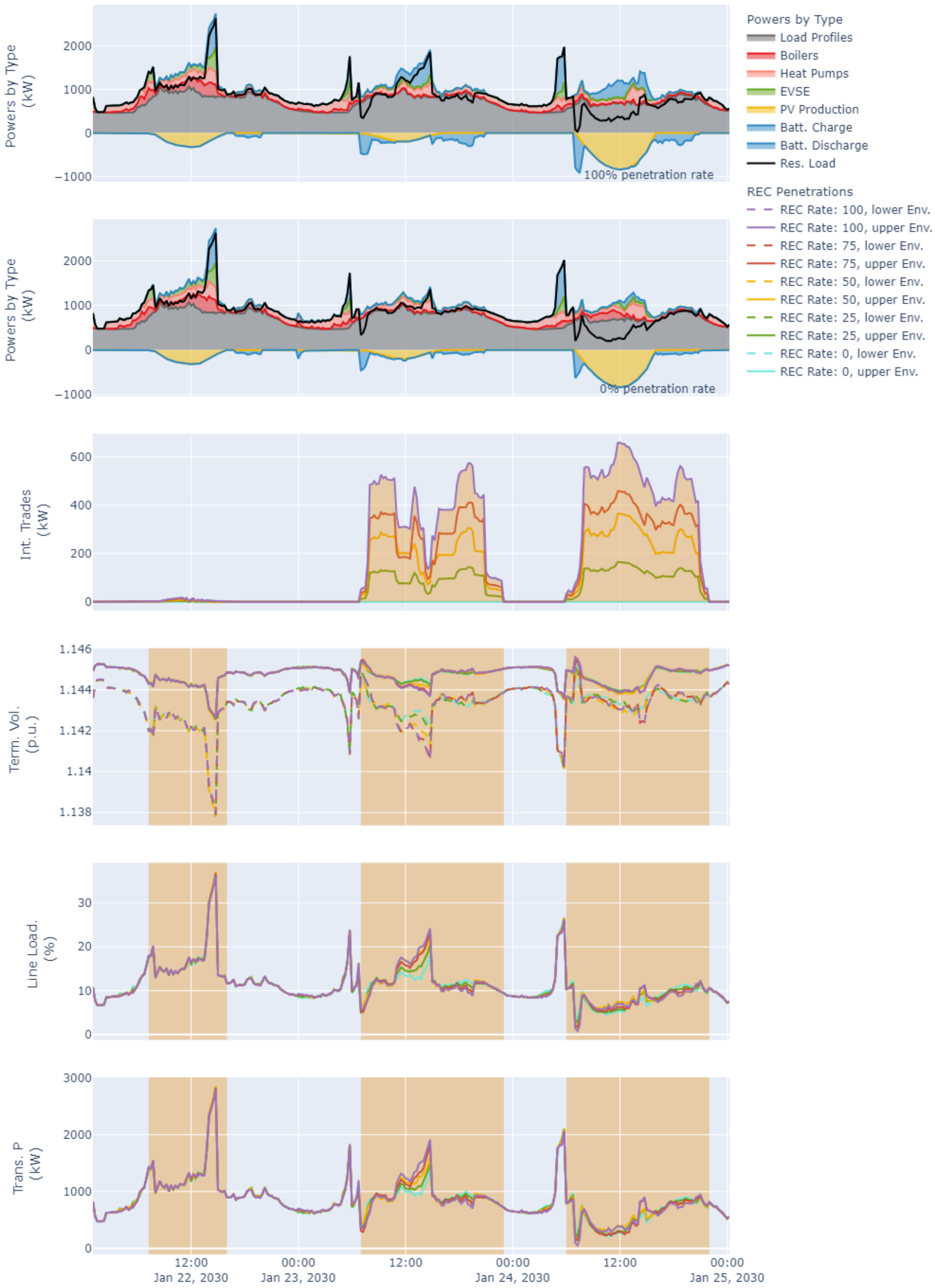

Figure 4.31.: „**Suburban, EAG 2030**“: Aggregated sources and sinks of power, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the penetration rates of communities with the 0 % and the 100 % case under closer inspection. The orange marked areas represent the times of trading.

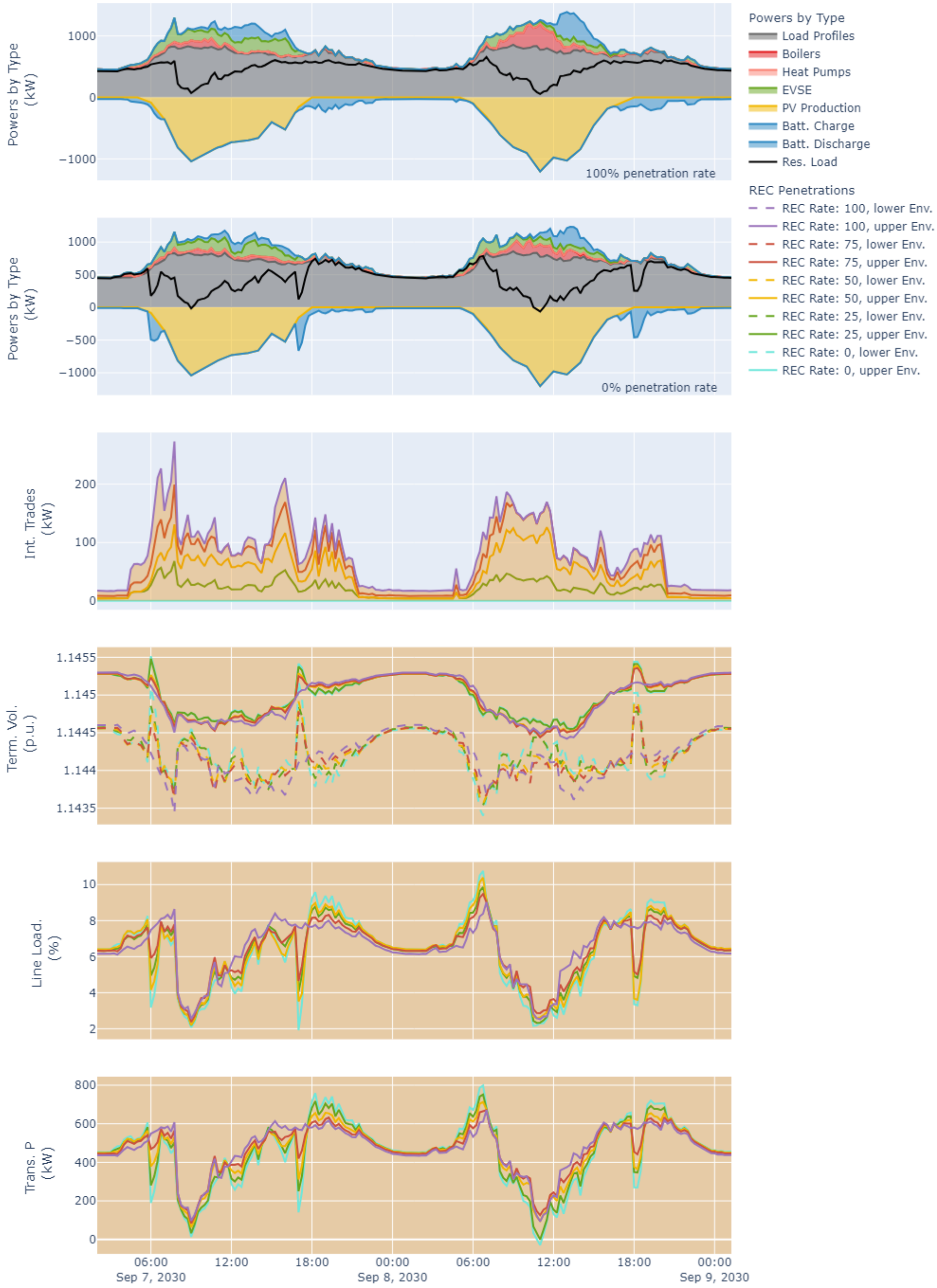

Figure 4.32.: „**Suburban, ÖNIP 2030**“: Aggregated sources and sinks of power, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the penetration rates of communities with the 0 % and the 100 % case under closer inspection. The orange marked areas represent the times of trading.

Urban MV Grid Figure 4.33 displays the load flow calculation results for the urban grid for scenario „**Urban, ÖNIP 2020** for two summer days. Even though the aggregated trading accounts for more than 150 kW, it still can be considered small when compared to the non-flexible loads. Also, as visible in the sources and sinks of powers for the 100 % penetration case, the existence of community-internal trading ensures economically viable PV production. However, due to limited installed capacities, this effect remains limited. Similarly to the outcomes from the LV investigations, limited flexibility installations simply do not allow for much trading, dispatched flexibilities and subsequent impacts on the grid. Therefore, the communities impact can be determined as limited. Still, an increase in community penetration results in reduced line loadings, residual load and also, again, more stable parameters.

Finally, Figure 4.34 shows the same outcomes, but for scenario „**Urban, ÖNIP 2030**" for given winter days. Unlike the previous scenario, trading accounts for a big portion of the total load. Here, PV production enables economic viably trading, which is majorly utilized to boost the usage of flexibilites - the dispatch of boilers in this instance as the heat demand can be guessed as high given the season. Therefore, the grid feed-in of PV energy is reduced when compared to the 0 % scenario. As a consequence, the line loading as well as the residual load increased with the community penetration. However, alike previous considerations, the increase is coupled with a more steady behaviour.

4.2.3. Conclusions of MV considerations

When looking at the outcomes from Figure 4.28 - 4.34, several conclusions can be drawn: First of all, just as presented in the LV results (see sections 4.1.1 4.1.2), the impact of energy communities remains limited.

However, assuming the randomly allocated LRECs within the LV subgrids (as specified in Section 3.4.2 and Appendix B), the residual of the MV transformer typially gets reduced with an increasing community penetration. Further, local MV parameters such as MV line loadings and MV terminal voltages, are usually also reduced or narrower in the case of terminal voltages. Also, the curve shape of those KPIs can generally be observed as being more steady in the communities case. Although, a distinction has to be made here: For scenarios with low to medium penetration rates of flexibilitites, the reduction of the residual load is the main impact while scenarios with a high penetration of flexibilities typically do not have a great reduction in the residual load but the more steady curve shape. In addition to that, external influences like a „Dunkelflaute" or electricity supply tariff price shocks can only be observed with a limited magnitude when compared with the LV results (see Figure 4.16 and 4.19 for reference).

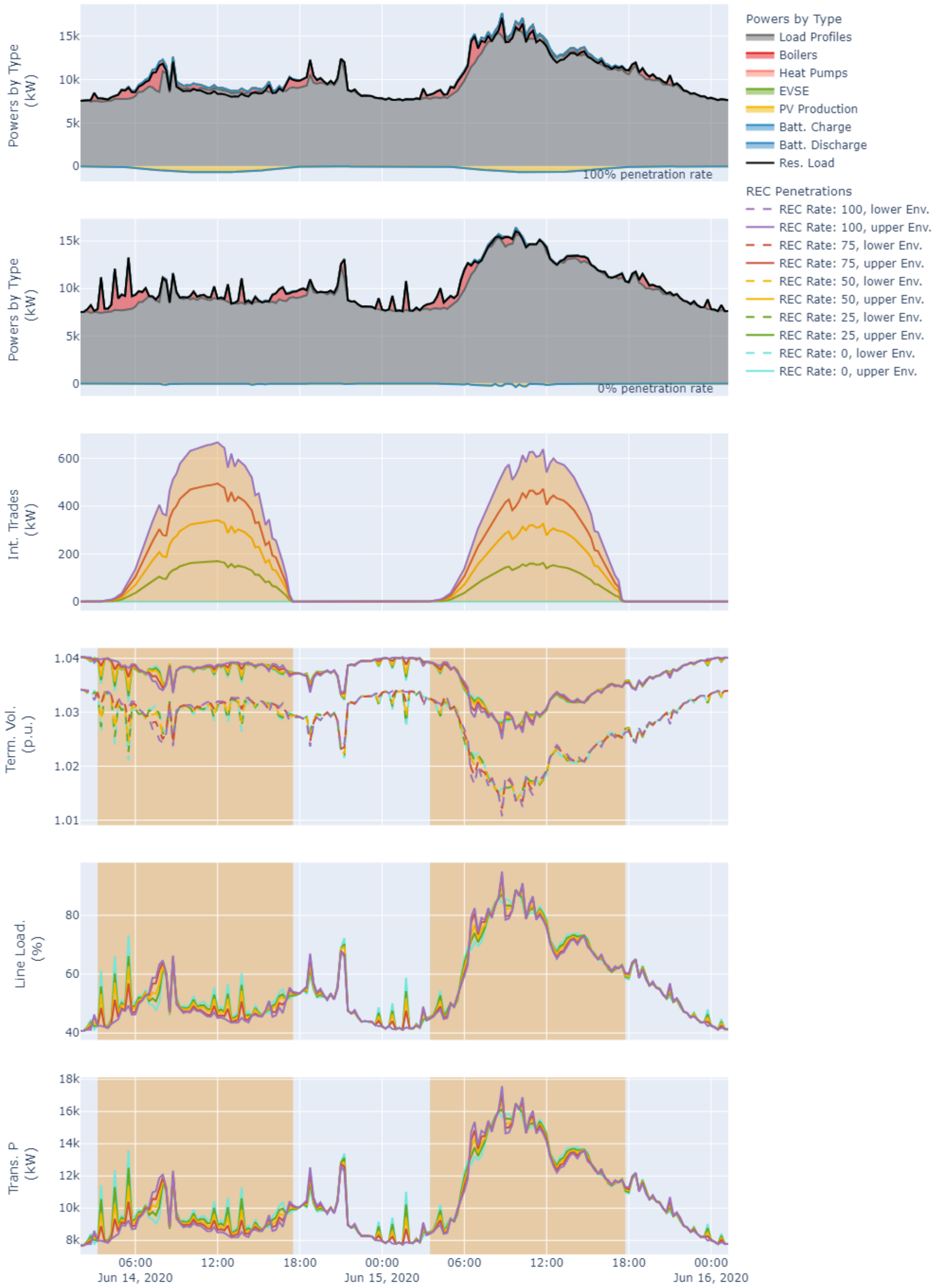

Figure 4.33.: „**Urban, ÖNIP 2020**": Aggregated sources and sinks of power, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the penetration rates of communities with the 0 % and the 100 % case under closer inspection. The orange marked areas represent the times of trading.

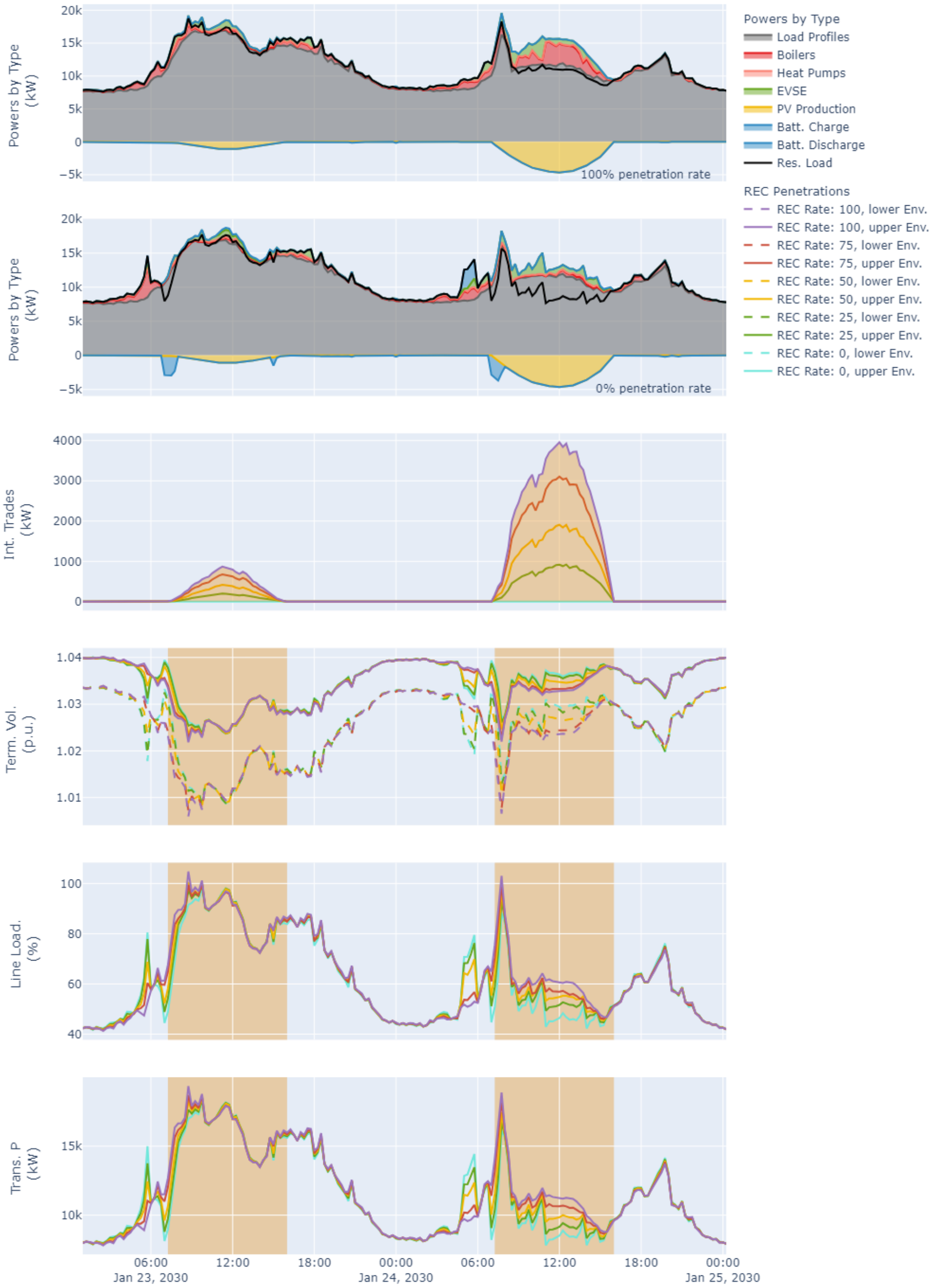

Figure 4.34.: „**Urban, ÖNIP 2030**“: Aggregated sources and sinks of power, total internal trading and the envelopes of all terminal voltages, line loadings and the transformers active power, again, for the penetration rates of communities with the 0 % and the 100 % case under closer inspection. The orange marked areas represent the times of trading.

5. Conclusions and Discussion

This chapter provides the conclusions drawn from the previously obtained results as shown in Chapter 4. Here, at first, the conclusions for low voltage grids and then, for medium voltage grids will be presented. Additionally, a discussion is provided.

5.1. Conclusion

In summary, when looking at the bigger picture, the following outcomes can be observed for the considerations at a low voltage level as shown in Section 4.1.1 and 4.1.2:

- Without any installed flexibilites, economic viable trading is merely impossible, thus diminishing the impact of the community on the grid (and furthermore diminishing the benefits of a community itself, at least within economic terms).
- Trading can result in a more stressed grid or grid code violations as visible in Figure 4.16 and 4.19. In particular, external shocks such as high electricity supply prices resulting in a high viability of trading and a subsequently high amount of trading will lead to a negative impact of the grid. However, the situations of occurrence can be viewed as limited.
- With PV installations over-accomplishing requested PV goals („ÖNIP 2030+" scenarios, for example - see Figure 4.17) the impact of the community is, again, greatly reduced during times of high potential production. The excessive installation of PV being far greater than the potential of self-consumption for the majority of the households results in a lack of potential trading partners and therefore little to no impact of the community per-se.
- For most scenarios aside mentioned extreme cases, the existence of a community causes slightly higher local grid parameters (such as terminal voltages and line loadings, i.e., parameters „within" the community) but, typically, a either reduced or - at least - a far more steady residual load curve. Therefore, it can be deduced, that in these scenarios a community can be beneficial to the remaining grid. Also, in these cases, the potentially negative impact of a community (that being very high trading in respect to the typical load) simply does not occur as options for

economically viable trading are generally limited assuming realistic scenarios as shown in Section 3.1.

In addition to above stated conclusions for the results at a low voltage level, the following outcomes can be deduced from medium voltage calculations as obtained from Section 4.2.1 and 4.2.2:

- Regardless of the grid level, limited installations of PV and flexibilities do not allow for substantial amounts of trading thus diminishing the potential impact on the grid.
- The thermal loading parameters (line loadings and transformer active power) generally decrease with an increasing community penetration rate as visible from Figure 4.28 to 4.34. However, for winter times, the residual load can increase as a result of dispatched flexibilities from PV prodcution due to trading (rather than grid feed-in).
- Additionally, the voltage band decreases in width with increasing community penetration.
- Usually, an increasing penetration rate of communities result in more steady curve shape of grid parameters. For instance, even with a higher residual load when comparing a 100 % penetration case to a 0 % penetration case, the curve is usually more steady.
- However, regarding the reduction of more steady residual load curve shape, a distinction has to be made: Scenarios with low to medium penetration of flexibilities have the reduction as main impact while scenarios with medium to high penetration of flexibilities feature the more steady residual load curve shape as the overwhelming influence.
- Further, external price shocks (as visible in the LV results in Figure 4.16 and Figure 4.18) that accounted for a drastic impact from the community in the LV results cannot be seen with the same magnitude in the MV results as visible in Figure 4.31 for example.

5.2. Discussion

With stated conclusions in mind, it can logically be deduced, that under the assumption of the realistic scenarios, as specified in Section 3.1, and further assuming an economically driven behaviour of the participants the existence of energy communities alongside installed flexibilities in general marginally aids the grid. However, under the assumption of realistic scenarios, the impact remains fairly small due to the limited trading options as well as both technical and economical constraints.

Aside from the grid impact correlating positive to the penetration rates of flexibilities, the potential impact also correlates positive to the „de-urbanization" of the scenario - as shown in greater detail in Section 4.1.1 (or Figure 4.1, 4.5 and 4.8). Therefore, all outcomes from, for example, rural grids apply just as well to suburban and even urban grids but with a drastically reduced significance. Again, as already mentioned, the reason is the higher share of non-flexible loads within the suburban and urban grids.

This leads to a thought experiment: If, let's say, not all flexibilities can be strictly controlled as assumed here or, for example, the thermal mass of the utilized building stock proves to be smaller thus decreasing the heating systems flexibility, these loads might be viewed as non-flexible loads and therefore decreasing the share of flexibilities in respect to the non-flexible loads. As a logic consequence, the impact of energy communities on the grids state of such scenarios can be described as even further reduced when compared to the high flexibility, high control counterparts presented here.

In addition to that, the grid impact of the installation of said flexibilities on the various grid types is far greater than the existence of an energy community alone. Therefore, energy communities can typically not be accounted for when looking for a measure in order to reduce grid loading since it cannot be reliably - and most importantly: scenario independent - deduced that the installation of such an community automatically aids the grid.

However, when keeping the underlying idea of energy communities in mind, that being increasing investments into renewables by enhancing public acceptance by incentivizing public participation (see Section 2.1.1 for reference), energy communities also do not automatically stress the grid by their sheer existence.

Therefore, it can be concluded, that energy communities in general do not offer themselves as a seemingly magic solution to grid capacity issues but also, more importantly, usually do not put additional stress on an electrical distribution grid.

6. Outlook

6.1. Outlook

As already mentioned several times, this thesis was carried out within a research project called ORANGE, destined to investigate into the incentives of various grid tariff design options to increase the utilization of flexibilities in the context of (renewable) energy communities [3, 44]. In the context of this work, multiple workshops including various stakeholders were included to present carried out research.

While the outcomes in general were highly regarded one key remark addressed the lack of availability of neither high quality nor real-time data from the distribution grid. As a consequence, it is of significant difficulty to first of all assess the current situation of a distribution network in terms of loading, hosting capacity and voltage band violations and second, merely impossible to plan ahead in order to properly dispatch flexibilities in a grid-friendly and economically beneficial manner.

Therefore, future work might primarily tackle the challenge of retrieving and processing incomplete data from a distribution network by developing and utilizing machine learning algorithms in order to create a useful model of a given grid so that both renewable generation as well as distributed flexibilities can be operated at an economic and technical optimum - machine learing grid estimation, so to say.

The benefits are clear: An observable grid can allow for a better and more adequate planning of grid reinforcements and might even further boost the usage of flexibilities and distributed, renewable generation thus contributing to the electrification and energy transition. As mentioned in the introductory part (see chapter 1.1), climate change poses a threat to general human well-being requiring rapid and far-reaching changes to significantly reduce carbon emissions. By improving one fractional part a distribution grid, that being yet again a fractional part of the energy system as a whole, an incremental contribution towards a more sustainable future can be achieved.

Appendix A.

Low Voltage Grid Topologies

Here, the topologies of the representative grids will be presented. As already mentioned in Section 3.1.2, the presented grids are actual Austrian low voltage distribution grids derived from project [2]. Therefore, all names and identifiers are erased to comply with data protection requirements. Further, the length of the lines correlates to the actual length of the lines, only the topology graphs have been generated automatically, again, to ensure an identification of the grids being impossible.

The grid models provide the following information:

1. Topology model
2. Electrical parameters for all utilities such as lines, transformers etc.
3. Yearly consumption of the loads
4. Load type of the loads. The load type categories are derived from [1]
5. Geographic location

Table A.1 presents the number of loads for each category as well as their corresponding yearly consumption. For the sake of simplicity, the various subtypes of one category, e.g. commercial loads such as „G0“, „G1“, „G2“, „G3“, have been condensed into their parent category, but only for this table. The types for the calculations will remain unaltered though.

Grid Name	Res. HH Num. (Cons. (MWh))	Comm. Num. (Cons. (MWh))	Agr. Num. (Cons. (MWh))	Water Htr. Num. (Cons. (MWh))	Publ. Ill. Num. (Cons. (MWh))
Rural 1	13 (59.1)	2 (19.71)	14 (136.78)	0 (0)	0 (0)
Rural 2	8 (28.29)	6 (51.3)	5 (60.35)	0 (0)	0 (0)
Suburban 1	28 (99.14)	17 (978.48)	2 (29.19)	5 (11.08)	1 (5.84)
Suburban 2	63 (174.34)	8 (219.05)	3 (15.67)	34 (110.88)	0 (0)
Urban 1	95 (268.64)	37 (1782.2)	0 (0)	0 (0)	0 (0)
Urban 2	144 (239.49)	109 (1626.46)	0 (0)	38 (55.78)	1 (8.15)

Table A.1.: Numbers (Num.) and yearly consumptions (Cons.) in MWh for the grouped load types Residential Households (Res. HH), Commercial Loads (Comm.), Agricultural Loads (Agr.), Hot Water Heaters (Water Htr.) and public illumination (Publ. Ill.)

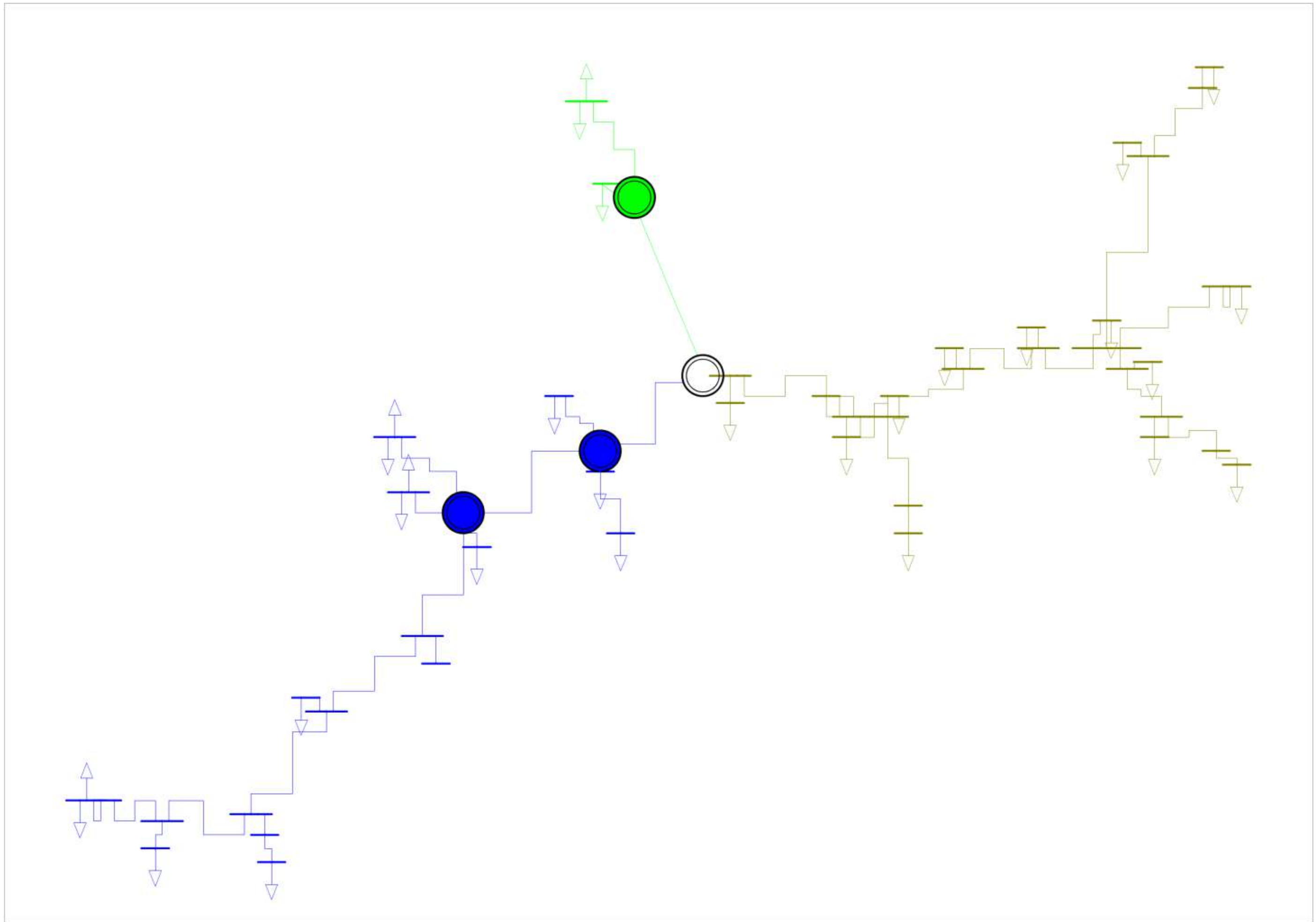

Figure A.1.: Topology of „Rural 1“

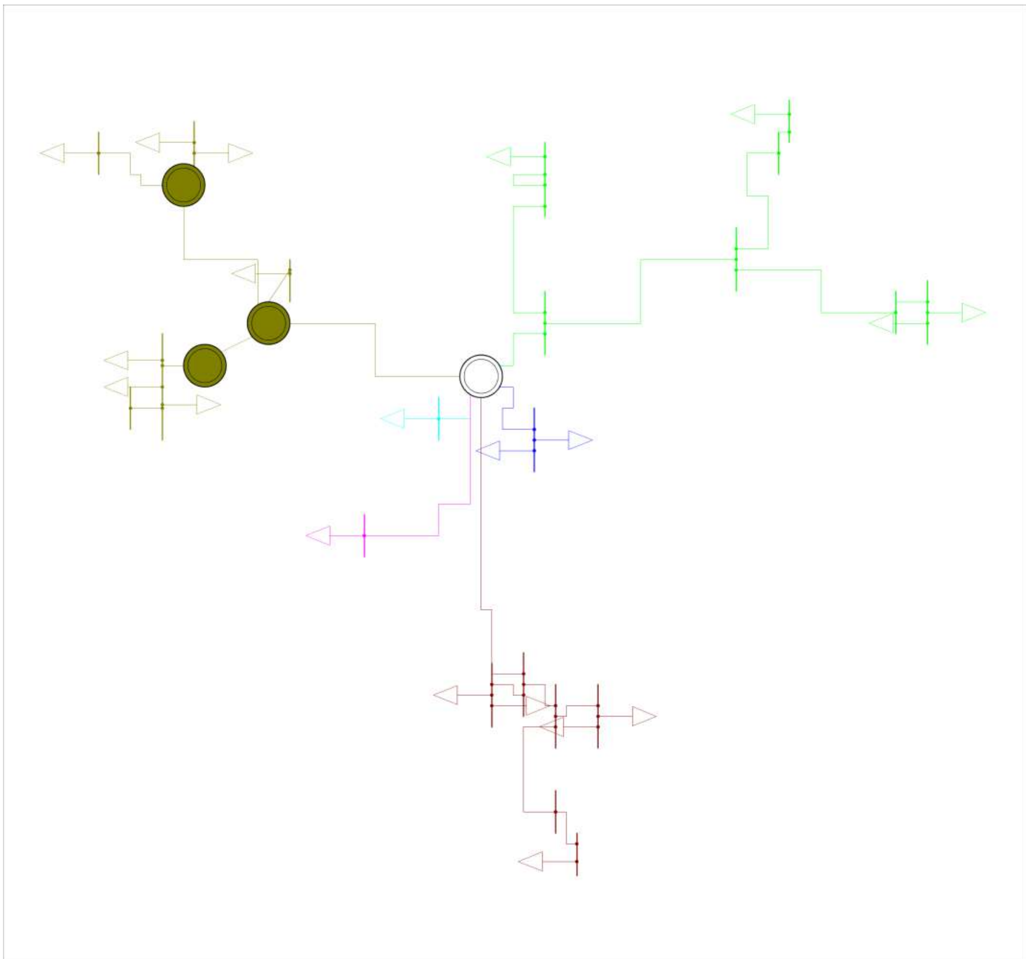

Figure A.2.: Topology of „Rural 2"

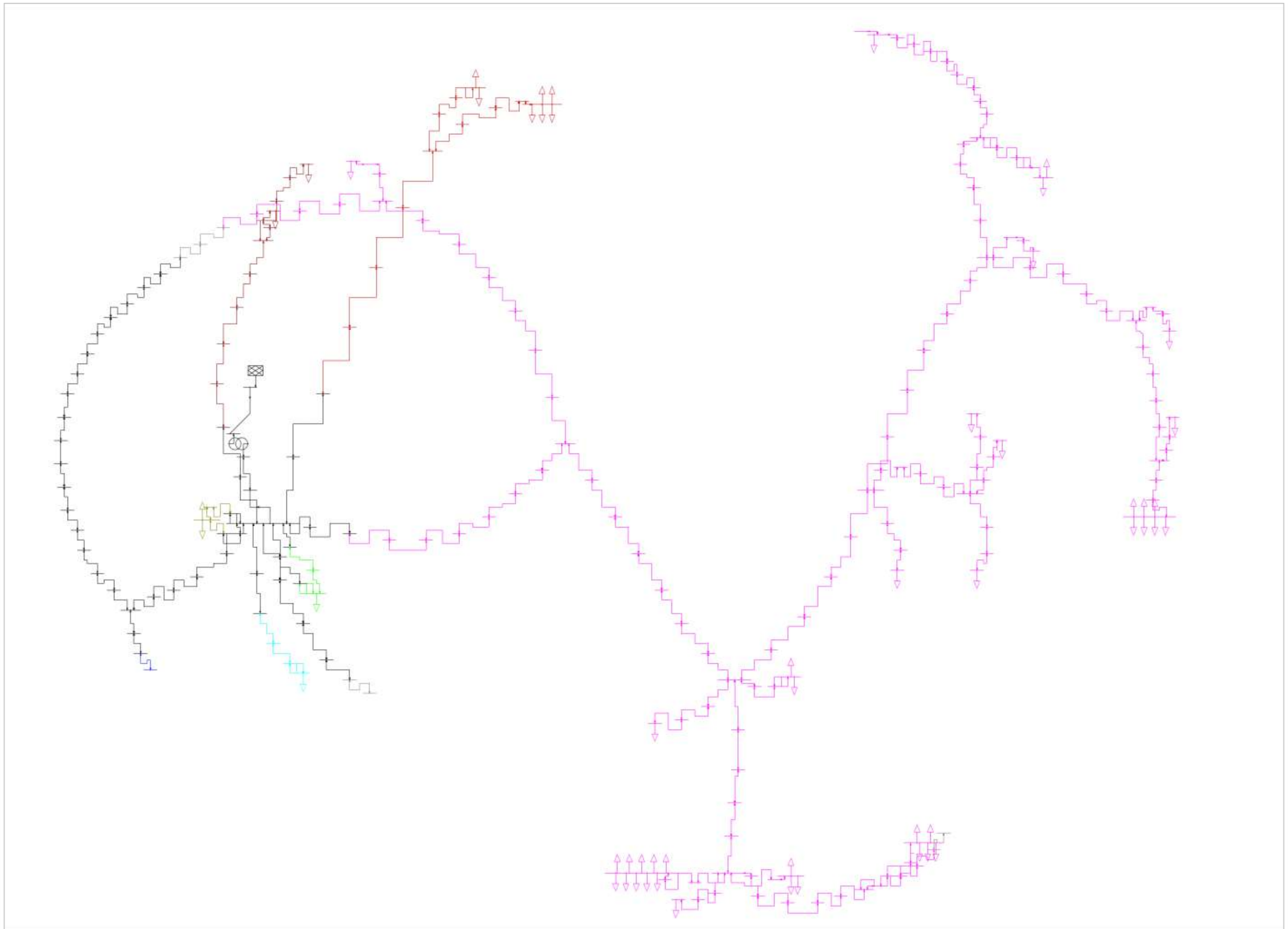

Figure A.3.: Topology of „Suburban 1“

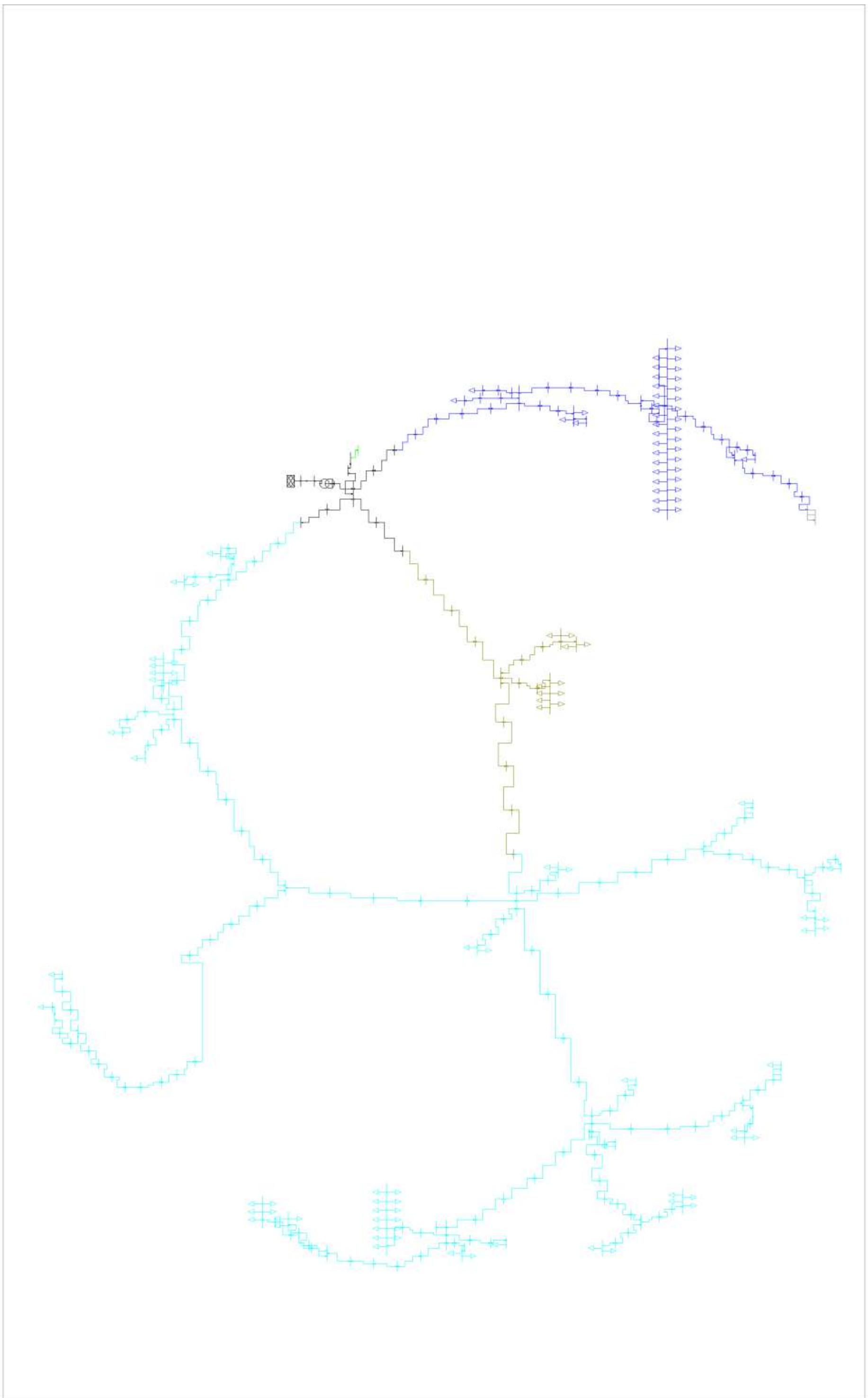

Figure A.4.: Topology of „Suburban 2"

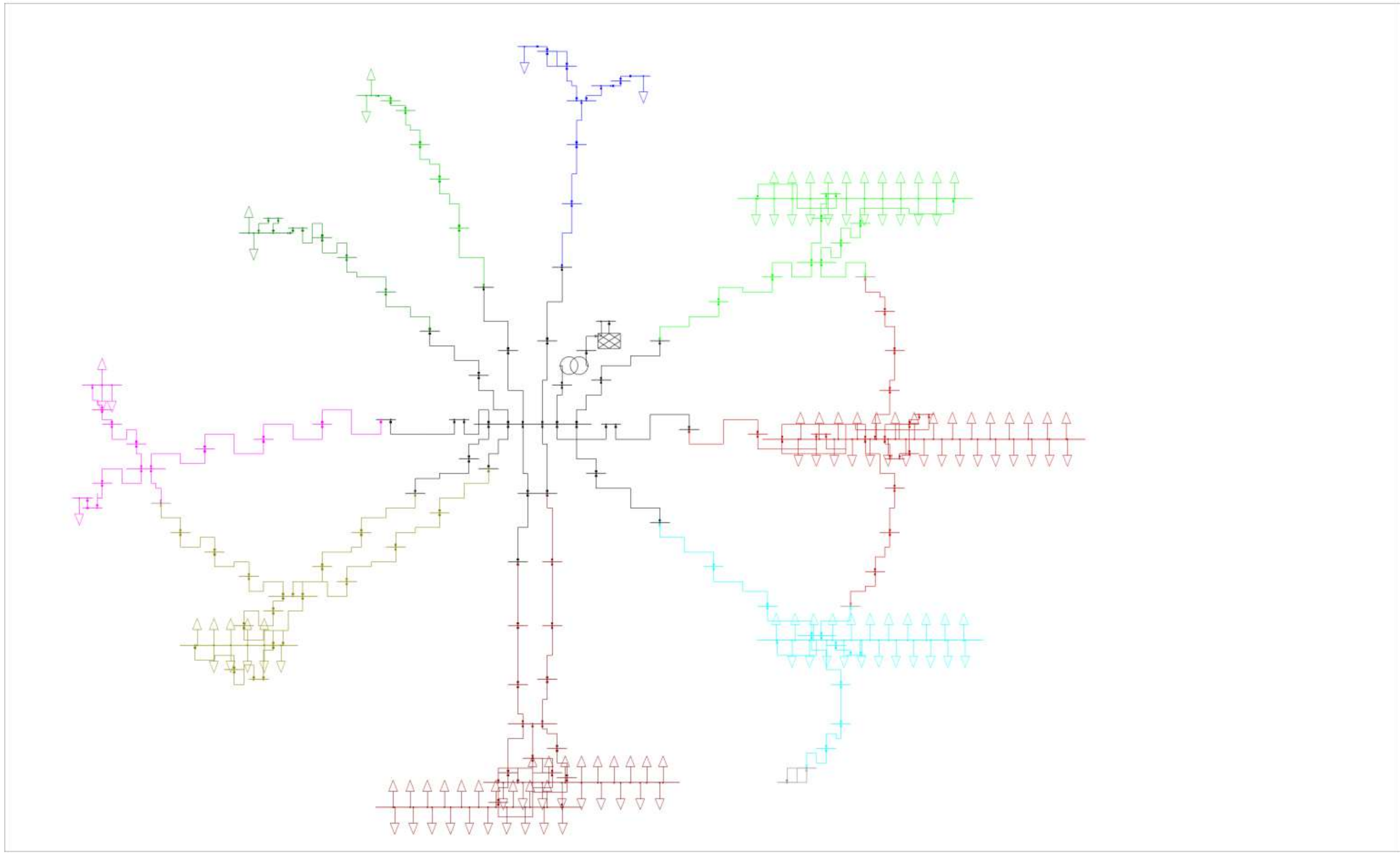

Figure A.5.: Topology of „Urban 1“

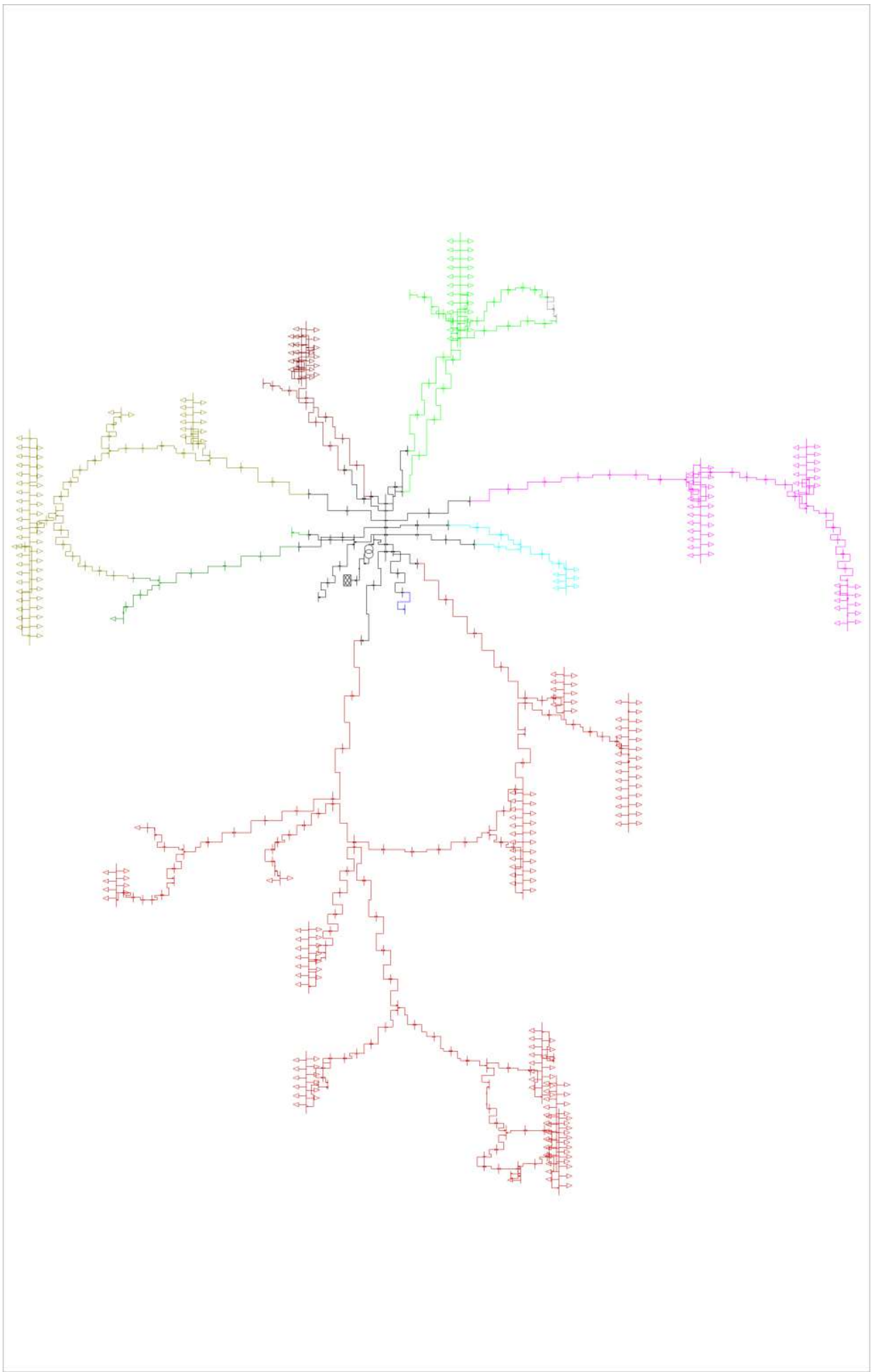

Figure A.6.: Topology of „Urban 2"

Appendix B.

Medium Voltage Grid Topologies

Here, the grid models used for the calculations regarding the impact on the MV level are presented. In contrast to the LV grid topologies presented in Section 3.1.2 and Appendix A, only one MV grid per spatial category was considered, henceforth named „**Rural Grid**", „**Suburban Grid**", „**Urban Grid**".

These grid models were, again, derived from publication [2] and represent real medium voltage grids located in Austria chosen as being very typical by power system experts and grid operators. Figure B.1 presents the „**Rural Grid**", Figure B.2 shows the „**Suburban Grid**" and Figure B.3 displays the „**Urban Grid**".

The grid model includes the following information:

1. Topology model
2. Electrical parameters for all utilities such as lines, transformers etc.
3. Geographic location
4. Each MV load: Amount, Types and aggregated consumption of all subsequent LV loads

It is important to state, that these models include information regarding the attached LV grids as shown above but the actual LV models are not directly attached. Also, the exact corresponding LV grids are not available, as only a handful of selected, typical grids from any location in Austria are available from publication [2]. Therefore, this connection has to be made while ensuring a best-representative result. Each and every load of a MV grid represents a LV grid coupled via a transformer in reality. With the attached information regarding connected numbers, types and consumptions of attached LV loads, one or many fitting (based on number of loads, load types, respective consumptions and geographical properties) LV grid models from Appendix A were attached via a transformer. To match the provided size, several different LV subgrids can be appended to one MV load as well.

Table B.1 shows the attached LV grids while Table B.2 displays all attached loads with their corresponding yearly consumption. As visible in Table B.1, a single subgrid can be used several times. To avoid having many duplicate subgrids, all subgrids line lengths have been randomly altered by $\pm10\%$.

Also, the provided MV models included various direct connections to big consumers, i.e. industry („LPZ“ load type in [1]). These loads were deliberately deleted, as the typical profile can be fairly specific and is furthermore not available. Apart from that, due to the sheer size of those MV models, not each and every branch was considered. Therefore, it is important to state, that the loadings of e.g. lines and transformers cannot be viewed as absolute accurate values as the deletion of several branches will definitely result in lower loadings but should rather be considered for a comparison with different scenarios.

The creation of the MV grids was carried out based on available data, yet done artificially. In order to ensure a realistic representation of typical MV grids, the created models were approved by power system and grid planning experts.

	Rural 1	Rural 2	Suburban 1	Suburban 2	Urban 1	Urban 2
Rural Grid	3	6	3	2	0	0
Suburban Grid	0	0	4	4	0	0
Urban Grid	0	0	0	0	18	26

Table B.1.: Number of the chosen LV subgrids for each of the MV grids. Note, one MV load can consist of several LV subgrids in order to match the provided information

Grid Name	Res. HH	Comm.	Agr.	Water Htr.	Publ. Ill.
	Num. (Cons. (MWh))	Num. (Cons. (MWh))	Num. (Cons. (MWh))	Num. (Cons. (MWh))	Num. (Cons. (MWh))
Rural Grid	297 (993.1)	109 (3740.5)	84 (891.3)	83 (255)	3 (17.5)
Suburban Grid	364 (1093.9)	100 (4790.1)	20 (179.4)	156 (487.8)	4 (23.4)
Urban Grid	5454 (11062.1)	3500 (74367.6)	0 (0)	988 (1450.3)	26 (212)

Table B.2.: Numbers (Num.) and yearly consumptions (Cons.) in MWh for the grouped load types Residential Households (Res. HH), Commercial Loads (Comm.), Agricultural Loads (Agr.), Hot Water Heaters (Water Htr.) and public illumination (Publ. Ill.) for the MV grids. For the sake of simplicity, the various subtypes of one category, e.g. commercial loads such as „G0“, „G1“, „G2“, „G3“, have been condensed into their parent category for this table

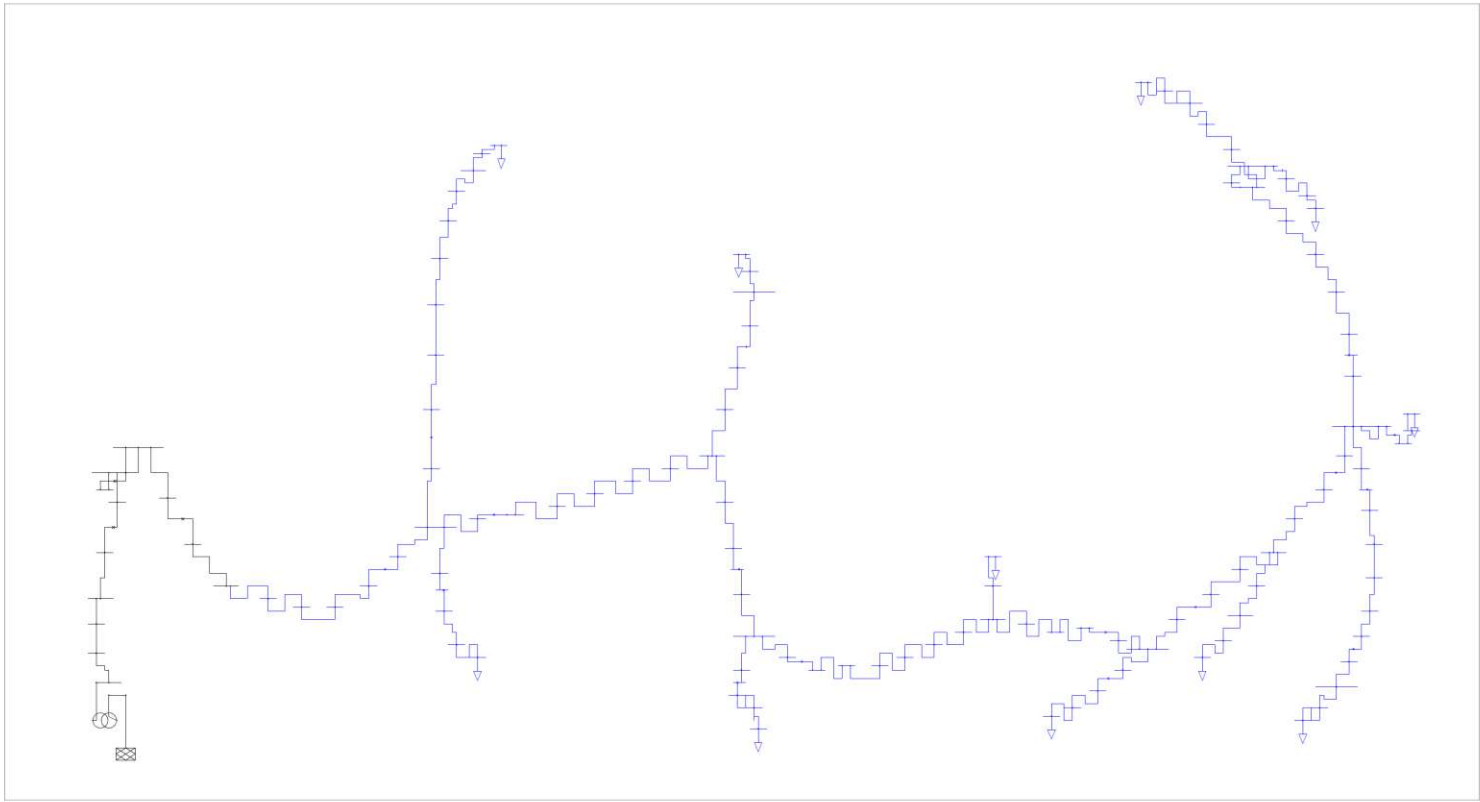

Figure B.1.: Topology of „Rural Grid“

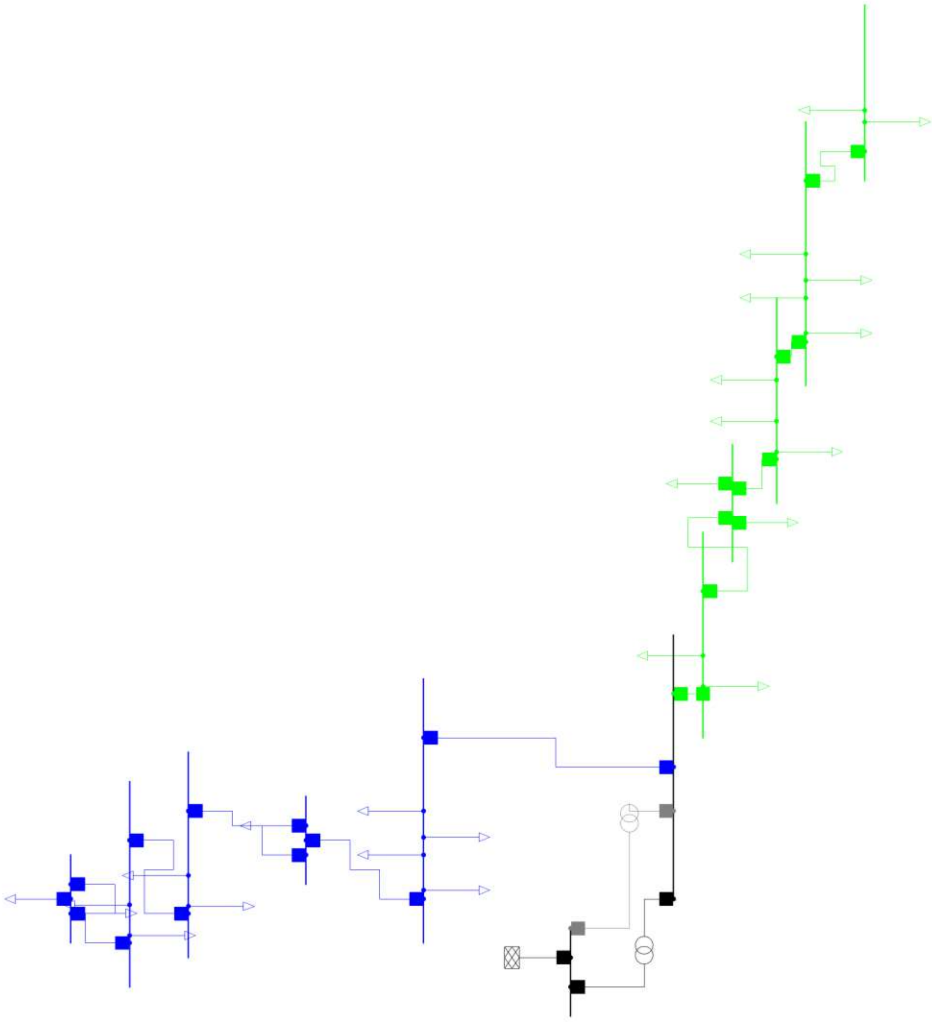

Figure B.2.: Topology of „Suburban Grid“

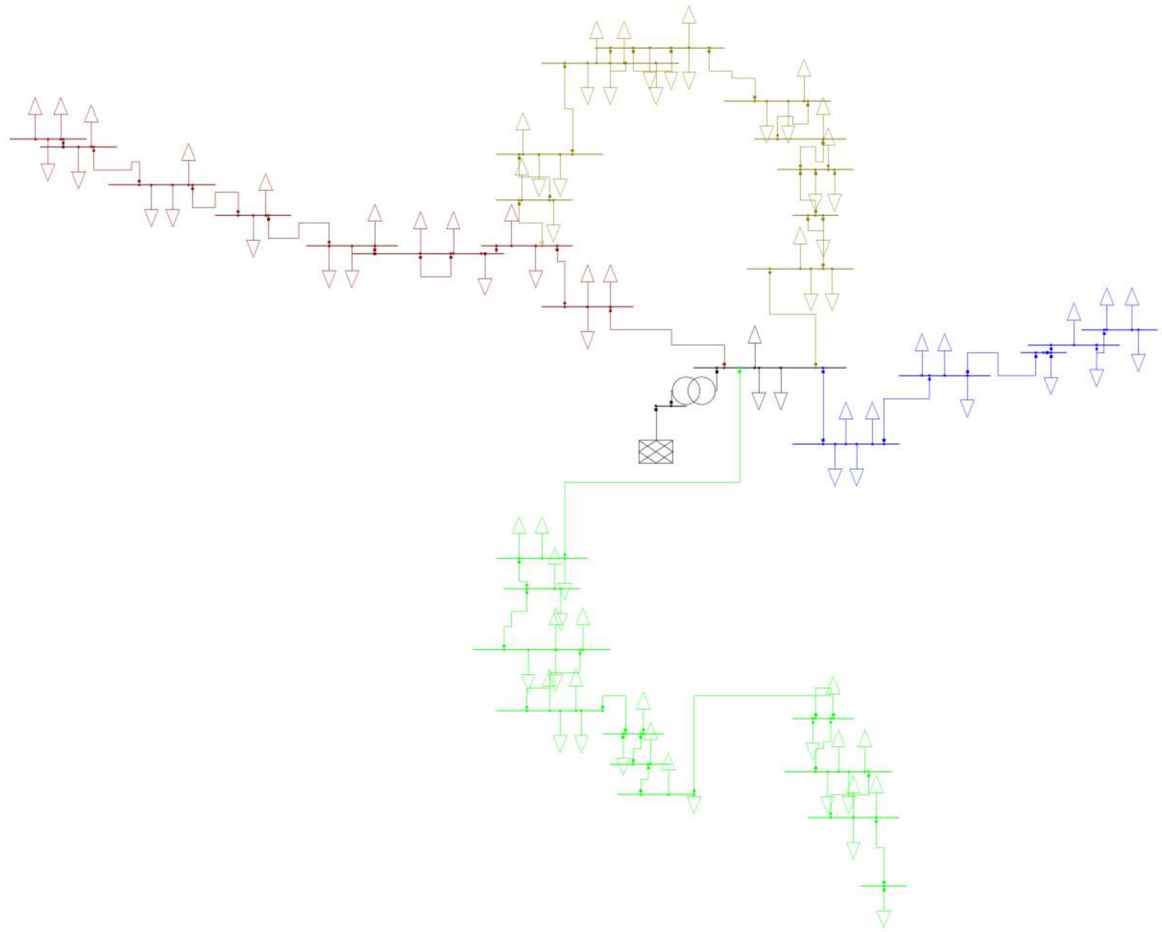

Figure B.3.: Topology of „Urban Grid“

Appendix C.

All results

For the purpose of increasing transparency and completeness as well as providing a as detailed as possible insight into the impact of a large-scale deployment of energy communities on distribution grids, additional results not shown in Chapter 4 are displayed here in this appendix.

C.1. Low Voltage Results

Here, additional results are shown for the low voltage grid simulations as seen in Section 4.1

C.1.1. Results from the Simulation and Optimization Framework

At first, further results from `Femto.jl` showing the community internal behaviour will be presented in addition to results shown in Section 4.1.2. Figure C.1 show „**Rural 2**“, Figure C.2 lays out „**Suburban 2**“ and Figure C.3 brings up the results for the scenario „**Urban 1**“.

C.2. Medium Voltage Results

In this section, some additional results from the calculations shown in Section 4.2.1 are shown. Here, Figure C.4 presents the community penetration rate sensitivity analysis for the scenario „**Rural, ÖNIP 2020**“, Figure C.5 scenario „**Rural, EAG 2030**“, Figure C.6 scenario „**Suburban, EAG 2020**“, Figure C.7 scenario „**Suburban, EAG 2030**“, Figure C.8 scenario „**Suburban, ÖNIP 2030**“ and Figure C.9 displays the scenario „**Urban, ÖNIP 2020**“.

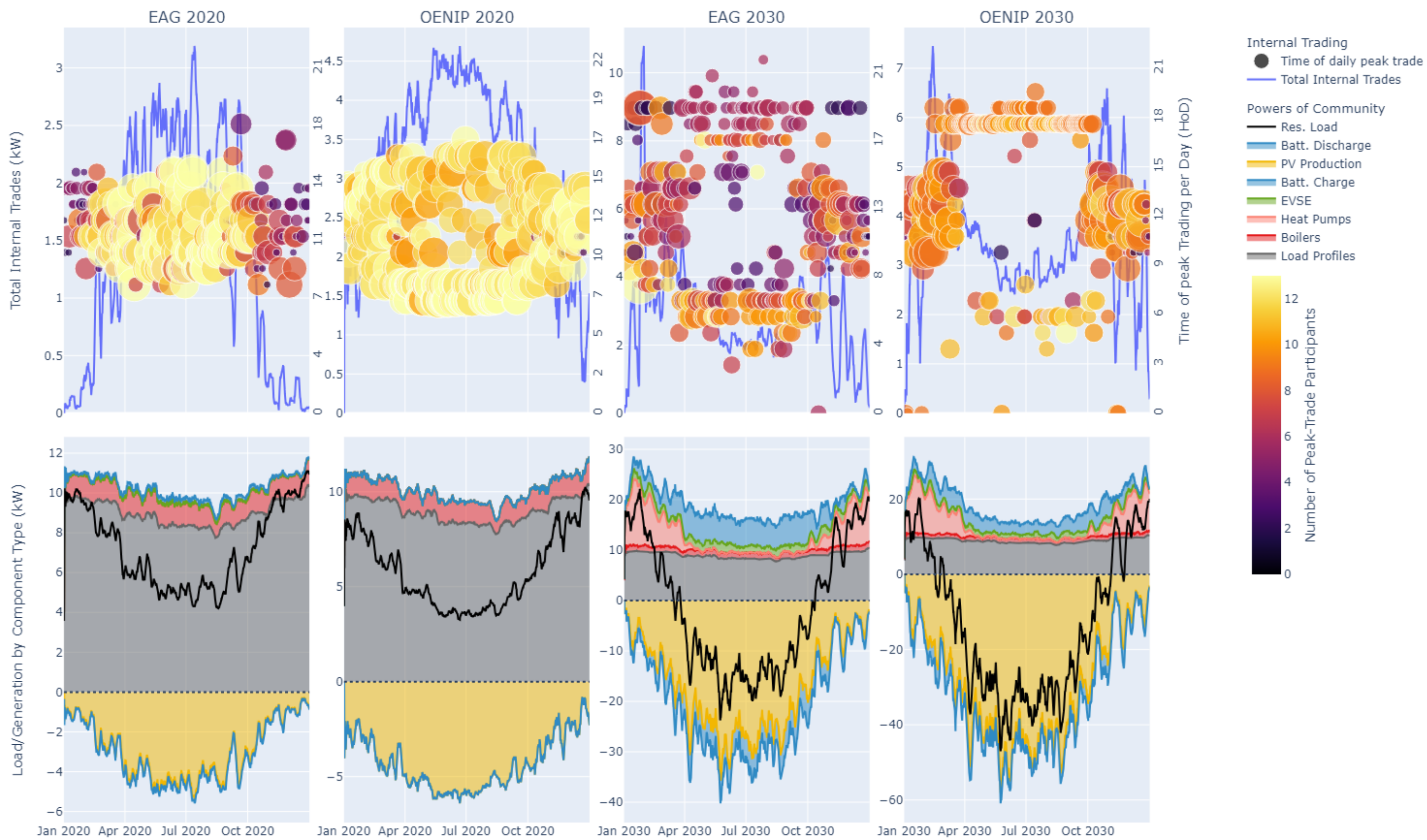

Figure C.1.: „**Rural 2**": Yearly aggregated community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

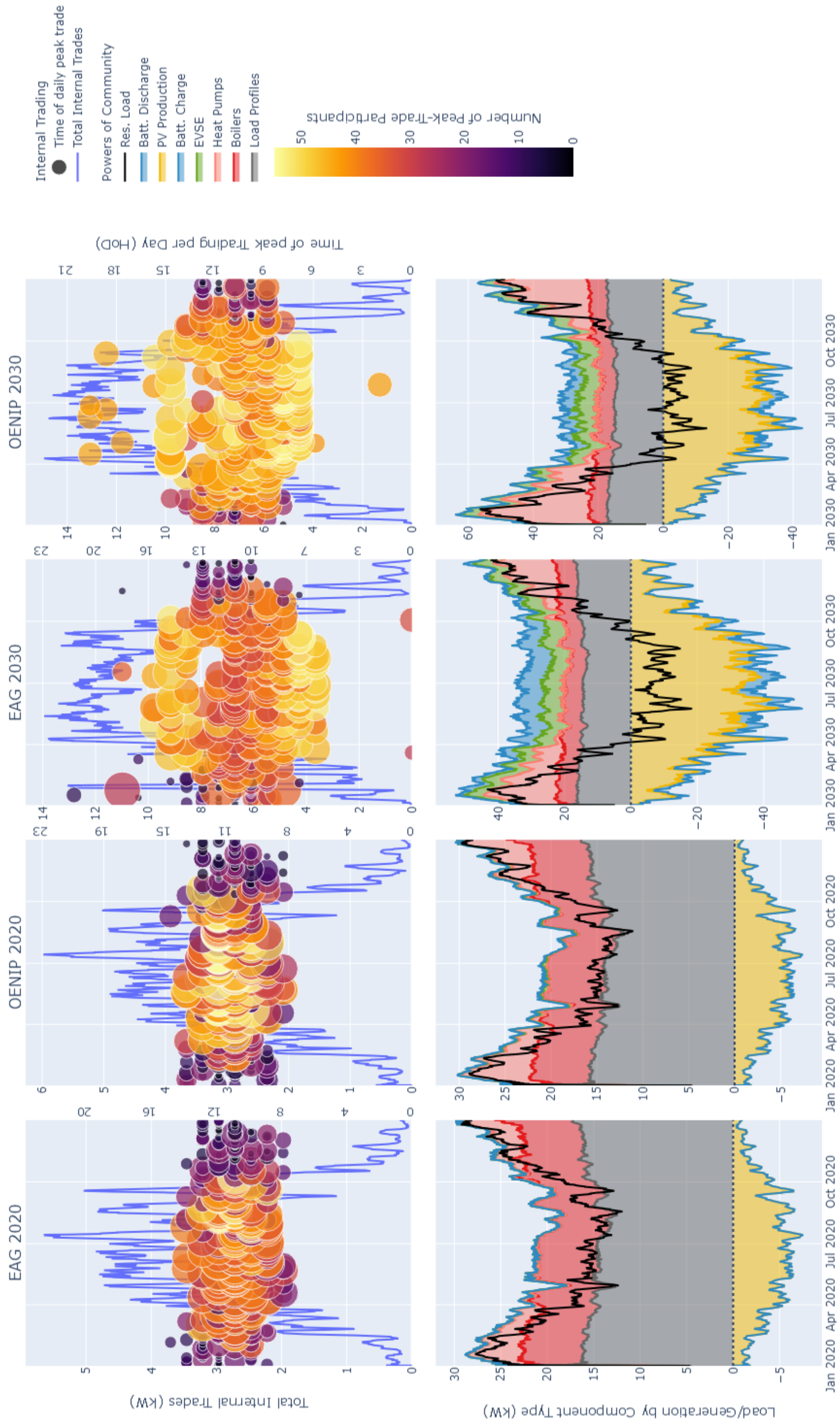

Figure C.2.: „**Suburban 2**“: Yearly aggregated community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

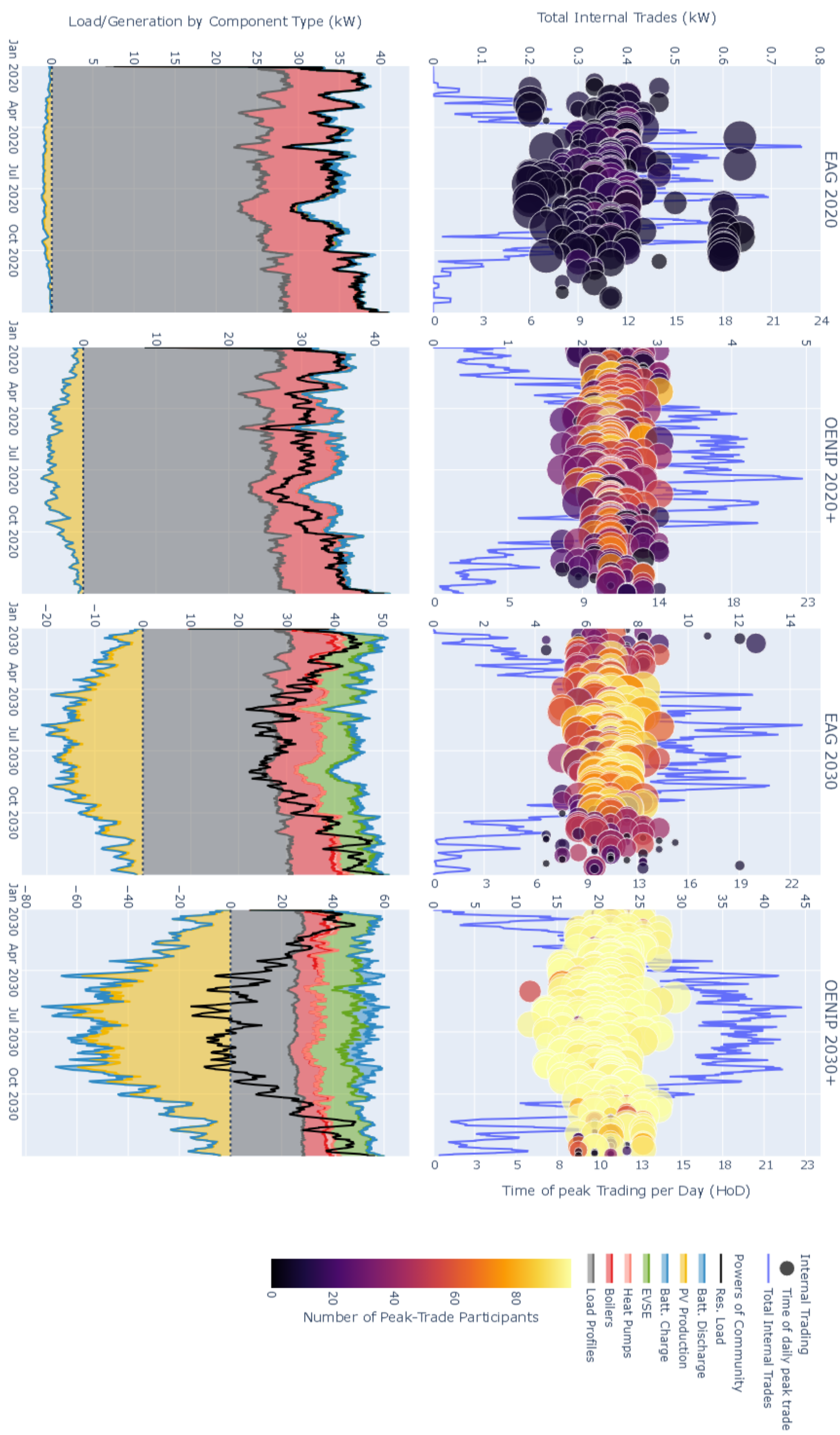

Figure C.3.: **„Urban 1"**: Yearly aggregated community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

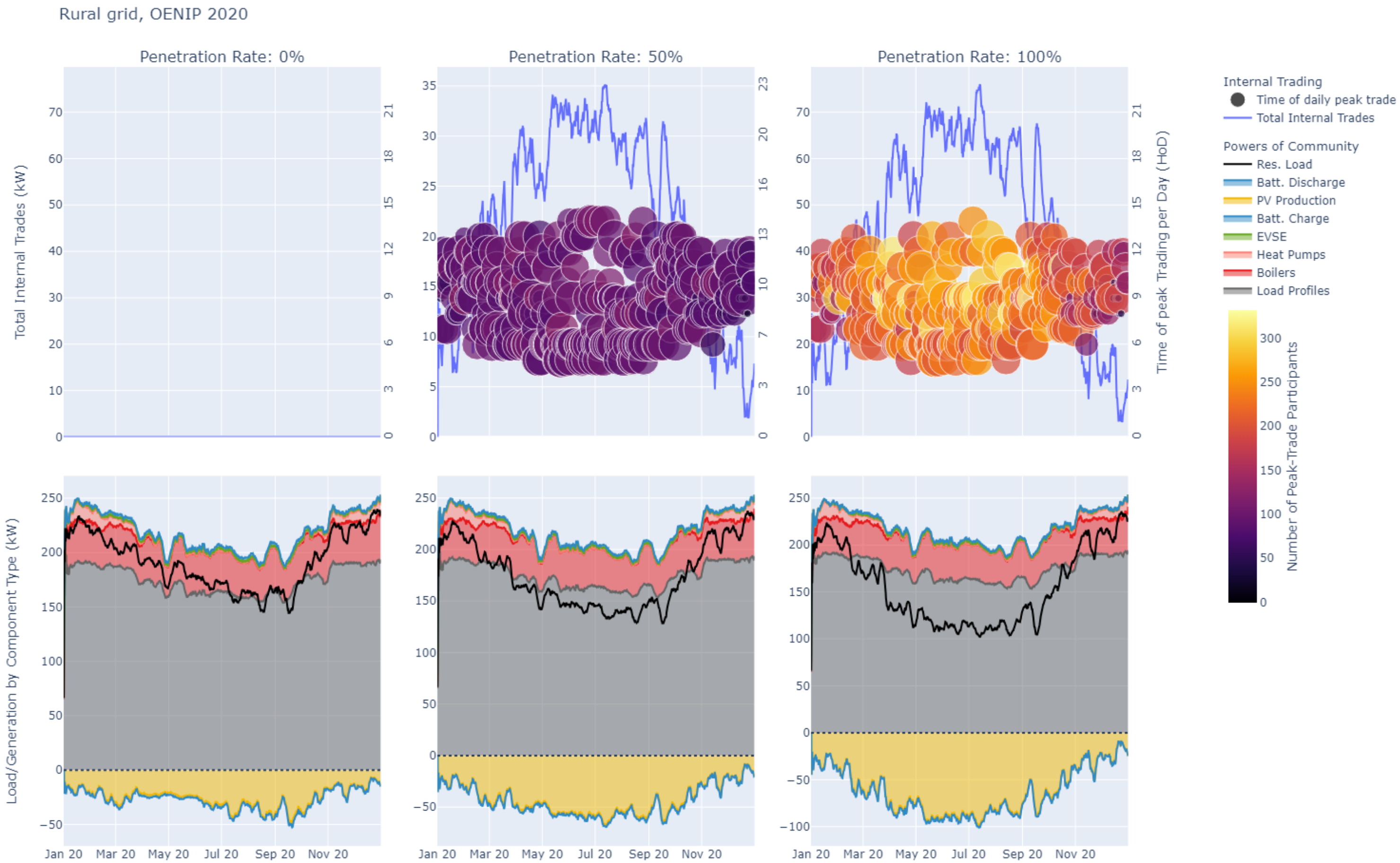

Figure C.4.: „**Rural, ÖNIP 2020**“: Community penetration rate sensitivity analysis with the aggregated yearly community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

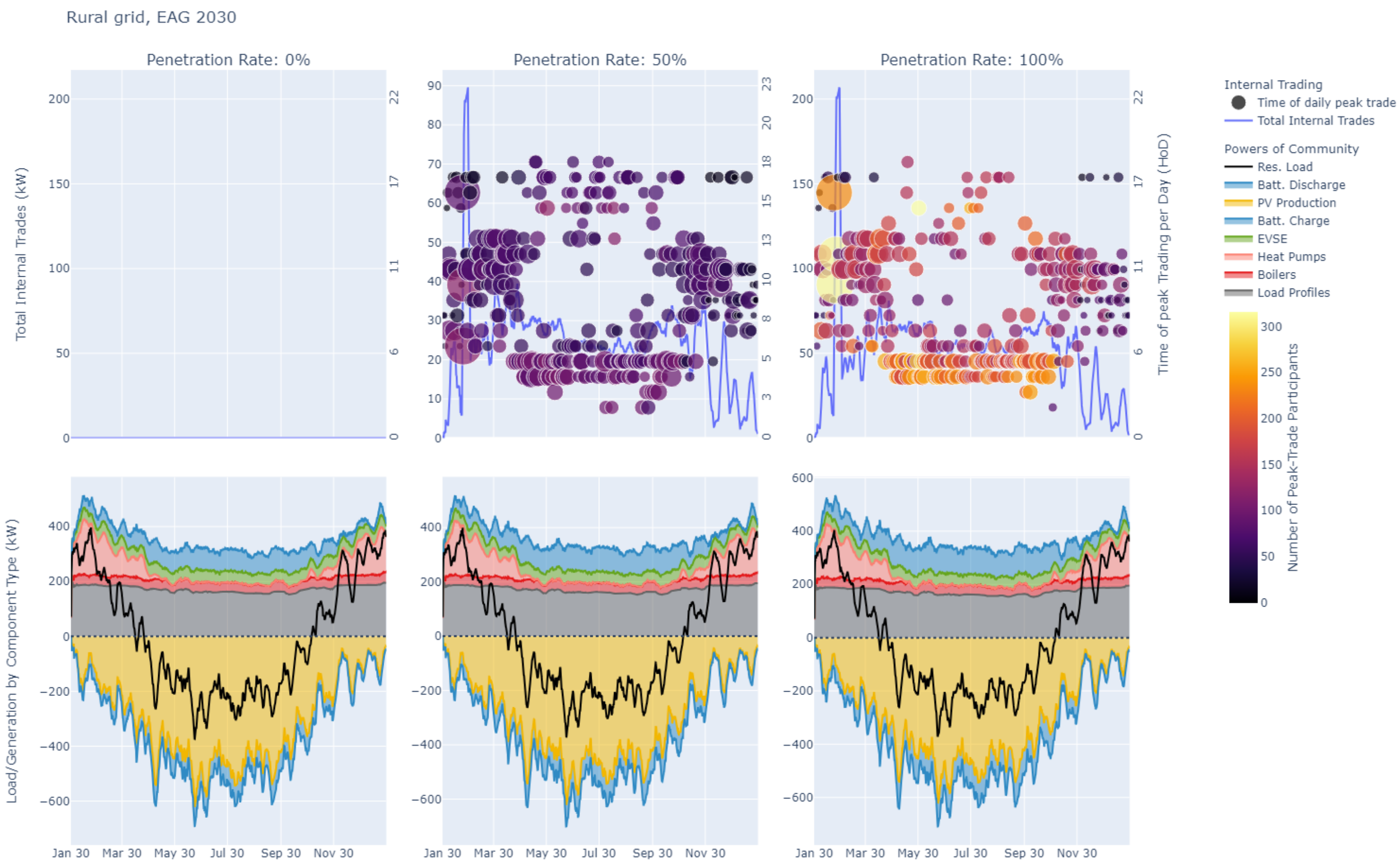

Figure C.5.: „**Rural, EAG 2030**": Community penetration rate sensitivity analysis with the aggregated yearly community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

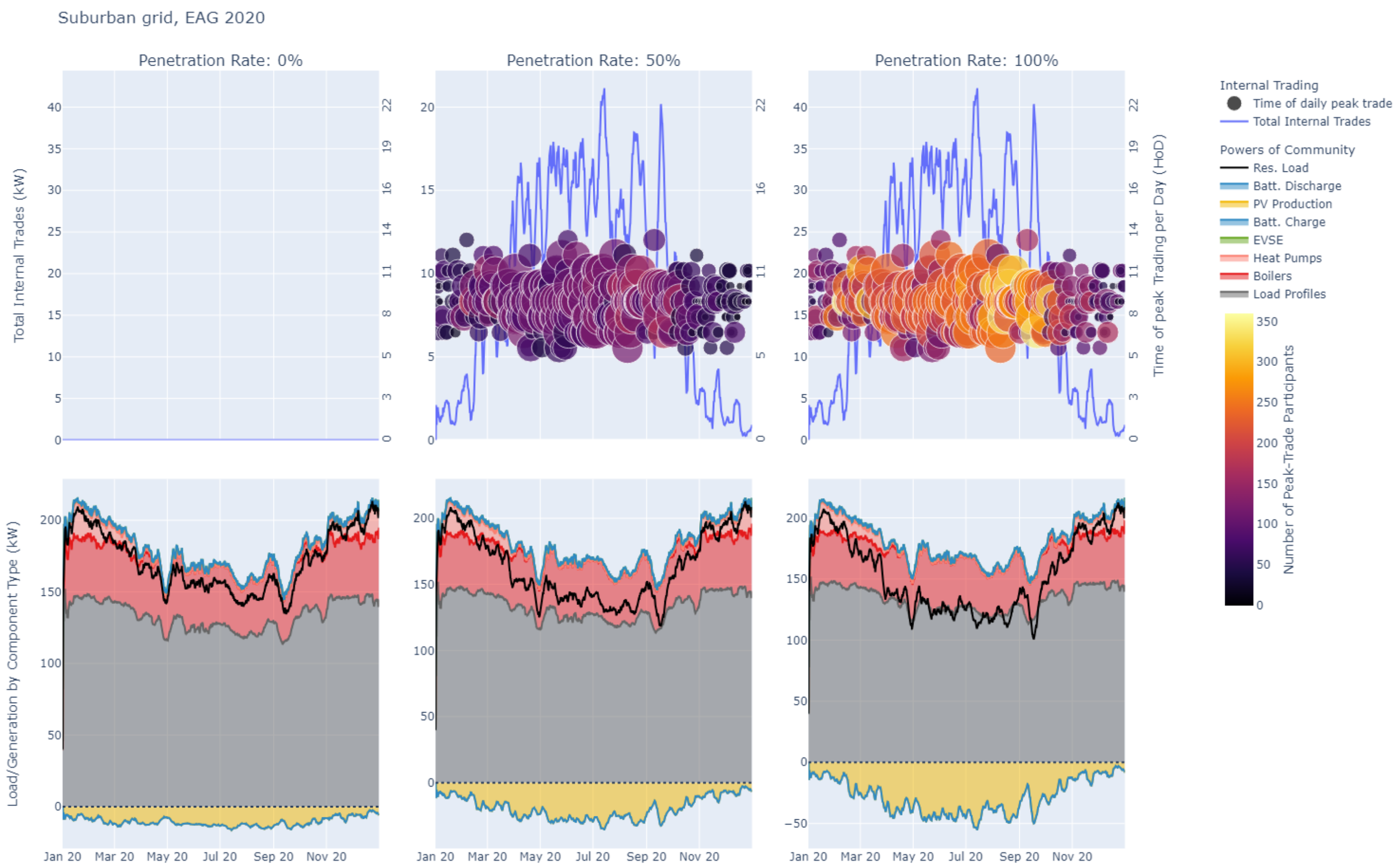

Figure C.6.: „**Suburban, EAG 2020**“: Community penetration rate sensitivity analysis with the aggregated yearly community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

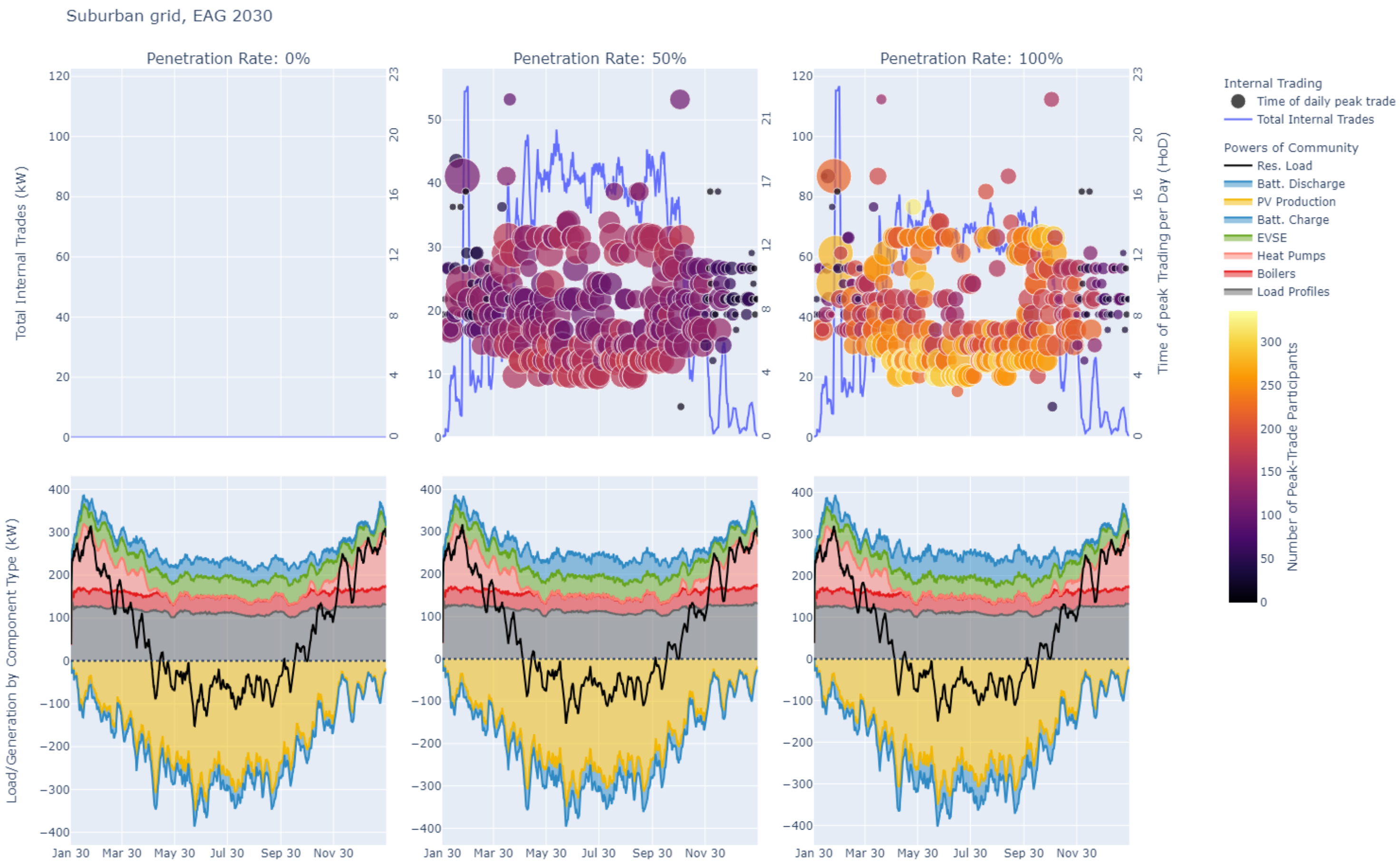

Figure C.7.: „**Suburban, EAG 2030**“: Community penetration rate sensitivity analysis with the aggregated yearly community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

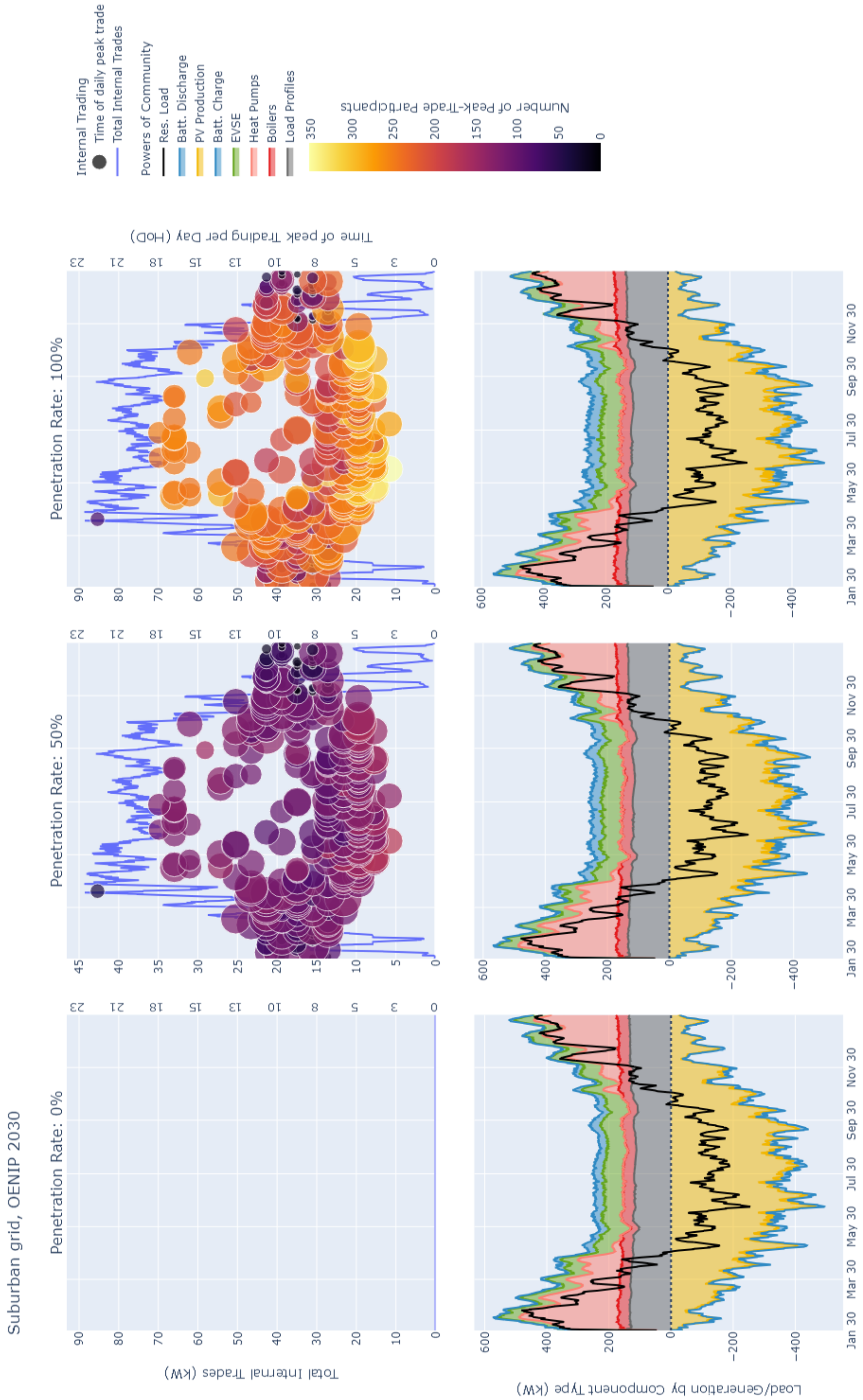

Figure C.8.: „**Suburban, ÖNIP 2030**": Community penetration rate sensitivity analysis with the aggregated yearly community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

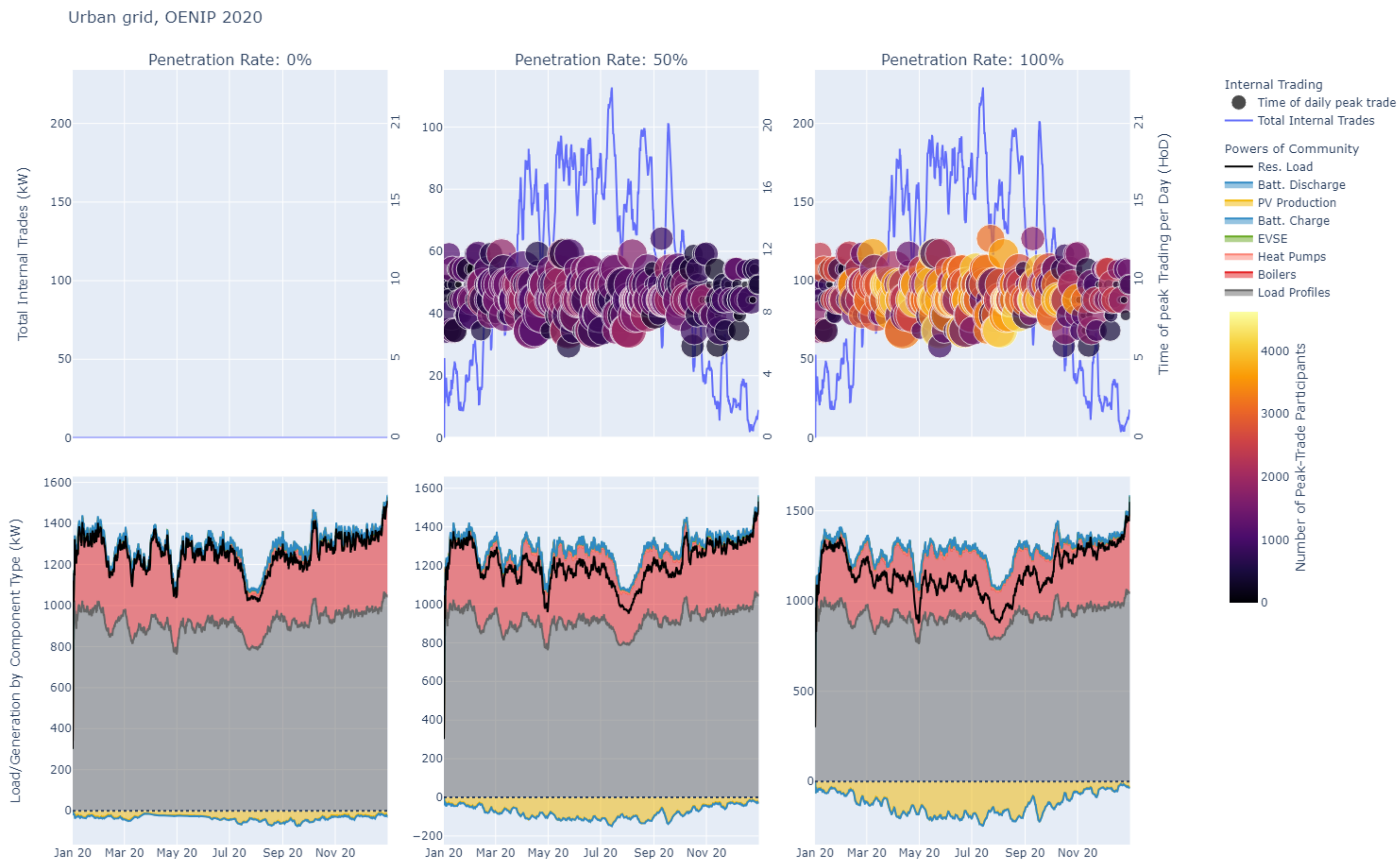

Figure C.9.: „**Urban, ÖNIP 2020**": Community penetration rate sensitivity analysis with the aggregated yearly community-internal trading (with a rolling average of 1 Week) with the times (HoD) of the highest daily trading, sized by highest tradings magnitude and colored by the participating members on the second y-axis. Also, the aggregated sources and sinks of powers alongside the residual load are shown (again, with a rolling average of 1 Week).

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