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SoloGrid

Experiences and results of a field project with GridSense, an intelligent, decentralized energy managing system

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Abstract

The SoloGrid lighthouse project showcases the effectiveness of the GridSense load management technology for a residential neighbourhood, the Riedholz pilot grid area, under real-life operation conditions, including a full-year measurement and analysis campaign. The effectiveness of the GridSense technology was validated by a mix of measurement and simulation data based performance analyses. Altogether more than 40 different full-year grid scenarios with future challenges (PV, heat pumps) as well as grid upgrade options (OLTC, conv. line upgrade) have been modelled, simulated and analysed. The validation shows that GridSense is effective in reducing local load demand as well as local production peaks and thereby significantly improving voltage quality in stressed low-voltage distribution grids.

The GridSense load management solution has a similar or even slightly better grid-stabilizing effect than a comparable conventional grid upgrade and performs significantly better than today's still dominating demand response technology – ripple control. It would indeed be conceivable that the GridSense solution could in the future become a better performing substitute for traditional ripple control technology.

Zusammenfassung

Anhand des SoloGrid-Leuchtturmprojekts konnte die Effizienz der GridSense-Lastmanagementtechnologie in einem typischen Wohngebiet, dem Riedholz-Pilotnetz, unter realistischen Bedingungen über ein volles Betriebsjahr evaluiert und validiert werden. Die Wirksamkeit der GridSense-Technologie wurde durch eine Mischung aus Messdaten- und Simulationsdaten-basierter Netzanalyse validiert. Im Rahmen der Simulationsanalyse wurden über 40 verschiedene Netzszenarien zukünftiger Herausforderungen, wie PV und Wärmepumpen, und möglicher Netzausbau-Optionen (RONT, Leitungsausbau) simuliert und analysiert. Die Validierung zeigt, dass GridSense eine effektive Lösung für die Reduktion lokaler Lastpeaks und damit indirekt auch für die Verbesserung der Spannungsqualität in stark belasteten Niederspannungsnetzen ist.

GridSense hat einen ebenso guten bzw. sogar besseren Effekt auf die Netzstabilität als der vergleichbare Netzausbau. Das Lastmanagement von GridSense verhält sich dabei deutlich besser als die heute dominante Rundsteuertechnik. Daher wäre es sogar denkbar, dass die GridSense-Lösung in Zukunft die konventionelle Rundsteuertechnik ablöst.

Résumé

Grace au projet phare SoloGrid, la technologie GridSense a pu prouver son efficacité et ce dans un quartier résidentiel typique, le réseau pilote Riedholz, et selon des conditions réalistes durant une année de fonctionnement. La validation de l'efficacité de GridSense a été effectuée par une combinaison d'analyses basées sur des données de mesure et de simulation.

Dans le cadre d'analyse de simulation plus que 40 scénarii différents ont été simulés et analysés tenant compte des futurs défis tel que PV et pompes à chaleurs, ainsi que les options de renforcement de réseau.

Le résultat principal montre que GridSense est une solution efficace pour réduire les pics de consommation mais aussi s'avère un moyen pour améliorer la qualité de tension dans des réseaux de basse tension surchargée.

GridSense a un effet comparable voire meilleur qu'un renforcement conventionnel du réseau.

Contents

List of abbreviations

API	Application programming interfaces
BC	Base case
DMS	Data Management System
DSM	Demand Side Management
EV	Electric vehicle
EVCD	Electric vehicle charging device
GS	GridSense
GSU	GridSense Unit
HP	Heat pump
HAN	Home Area network
OEM	Original Equipment Manufacturer
OLTC	On-Load Tap Changing
PLC	Power line communication
PV	Photovoltaic
SOC	State of charge
ToU	Time-of-Use Electricity Tariff

1. Project Setting

1.1. GridSense – the new approach

1.1.1. Motivation

The prevalent deployment of residential photovoltaic (PV) installations, as well as the present electrification of the residential heating- and mobility sector implicate more and more instability problems in the electric distribution grid such as over- and under voltage events as well as grid overloading. The electrification of the heating sector is due to the increasing use of heat pumps and electric water heaters, the electrification of the mobility sector because of the growing penetration of electric vehicles. In order to avoid such grid issues, SmartGrid technologies exist such as On-Load Tap Changing (OLTC) transformers, and conventional methods are used such as curtailing PV production or grid and transformer reinforcement and expansion. The necessary additional investments into the Swiss distribution grid for the energy transition are estimated to be CHF 12.7 billion until 2050, depending on the amount and distribution of the installed energy production plants and type of grid expansion (BFE Strategie Stromnetze) [1]. Additional investments of approximately CHF 1.3 billion are ear-marked for ICT measures (smart metering, other sensors and grid intelligence).

To prevent such high investments, InnoSense is developing the product GridSense. GridSense proposes an innovative energy management concept. The GridSense technology provides a decentral intelligence in the households, which smooths the load curve by displacing flexible loads (such as electric boilers, heat pumps and charging stations for electric vehicles), leads to a voltage friendly behavior of the household devices, reduces over- and under voltage events and consequently minimizes grid investments.

In the context of the transforming energy system, new players will enter the market and energy suppliers will offer new services. The GridSense solution facilitates the creation and integration of such new services like energy monitoring and automatic Demand Side Management (DSM). It has several advantages: For households, costs can be reduced. For prosumers the on-site utilization of self-produced PV electricity production can be maximized. According to the different applications and purposes of the GridSense solution, it comprises of several optimization modes, as described in the following sections.

1.1.2. Concept description

In contrast to other voltage control technologies in households such as e.g. reactive and active power control of PV inverters or the use of grid supporting batteries, GridSense provides a manufacturer-independent solution. The GridSense system architecture – corresponding to the state-of-the-art version used in SoloGrid – is illustrated in Figure 1.

The lowest level of the system represents the field which consists of the following household devices: PV plant, heat pump (HP), electric boiler, house battery (batt) and electric vehicle charging device (EVCD). Hardware, firmware and algorithm are locally installed at or in these devices, which are connected via power line communication (PLC) to the internet and therewith to the data management system (DMS). By corresponding application programming interfaces (APIs), external data such as meteorological forecasts (global irradiance and outside temperature) and electricity tariffs are communicated to the devices and data, e.g. energy production and consumption (recorded data and forecasts), can be accessed via DMS by the distribution grid operator using an admin user app or by end-users using a mobile app. In case of the charging station, the end-user can even control it actively.

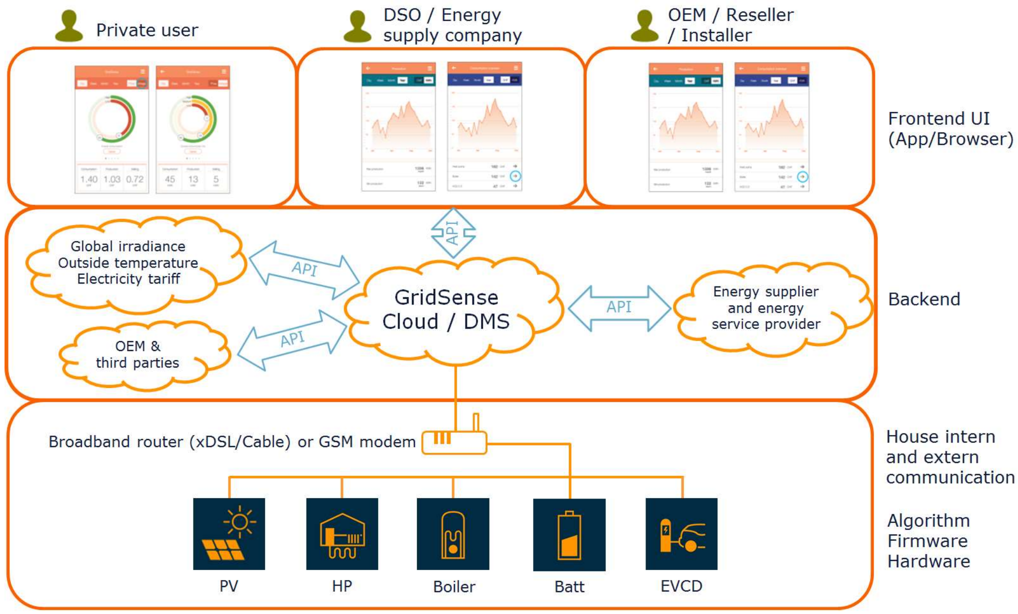


Figure 1 – GridSense system architecture. In the following sections, the different layers and components of the GridSense system are illustrated in detail.

Field Devices

GridSense can be installed within the following household devices: PV plant, heat pump, electric boiler, house battery and electric vehicle charging device. The GridSense logic can run either on the GridSense hardware or directly embedded in the controller of an OEM partner's device. In case of the GridSense hardware, this is locally installed at the device. The communication with the data management system (DMS) is based on the https protocol. Through Webservices (Rest API), external data (meteorological forecasts and electricity tariffs) as well as device and system configurations are communicated to the field devices. In the other direction, measurements data, energy production and consumption forecasts, alarms and other parameters are sent to the DMS.

The GridSense Unit (GSU) is depicted in Figure 2. It measures electrical parameters such as voltage, current, frequency and cosphi, calculates energy needs and production forecasts, and according to the best possible scheduling it controls the household device decentral and autonomously.

There are three different options of implementing the GridSense algorithm in the device:

1) The *Plug.On* represents the retrofit solution if no further integration is possible.

2) With the *Plug.In* solution, the GridSense hardware is integrated into the device, communicating directly with the appliance's controller.

3) The GridSense Application logic can also be implemented directly into the control unit of the connected device as a software library.

The GridSense unit is installed between the controlled appliance, e.g. the heat pump, and the power supply, through which it communicates in the Home Area network (HAN) by means of Powerline Communication (PLC). This method allows a simple and cheap installation. The GridSense connected appliances are actively controlled by means of digital outputs (relays) or via Modbus TCP/IP protocol over a standard Ethernet interface, depending on the level of integration, as described above.

Figure 2 – GridSense Unit with current and voltage measurements, power supply, keys and indicators.

Algorithms and optimization modes

As mentioned above, the algorithm runs decentral in the GSU and controls the connected household appliances. Every component is modelled and considers device specific operation and comfort constraints. State variables can be learned by the algorithm itself and no corresponding inputs are required but can be communicated optionally via user app. Voltage, current, active and reactive power, frequency as well as the impedance are detected for each GridSense component. The GridSense algorithms forecast the next 24 hours of the following profiles: PV production, energy consumption of heat pump, boiler and electric vehicle charging device, and the voltages of each component. The algorithm learns regularities such as absence and habits of end-consumers or building-induced shading of the PV installation using historical data. The 24 hours forecasts are generated by considering the past, current measuring data as well as weather forecasts. Based on the energy need forecast of boiler and electric vehicle charging device, the state of charge (SOC) of these two devices is forecasted as well. The computed forecasts are revised every five minutes by up-to-date inputs. Based on the different forecasts and the electricity tariff (if required by the optimization mode), the algorithm determines the load flexibility and in dependence of the configured optimization mode, it decides for each device when load should be energized or inhibited in the next 24 hours. Also, the schedules are revised every five minutes by up-to-date inputs. The 24 hours forecasts allow for an intelligent and adaptive scheduling of the loads and distinguish the optimization procedure from pure reactive optimization concepts.

Currently, the GridSense solution comprises four different optimization modes:

1) grid optimization mode,

2) consumer cost reduction mode,

3) hybrid mode, and

4) self-consumption mode.

The self-consumption mode implies communication among the GSUs within a household and includes a so-called coordination mechanism. Modes 1–3 can run with or without a coordination mechanism.

1. Grid optimization mode. This optimization mode aims at reducing over- and under-voltage events as well as grid overloading, i.e. of lines and transformers. This operation mode avoids otherwise necessary high grid investments. Due to the correlation between active power and voltage in the low voltage grid, the loads are scheduled as a function of the locally measured voltage profile. During low voltage periods the loads are reduced so that the voltage is increasing again. Vice versa, the loads are increased during high voltage periods in order to lower the voltage again. Curtailment of PV production is explicitly avoided.

2. Cost reduction mode. This mode reduces costs for the end-consumer (without own decentral production) by considering the electricity tariff. The cost reduction mode (without coordination) is useful for Time-of-Use (ToU) electricity tariffs, i.e. non-flat tariffs such as high/low period tariffs typically used in Switzerland. This optimization logic supports already future more dynamic time-of-use tariffs.

3. Hybrid mode. The hybrid mode combines the cost reduction mode with the grid optimization mode, where the cost reduction has priority over the grid optimization. The hybrid mode (without coordination) is useful for ToU electricity tariffs.

4. Self-consumption mode. The target in this optimization mode for prosumer households (with own decentral electricity production) is to maximize the on-site utilization of self-produced energy by scheduling relevant loads during convenient timeslots, i.e. when an energy surplus is available, and thus minimizing the injection of self-produced energy into the grid. This optimization requires communication among the devices within the household, also called coordination mechanism.

Data Management System (DMS)

The Data Management System (DMS) consists of scalable database- and application servers. Data communication between DMS and field devices is encrypted and satisfies all relevant security requirements. The management system is operated with SaaS (software-as-a-service) and does not need any software installation at customer level.

The DMS frontend comprises of two different applications:

- The admin web app for system operators, installers and OEM partners
- The mobile app for end-customers

Admin web app

The clearly structured and user-friendly admin web application is based on the latest standards and can be operated with tablets as well as desktop PCs. Operators (Grid Operator, Energy provider, Installers or OEM Partners) receive an administrator account with which they can log in and administrate their own users and customers. In Figure 3, a snapshot of the admin web app (device views, PV Production data in the example) is depicted. The following main functionalities are available for operators and installers in the admin web app:

- Master Data Management: With the help of master data management, end users, households and GridSense devices can be recorded and administered. The operator always has an up-to-date view of his entire system.
- System configuration: With the help of the system configuration the installed GridSense devices can be configured.
    - Selection of the algorithm optimization mode
    - Activation /deactivation of the GridSense algorithms
    - Activation / deactivation of users/devices
- Remote maintenance and support: following functionalities are possible.
    - Monitor the status of GridSense units (online / offline)
    - Retrieve alarm and warning messages
    - Download new firmware versions
- Alarm management: A system message can be used to quickly identify the issue. Alarms can be listed and acknowledged as soon as they have been triggered. GridSense supports three classes of events: Alarms (e.g., failures), Warnings (e.g., timeouts) and Notifications.
- Visualization of measurement data: The fully integrated measurement data visualization allows the display in several time resolutions from 15min to 1day (depending on the selected time window) of the following measurement data: Power for a single device or a group of devices, Energy for a single device or a group of devices, State of Charge (SOC) for the batteries.
- Export of measurement data, in several time resolutions from 1min to 1day averages) of the following measurement data: active and reactive power, voltage, current, frequency.
- Commissioning of field devices the commissioning of GridSense devices is very simple and efficient. After the electrical installation, only a serial number has to be transferred to the management system. The web application can be used with a commercial tablet as well as with a notebook, if it is connected to the Internet. With the help of LEDs on the GridSense unit, the installer is also informed about the success or failure of the communication connection in cases where the Internet connection is not established.

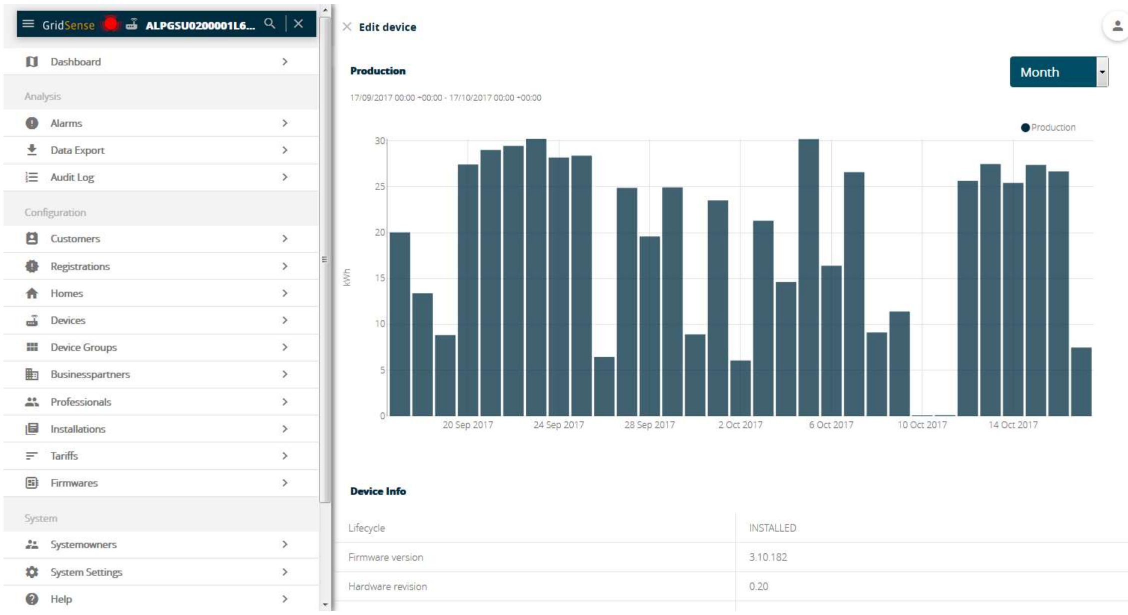


Figure 3 – Device view in the DMS Admin web app (Monthly production data for a PV device).

Mobile app

The GridSense app for householders is available for Apple and Android devices and can be downloaded from the corresponding app stores. In Figure 4, snapshots of different mobile app's views are depicted. Following information can be displayed for the selected time interval:

- Energy consumption and energy production
- Autarky: percentage of used own produced energy versus overall consumption
- Self-consumption: Percentage of total produced energy versus consumption
- Cost Distribution: indicate the costs according to the consumed energy

In more, the mobile app offers following functions to the end-user:

- Enter the desired departure time for electric vehicles. If a charging station is connected to the GridSense household, the app can always display the departure time calculated by GridSense. If the electric vehicle is needed earlier than planned, this can be manually overridden.
- Edit personal information: the end-customer can change personal data independently.

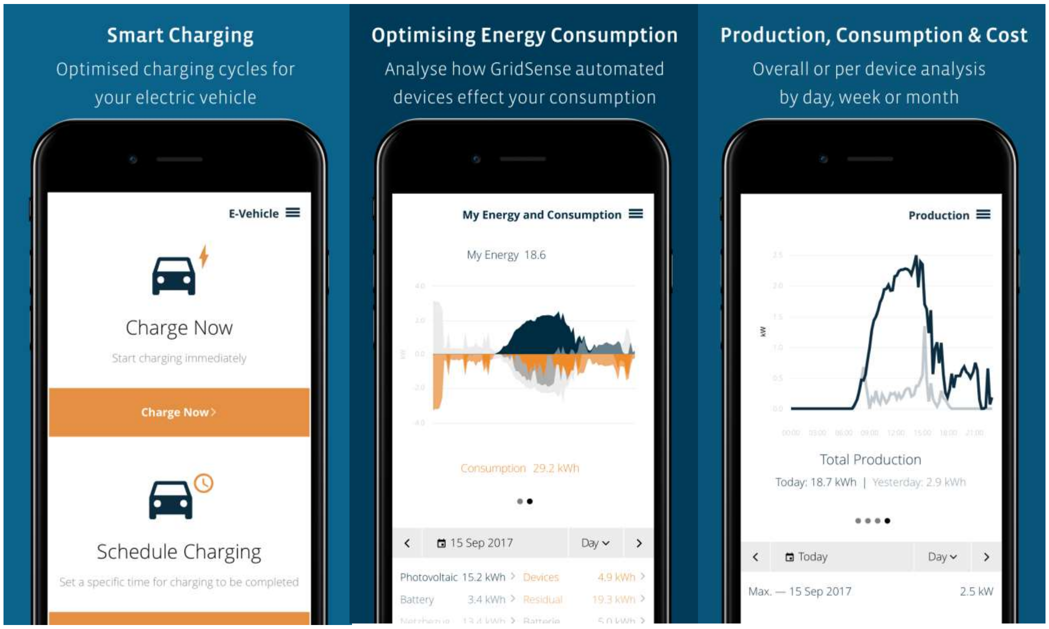


Figure 4 – Snapshots of different mobile app's views (autarky grade, consumption and cost report).

1.2. Project motivation

The SoloGrid project in Riedholz was launched in order to

- gain experience with GridSense regarding installation, operation and effectiveness in a representative field application
- collect, complete and share system know-how with several qualified and experienced partners
- To benchmark GridSense with other technologies (OLTC, grid extensions)
- create a win-win situation as part of a BFE lighthouse project with open communication and information exchange

A combination of Alpiq as electricity and energy services provider as well as GridSense product owner, AEK as utility and therefore grid responsible and potential customer, Adaptricity as specialist for grid simulations and data analytics as well as Landis+Gyr as smart meter provider, sponsored by the Swiss Federal Office of Energy (SFOE) and the canton of Solothurn, showed the most promising conditions regarding know-how, synergies and results.

1.2.1. **Product status before the project**

Prior to the project, soft- and hardware had been tested and optimized as far as possible and pre-series had been installed to gain first experience with the installation and operation process.

Nevertheless, the product had not yet been demonstrated or applied on large-scale field installations, with corresponding customer feedback and effects on larger grid areas. In addition, no simulation results had been available so far, as such information depends on an integration of the GridSense algorithm into the simulation model, a calibration of the simulation model with large-scale measurements as well as a refinement of the model by entering the building structure and including energy consuming components as heat pumps, boilers, electric vehicles or the like. Another white spot of missing information had been related to the boundary conditions, like temperature, user behavior, grid topology or the like, and their interdependencies with GridSense units and technical components on a large scale and under real conditions.

Following this, one major goal of the SoloGrid project was to lift the GridSense technology from a "prototype" to a "ready-to-market" level.

1.2.2. Why an SFOE lighthouse project

The setup and scope of the SoloGrid project has clear overlaps with the scope of the proposed energy transition policy agenda (Energiestrategie 2050) of the Swiss government.

Testing the GridSense Demand-Side Management (DSM) technology, which proposes to improve grid integration of Renewable Energy Sources (RES) while reducing stress on distribution grid infrastructure, in a realistic setting is in line with the implementation of the Swiss energy transition.

The results and learnings that would be the outcome of this pilot project would not only be beneficial for the involved project partners, e.g. testing and refining new products and building up expertise. It would also be beneficial to the public community as the project showcases how the existing grid infrastructure can be utilized more efficiently in light of the new challenges from the energy transition (PV production, heat pumps and electric mobility).

Realizing such a large-scale pilot project with all the associated risks would not have been possible for the project partners without financial support from R&D budgets.

This was the motivation of the project partners to apply for the SFOE 'lighthouse' status in order to better publicize the project results and the capabilities of the GridSense technology both in Switzerland and abroad.

2. Project goals

The overall project goals were related to the marketability of GridSense as a product, especially regarding the functional effectiveness and customer acceptance, as well as to the interaction of smart technologies.

Therefore, the project provided answers for the following aspects of the GridSense technology:

- What are the effects of GridSense on grid loading, self-consumption share and reducing electricity cost, according to the different operational optimization modes?
- Under what conditions and for which use-cases does GridSense show the biggest effect?
- Up-scaling and scenarios for the future electric grid
- How reliable and robust is the GridSense technology?
- Technical and financial benchmarking with both conventional grid upgrades as well as with other alternative voltage supporting technologies, such as tap-changing transformer and PV curtailment.

The project results to the above stated project goals can be found in detail in the results section as well as in the conclusions of this project report.

In addition, an open communication and information exchange was considered as project goal and therefore planned, executed and tracked specifically.

3. Project description

3.1. Challenges

The project was split into the phases “Installation”, “Operation and Measurements”, “Simulation”, “Analysis & Conclusions” and “Communication”. Whereas most of these tasks were self-explanatory, the execution of the measurements as well as the analysis of the measuring data and the conclusions from the simulations required further evaluation.

Two basic questions had to be answered:

- What configurations do we measure and simulate in which sequences?
- Which of the measured and simulated effects can be clearly attributed to GridSense activation?

Because a measurement can only be carried out once and the boundary conditions are changing constantly – sometimes with more effect on the system, i.e. the distribution grid, than the GridSense activation itself – the tests and simulations had to be planned with maximum flexibility with regard to the later data analysis.

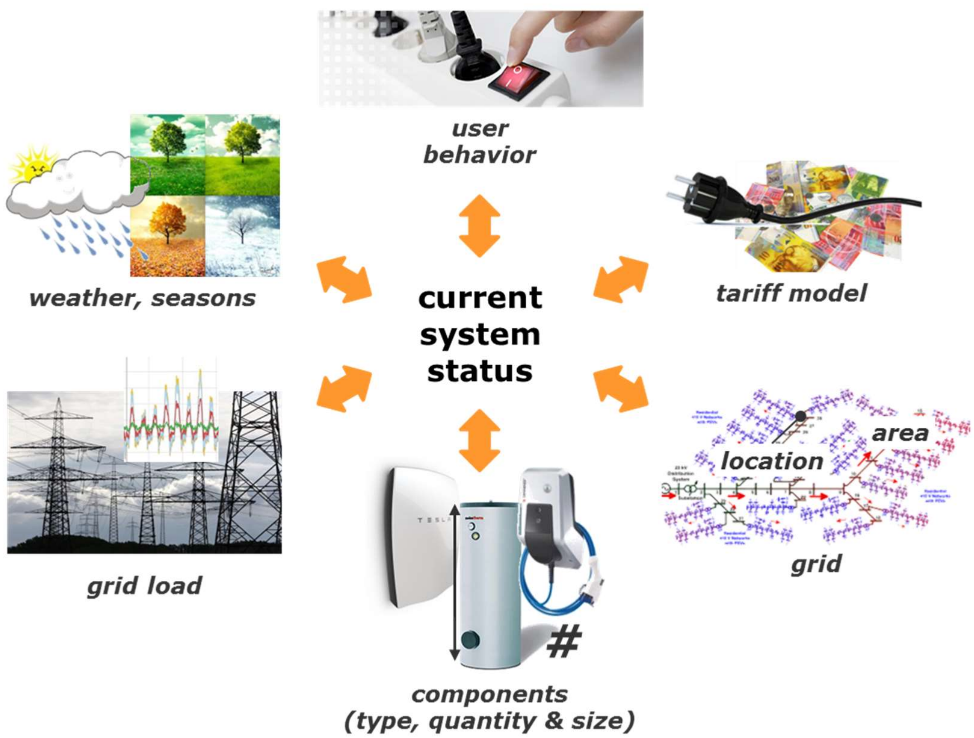


Figure 5 – Boundary conditions that affect the current system status.

When planning the measurement and simulation setups, some key decisions with effects on the analysis results had to be taken:

- Reference measurements: When (continuously or in blocks), in what households and how (with or without ripple control) shall they be carried out?
- What are realistic component combinations and variations regarding sizes and quantities?
- What is the validity of results directly depending on the assumptions made, e.g. effectiveness of e-mobility resulting from assumed loading profiles?
- What values shall be used as "results": EN 50160 (voltage violations), cable loads, others?
- How to judge opposing results, e.g. RONT effects on voltages and grid load?

3.1.1. Basic approach

In order to deal with the above-mentioned questions and challenges, the test and simulation plan, Figure 7, was set up as follows:

- The tests were categorized in functional tests (works/works not), effectivity tests (effect, potential), effort-benefit tests (features and functions) and comparisons with alternative technologies (benchmarks).
- The sequence of the major topics was aligned with the priorities and the necessary knowledge build-up.

Figure 6 – Sequence of major topics.

These major topics were then divided into so called test cases, which represented important questions to be answered for technical as well as sales and marketing reasons. Subsequently these test cases were split up again into specific measurements and simulations.

Test Case			Specific test / simulation			Influences				Konfiguration								Evaluation		
						Season				GSU's		Opt. mode			Tariff					
No.	Description	Aim, result	No.	Description	Indicators	Spring	Summer	Fall	Winter	activated	obs. mode	grid	cost	self-cons.	flat	high / low	dynamic	State	Illustration	Result

Figure 7 – Setup of the test and simulation plan.

3.1.2. Measurements

The original approach of using 3 to 5 suitable households for permanent reference measurements (so called baseline) had to be dropped, because such a baseline behavior would have had to be measured on another line within the local grid in order to compare the system behavior with and without GridSense. Therefore it was decided to run all households with the same operational mode (grid or cost) in parallel. Only households with home batteries were running in self-consumption mode. Therefore, alternating measuring blocks were chosen according the principle shown below (Figure 8).

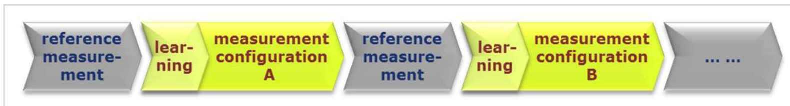


Figure 8 – Alternating measuring blocks.

This resulted in the following continuous test plan (October 2016 to September 2017):

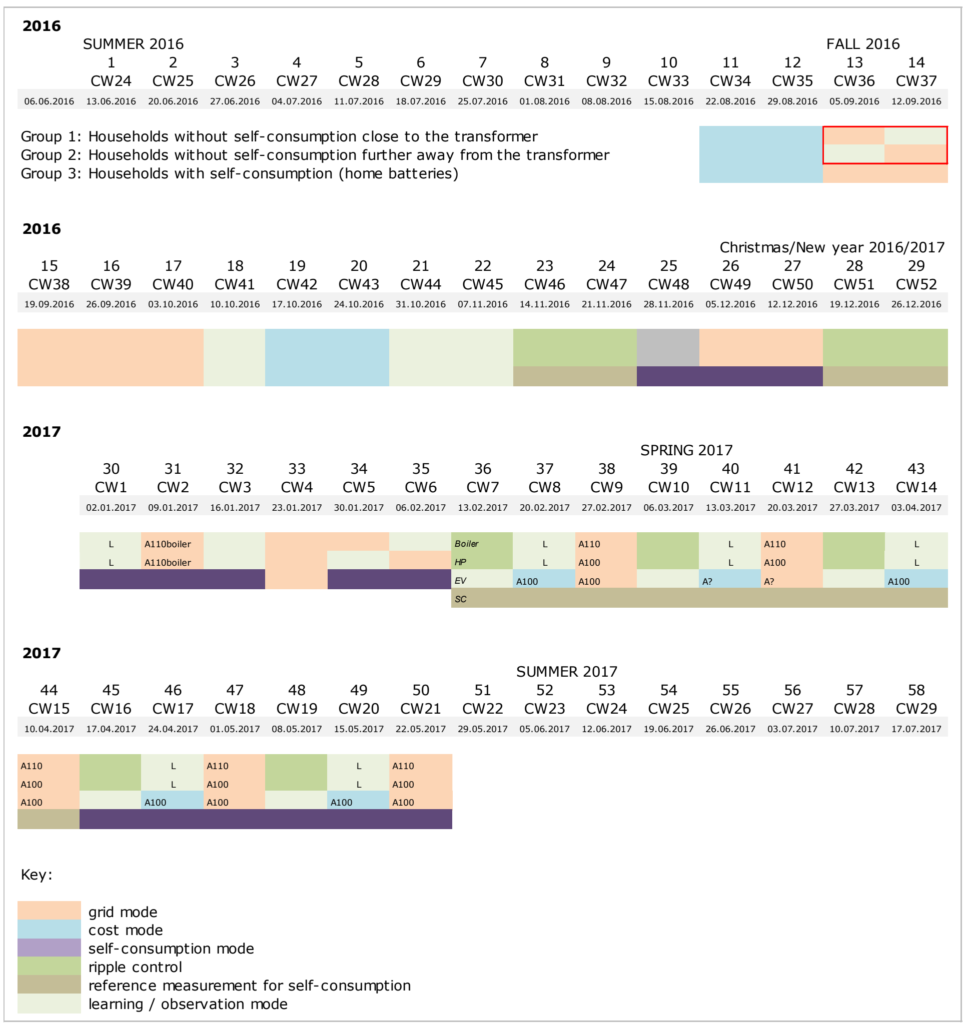


Figure 9 – Test plan extract.

3.1.3. Analysis of the measurement data and conclusions from the simulations

In order to evaluate the product effectiveness, to obtain clear results from the measurements and to draw the right conclusions from the simulations, the data comparability turned out to be one of the biggest challenge. Not only the boundary conditions had to be taken into consideration, but also the analysis of the gained data had to be chosen carefully in order to evaluate the right effects.

As an example, the time dependency of the energy consumption and production as well as the user behavior had to be considered when doing the arithmetic averaging, because they vary over:

- A day: Day/night, morning/noon/evening, ripple control times
- A week: During the week / specific days / weekends
- (School) vacations, holidays
- Seasons: Summer, winter, spring/fall

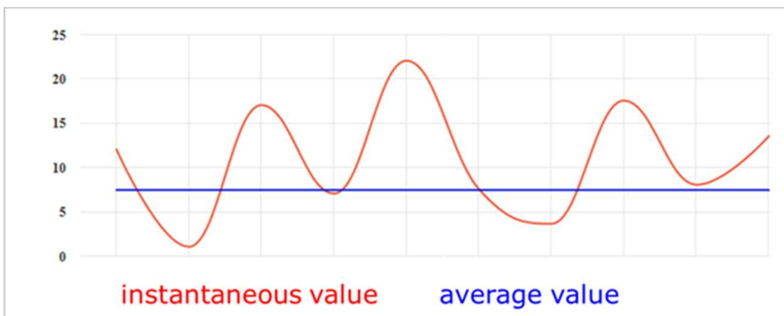


Figure 10 – Different mean values show different results.

Besides the directly measured values, further processed data has to be used as well for evaluation and communication reasons (Figure 11):

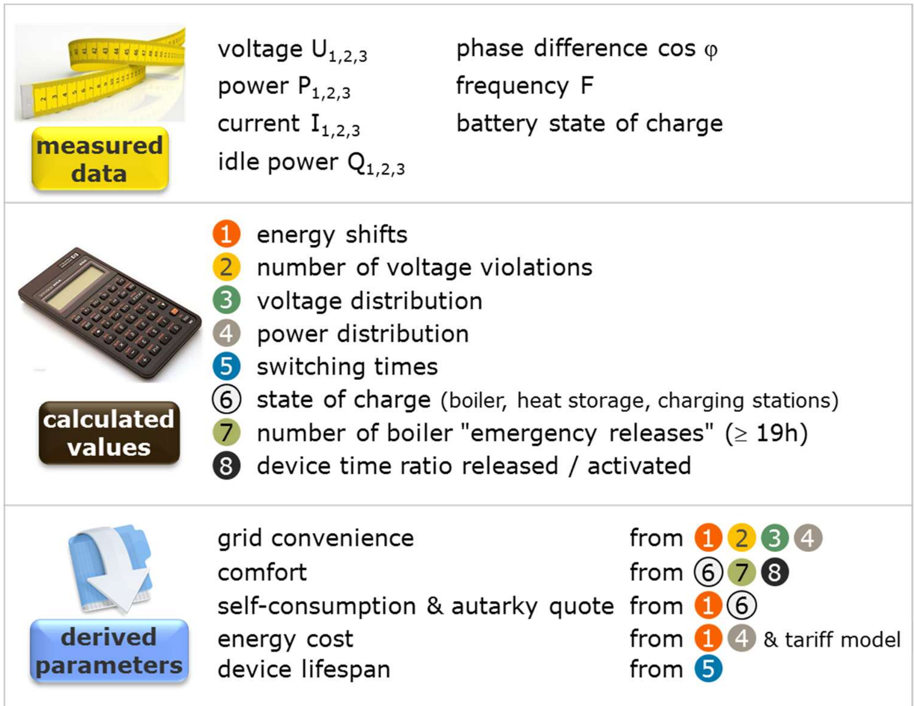


Figure 11 – Overview of Measurement Data and principle Analysis Questions.

3.2. Selection of suitable pilot grid area

(Due to potentially differing view-points and foci the project partner statements are separated here.)

AEK Energie AG

Several different indicators were important for selecting an appropriate distribution grid as pilot grid area for the SoloGrid project.

The pilot grid area should already contain significant installations of switchable thermal loads, such as hot-water boilers and heat pumps, as well as photovoltaic units. This should already lead to measurable voltage problems according to the voltage norm EN 50160 with the need for a conventional grid upgrade.

Exactly these constellations were found in the Riedholz community. Furthermore, due to its location in the south-facing Jura foothills, there is a large potential for additional photovoltaic installations. Indeed, during the project phase, local PV capacity nearly doubled from four to seven installations.

InnoSense

From the InnoSense side, the main requirements and characteristics to be considered for the selection of the appropriate pilot area were the following: a distribution grid with already many decentralized PV plants that was already suffering from over- and under voltage problems; the majority of the households equipped with flexible and interruptible loads (heat pumps and electric water heaters) and located within the same low-voltage line (feeder); house owners generally affine to technology, ready to personally try out new optimization solutions and proud to be part of an innovative demonstration project with a pioneer role.

The region of Riedholz was found and quickly proved to satisfy all the defined prerequisites. Riedholz is a political community near Solothurn, the canton's capital.

AEK as the electric utility of the Solothurn region is responsible for the overall distribution grid operation and management. The completely residential neighborhood (Figure 12) consists of about 56 households, both single- and multi-family houses, all connected to one transformer feeder, i.e. a transformer unit (secondary substation) with an apparent power of 400 kVA. The majority of households possesses heat pumps and electric water heaters. From the 56 households connected to the selected feeder, 35 have GridSense installed for the project duration.

The goal to obtain a relevant penetration of GridSense, allowing the control of the majority of flexible loads in the distribution grid was thus achieved. Here it is important to underline, that the region is completely residential, without any commercial or industrial loads (no loads >10kW).

Figure 12 – Riedholz pilot region (GIS viewer).

3.3. Installations in distribution grid area

3.3.1. **Household installations**

Table 1 summarizes all the households with the corresponding appliances where GridSense has been installed for the SoloGrid project. From the overall 35 households, only 2 (AEK12/13 and AEK_30 are multifamily houses, while the other are all single-family houses. The combinations of different GridSense households' configurations are depicted in Figure 13.

In every house a GridSense unit was installed at the house connection point (Main) in order to measure or readout from the existing meter the overall power flows to and/or from the house. Every household was already equipped with an electric boiler (except from AEK_07 which is equipped with a combined heat pump providing also domestic hot water). Altogether 23 households are equipped with heat pumps. The majority of these are air/water-heat pumps, except for AEK_21 which is a brine-water heat pump, and was not controlled by GridSense because of the low power rates and the special functioning patterns.

All the electric water heaters and the heat pumps were already switched off during constant and pre-configured time intervals (boilers mostly daytime, heat pumps only during midday time) via the ripple control signal of the power utility. Several roof-top solar PV plants were already installed in the households prior to the project (four before the start, while three more were added during the project, as depicted in Table 1).

Out of these, three households (AEK_30, 34 and 38) were selected as candidates for testing the newly developed GridSense self-consumption mode, and were thus equipped with a battery system to increase the usage of self-produced energy. In the scope of the SoloGrid project, also five private charging stations for electric vehicles were additionally installed in some of the participating households, in order to increase even more the flexibility in the network and to test the specific operational behavior of these novel power system unit types under GridSense control. The five electric vehicles (BMW i3) were made available to the house owner by the SoloGrid Project. Two electric vehicles changed the user during the project (the charging stations of AEK_7 and AEK_23 – depicted in yellow in Table 1 – were installed after the first project year at AEK_39 and AEK_40 respectively).

Overall, 103 GridSense units were installed, thereof 64 were actively controlling a house appliance. Here some additional details about PV plant, battery and charging station installations:

- Installed PV plants are all 3-phases and have a nominal power between 4.8 and 10 kW_p.
- Rated power and capacity of the installed battery systems are between (2.4kW / 4.5kWh) and (6.4kW / 12kWh). All the batteries systems are 3-phases.
- The charging stations with integrated GridSense control functionality are all 1-phase and allow to charge an electric vehicle up to 16A (3.5kW).

Table 1 – List of the households with corresponding appliances monitored or controlled by GridSense.

	# total amount of installed GridSense devices							
	35	34	21	3	3	5	101	
House Name	**Main**	**Boiler**	**HP**	**PV**	**Battery**	**EV**	**#GSU operational**	**Notes**
AEK_01	1	1		0			2	PV not monitored
AEK_02	1	1	1				3	
AEK_03	1	1					2	
AEK_04	1	1	1				3	
AEK_05	1	1					2	
AEK_06	1	1	1				3	
AEK_07	1		1			0	2	WP-Boiler Combi system, no control
AEK_10	1	1	1				3	
AEK_11	1	1	1				3	
AEK_12	1	1	1				3	
AEK_13	1	1					2	
AEK_15	1	1	1				3	
AEK_16	1	1	1				3	
AEK_17	1	1	1	0			3	PV not monitored
AEK_18	1	1	1			1	4	
AEK_19	1	1					2	
AEK_20	1	1	1	0			3	PV not monitored
AEK_21	1	1	1			1	4	No HP control
AEK_22	1	1	1				3	
AEK_23	1	1	1			0	3	
AEK_24	1	1		0			2	PV not monitored
AEK_25	1	1					2	
AEK_26	1	1					2	
AEK_27	1	1					2	
AEK_29	1	1	1				3	
AEK_30	1	1	1	1	1		5	
AEK_31	1	1					2	
AEK_32	1	1	1				3	
AEK_33	1	1					2	
AEK_34	1	1	1	1	1	1	6	
AEK_35	1	1					2	
AEK_37	1	1					2	
AEK_38	1	1	1	1	1		5	
AEK_39	1	1	1			1	4	EV not from beginning
AEK_40	1	1				1	3	EV not from beginning

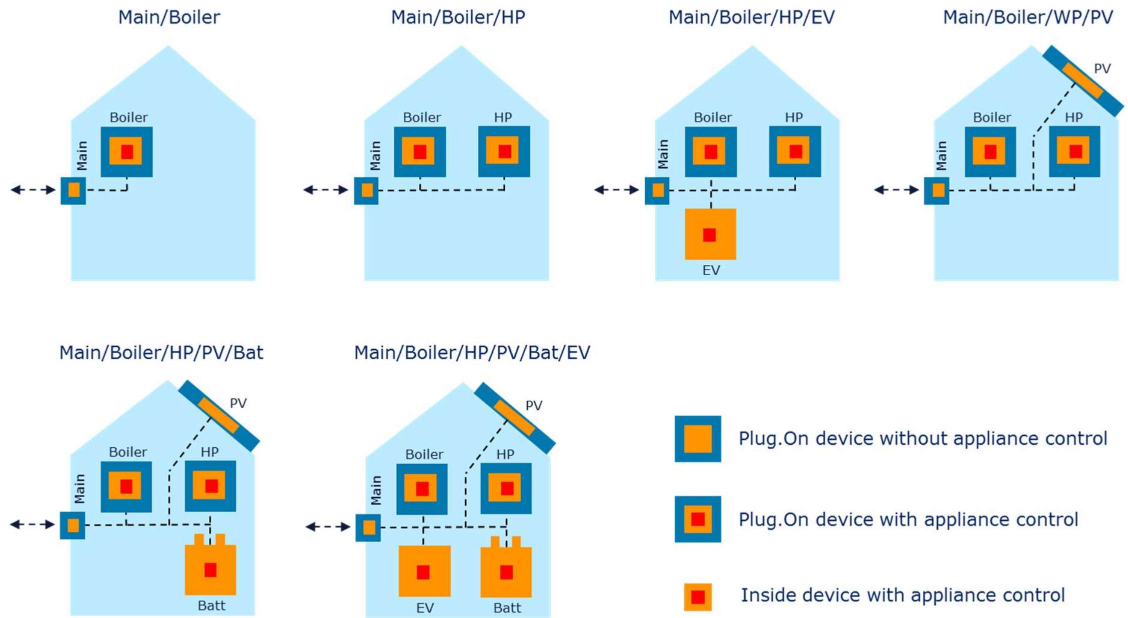


Figure 13 – Visualization of the different GridSense household configurations.

3.3.2. Measurement equipment

GridSense Units

For electric data measurement and appliance control, the GridSense hardware presented in Chapter 1.1.2 was used. According to the GridSense standard system architecture, one GridSense unit per appliance was installed. Every unit is connected to the internet and communicates with other GridSense devices in the Home Area Network via PLC (powerline communication) using the existing electric network. The access to the WAN (Wide Area Network) is provided either by the home internet connection or by a dedicated GSM solution, e.g. 3G modem, which are connected to a PLC-Ethernet adapter, as described in Chapter 1.1.2.

Landis+Gyr smart meters

The E350 meter is a standard product from Landis+Gyr. Its modularity makes it a smart meter-ready counter. In the AEK Energie AG supply area, it has been used for a long time as a standard household meter for billing consumer energy consumption by end users and satisfied the legal requirements according to METAS. This meter is installed in every household participating in the SoloGrid project.

The characteristics of the E350 meter of Landis+Gyr are listed here:

- Type: ZMF 120 ACtFs2 (E350)
- Voltage: 3 x 230/400V
- Frequency: 50Hz

- Current: 0.5 – 10 (80)A
- Cl.: A
- Measurement data has 2-3 seconds resolution:
- 4 Energy quadrants (Active and reactive power, supply and delivery)
- Phase voltages
- Phase currents
- Phase angle
- Instantaneous power
- Frequency

The first idea in the project definition phase was to integrate GridSense directly in the meter as a software library, making thus the meter "smart". This was unfortunately not possible because of the high invasive nature of the needed integration. It was decided to develop a dedicated USB interface in the GridSense unit to allow the read-out of the main meter data through the optical interface of the E350 (compliant with the IEC62056-21 standard).

The scope of this interface is to allow the GSU to acquire the information from the meter and make the information available for the other GridSense units within the same household through a so-called "co-ordination mechanism" and for the GridSense backend system (DMS). Figure 14 illustrates the complete system setup: The electricity meter which gathers the data, the USB optical interface for the data readout, the GSU acting as a USB host and the GridSense DMS where the relevant data are stored. The USB FTDI interface converts the serial transmission data (RS232) of the optical interface into a USB compliant data stream.

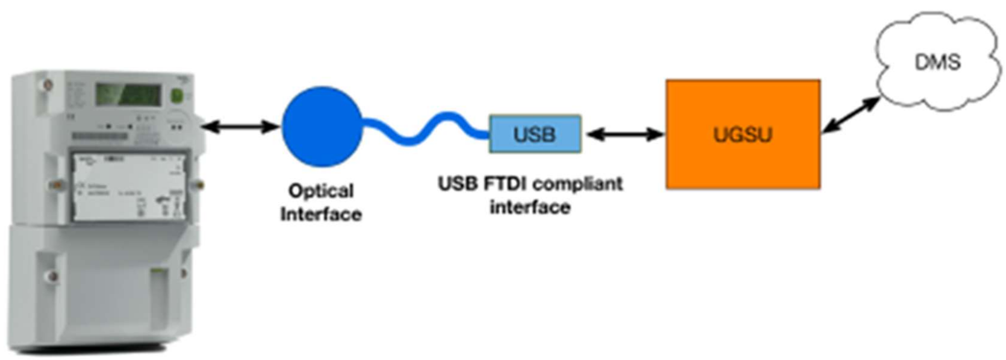


Figure 14 – System architecture for data readout from the L+G E350 electricity meter.

The GSU has been modified to integrate a Full Speed USB host A-Type interface. The hardware interface is compliant with the USB standard and delivers the necessary power supply for the optical interface used by the meter (TVS1). Optical interface vendors provide USB drivers for computer with OS like Windows or Linux but not for embedded devices. The GSU is an embedded device with a custom USB driver design to read the USB optical interface, so the needed drivers had to be specifically developed.

The main goals of gathering data from the electricity meter of Landis+Gyr and making them available via DMS are:

- Since in the standard architecture of GridSense no central measurement is foreseen, we wanted to assess the potential performance optimization with this additional data point, especially for the self-consumption optimization.

- Make electrical measurement data at the entrance of the house available for the simulations performed by Adaptricity (see Chapter 5).

- Integrate a gauged measurement within the GridSense ecosystem for future potential billing features.

Measurements at the transformer station

A S650 meter from Landis+Gyr, in combination with current transformers of type KBR 32 from the manufacturer MBS AG have been used for the measurement on the transformer (outlet TK22). This counter type fulfills the statutory requirements according to METAS and is used as a meter at end-user locations in the AEK Energie AG supply area. The required measured values were read out daily via GPRS with the meter readout AIM from Landis+Gyr. A data export of the measured values took place monthly for data analysis and validation of the simulation environment.

The characteristics of the S650 meter of Landis+Gyr are listed here:

- Type: SMA 410CT44.4207
- Voltage: 3 x 230/400V
- Frequency: 50Hz
- Current: 100/5A / 0.05 – 5 (6) A
- Cl.: 2
- Current transformers
    - Type: KBR 32
    - Primary current 400 A
    - Secondary current: 5 A
    - Frequency: 50Hz
    - Apparent ohmic resistance: 5 VA
- Measurements (1 minute average values)
    - Phase voltages
    - Phase currents
    - Phase angle

4. Results I: Learnings

4.1. Learnings from GridSense installation

The SoloGrid project has been the first real test bench to assess the suitability and complexity of the GridSense installations in a large-scale project. The learnings are extremely precious for product development and were used or will be used to implement correcting measures (both technical and operational) to improve installation performance and reduce installation time and costs.

Positive feedbacks

GridSense was perceived as an innovative project, and the customers were generally very interested in learning about the new technology. In the most cases, the GridSense technicians were very welcome when arriving for installation appointments. Already since the first on-site inspections, the house owners were fascinated and posed a lot of questions.

Learnings and difficulties

The process to plan an installation appointment with the customer was often challenging and time consuming, because some of them were on holidays or not reachable. For several customers, only after the second or third attempt we were able to find an installation date. In some cases, installations appointments could be planned only after 2/3 weeks or even had to be postponed. As a result, the installation timeline had to be stretched compared to the initial plan.

Although the installers have been accurately instructed on how to install the GridSense devices, several installation errors have been made. Installers did not always read the full product- and installation documentation. With a better preparation and communication, some installation failures could have been avoided. The wrong installations had to be corrected, which resulted in a delay of the installation planning. The most common errors were a reversed current measurement or an inverted installation of the power phases. In the meantime, based on this experience, a “measurement plausibility check” was already implemented in the installer application in order to guide installers during the installation process and minimize potential errors.

At the beginning, the easiest installations were performed in order to gain experience. The installations proceeded then one after the other (never in parallel to avoid potential errors repetition).

In the household where a customer’s router was not present or could not be used for GridSense communication, the device Internet connectivity was provided by a 3G mobile solution. In some cases, this resulted in some communication problems because the network reception of the selected provider in the specific location was not always optimal. The communication infrastructure had to be corrected.

Without inspection prior to the installation, and in some cases with an insufficient documentation of the appliances where GridSense had to be installed at, it is difficult for a common electrician with limited technical competences to understand the heating system complexity and judge whether an installation of GridSense is meaningful or not – for example, an electric boiler which is heated also by solar heat or fossil fuels. Since the GridSense installation planning and execution requires a combined electrical and thermal know-how, it is not always easy to find the best skilled installation personnel.

4.2. Learnings from GridSense operation

(Due to potentially differing view-points and foci the project partner statements are separated here.)

AEK Energie AG

The first-level support for the SoloGrid project was provided by AEK Energie AG (Pikettstelle). Altogether 12 customers had problems over the course of the project, which were addressed to AEKs support line. The customers where consulted and feedback was taken into account for improvement of installation and the GridSense solution.

InnoSense

As for the installations, SoloGrid has been an extremely important test bench to gain experience about the operation of GridSense in a large-scale project under real conditions. The learnings are extremely precious for product development and were used or will be used to implement correcting measures (both technical and operational) to improve system stability, adapt product features and optimize the defined operational processes.

In the following, the most relevant learnings are listed:

- Device communication (Device online/offline) has often been an issue in the starting phase. After an optimization period where improving measures were implemented, the percentage of communicating devices reached nearly 100 % over the entire day. The following main reasons were responsible for communication losses:
    - Customer's router was switched off (provider change/maintenance or customer on holiday)
    - GridSense interruptions
    - PLC network had some problems or was influenced by other appliances in the house.
- The monitoring of the whole GridSense system (35 households, 101 devices) is time consuming and requires specific tools and processes. These have been developed or optimized also according to the experiences collected during the project.
- Troubleshooting – if it was not possible to repair the failure remotely, an onsite visit had to be planned and performed. As a consequence, the contact with the end-customers was intensified. Although we had some problems to be solved onsite, the GridSense team was generally well perceived and the collaboration with the customers very positive, since all people involved always did their best to react quickly and find a solution.
- The problems occurred during the operation under GridSense control yielded only in some few cases to a comfort problem for the customer. During one year of operation in 35 houses with more than 100 GridSense devices (thereof 64 devices actively controlled by GridSense) only 5-7 comfort issues were signaled (cold water or ambient temperature). In some cases, it was then verified, that the problem was not generated by the GridSense control (for example, the electric boiler was calcified and was not able to heat normally or the heat pump which needed a service).

- In a couple of cases, using the customer's router as communication channel carried to some discussions with the house owner, when he felt GridSense was responsible for Internet connection problems, which was never the case.
- In some cases, particular non-standard system characteristics (for example heating systems with more than one heating source) were detected only in the operation phase after data monitoring and analysis.

4.3. Learnings with participants

(Due to potentially differing view-points and foci the project partner statements are separated here.)

AEK Energie AG

Different customers had different reasons for participating in the SoloGrid project. Interest in innovative energy technologies and/or environmental sustainability was one motivator. An attractive financial rebate on electricity bills (-20%) was certainly a motivator for the majority of participants. The interest in information events for customers was large at the beginning but clearly reduced over time.

InnoSense

Customers were informed beforehand over the project scope and first information event via mailings and personal telephone calls by AEK.

As a compensation for their project participation, all participants received a 20% rebate on their electricity bill. This was both used as a motivator as well as a compensation for shifting thermal loads from cheaper night-time hours to more expensive day-time hours in order to use this flexibility for improving the grid loading.

Altogether 34 households out of 40 pre-screened suitable households and 56 households altogether in the Riedholz pilot grid area participated in the SoloGrid project. Altogether 16 households were deemed unsuitable due to missing thermal loads, and hence, no flexibility potential.

The project team had a strong interest to be in constant contact with the project participants. This was realized via different channels, i.e. regular information events in Riedholz or the Luterbach information center (every 4-5 months), mailings of summaries from the most important information events as well as an online survey after the installation phase.

The most efficient and honest customer feedback came from the anonymous online survey, which was replied by one-third of all participants. In comparison to this the number of participants at the information events dwindled over time (to about 20%).

4.4. Learnings from measurement data analysis and simulation

4.4.1. **Assessment of Data quality**

An extensive effort had to be spent on data consistency. Due to the need of accurate and consistent data for the simulation calibration, the base data set had to be prepared and missing data interpolated. Over the course of the project, the amount of gathered data from transformer stations, 100 GSU units, smart meters, GIS systems and weather management summed up to a level, where manual consistency checks where not feasible anymore. Consequently, development effort was spent to automate the data consistency verification and interpolation processing.

It is important to distinguish two different usage of data within the project.

1. GridSense operation: local GridSense devices sample electrical quantities on site. Thanks to the distributed nature of GridSense, this data does not need to be shared across devices.

2. GridSense validation: the validation of the GridSense algorithm, carried out by Adaptricity, required the data to be retrieved from GS devices and restructured for further processing. The data-gathering infrastructure was setup as complementary to GridSense and it is normally not required. The process of data retrieval and transmission relies upon optical readers and wi-fi connections installed within the households. An overview of the data gaps created by temporary interruptions of service within the households are reported in Figure 15.

Concerning the data processing for GridSense validation, the key learnings are hereby summarized:

- The data delivery infrastructure has been improved over time. In addition, automated tools for data diagnostics have been developed to timely identify and correct unexpected behaviors that would have otherwise gone unnoticed. The know-how that was acquired supported a smoother deployment of the further development and a more reliable assessment of performance.

- Disturbances or failures in communication channels may lead to gaps in data. Robust methods of reconstruction and replacement are a key to mitigate the impact. This ensures a solid foundation for simulations and further statistical analysis.

Any data gathering infrastructure is subject to disturbances in communication channels. The proper application of methods for imputation of missing values help in addressing the problem. Figure 15 reports an overview of the completeness of the data used for analysis. Each row illustrates the completeness of the data stream that could be retrieved from one GridSense device. Devices are clustered by household. Blue lines represent missing values in the available series. The figure highlights how data gaps tend to happen simultaneously for all devices within a same household, suggesting a common cause. This can be imputed to temporary misfunctioning or deliberate, absence-related shutdown of the household wifi network or transitory impairment of the optical reader used to fetch the data. Thanks to continuous data analysis, feedback, and measuring tuning, the measurement data quality improved during the year-long measurement session.

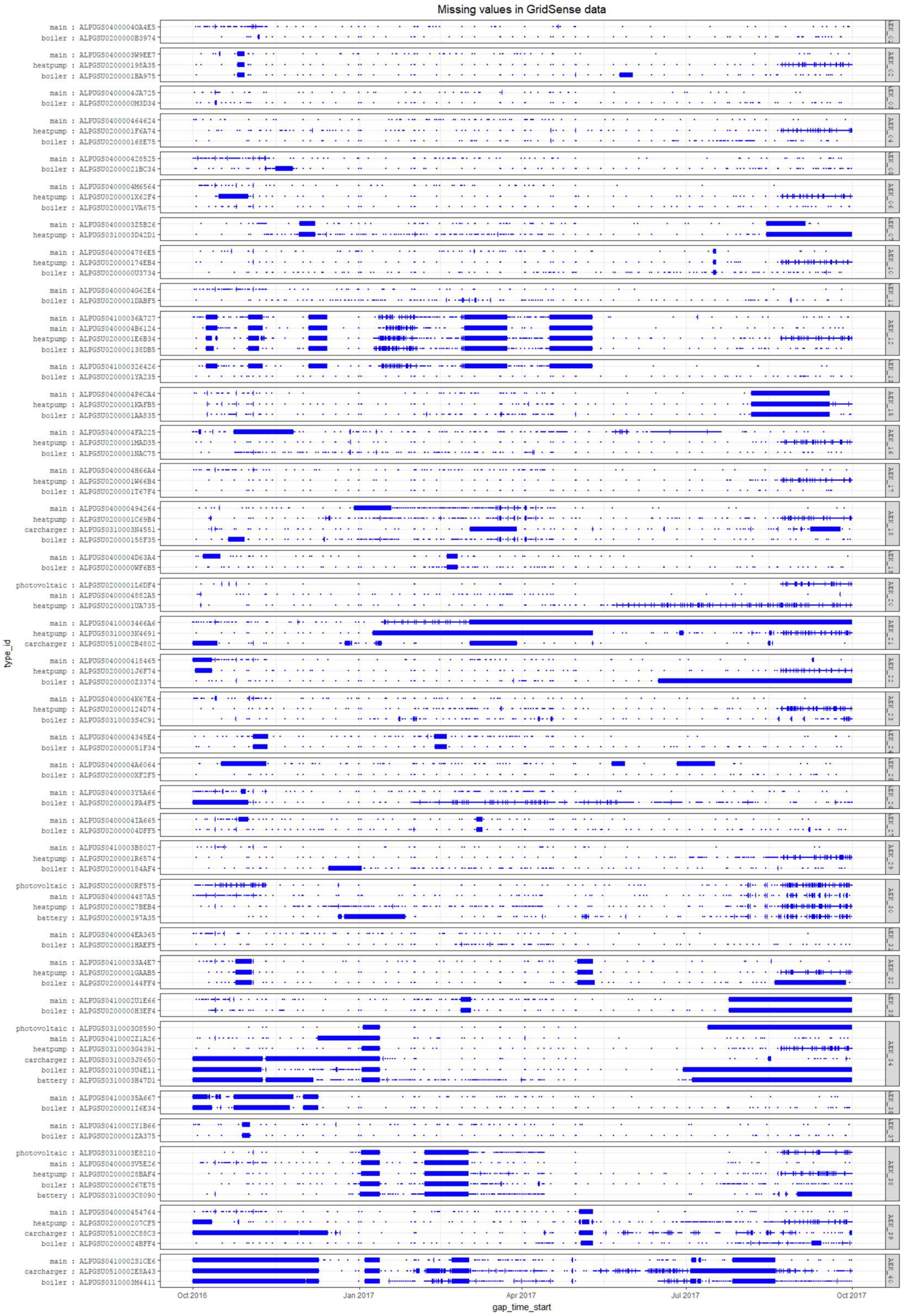


Figure 15 - Assessment of missing GridSense measurement values
(dots are gaps with less than 100 samples).

Due to the initially delayed GSU installation phase and the late start of the continuous measurement period (October 2016), a project extension until end of October 2017 was reasonable and in fact necessary for obtaining a meaningfully large set of measuring data, i.e. one full reference year.

4.4.2. Simulation tasks & Algorithm integration

Defining representative scenarios that answer as many questions as possible without getting an exploding scenario number is difficult but very important. General benchmark systems would make simulations more representative and limit the number of simulation runs.

Devices whose demand is mainly behavior-dependent, such as electric vehicles, are delicate to model and highly dependent on the assumptions taken. In general, simulation results can strongly be influenced by assumptions. We chose to model all scenarios conservatively. An alternative way would be to create several scenarios, including less conservative ones, with rigorous reporting of assumptions. However, this would yet again lead to an exploding number of simulation scenarios.
It is in this context necessary to decide up-front if qualitative evidence suffices or if detailed quantitative results are needed. In order to obtain quantitative results, a high number of simulation scenarios with incremental variations are needed and these results are typically only valid for specific system configurations. With a fixed amount of resources, the choice is thus a trade-off between qualitative results for a wider range of questions or quantitative results for a very specific question. The challenge is that decision makers usually demand quantitative, yet generally applicable results.

In order to run simulations with GridSense controlled units, the same GridSense algorithm from the GSUs in the field needed to be embedded in the simulation environment. The main challenge for Adaptricity in this context was to integrate the patented GridSense-algorithm with undisclosed source code via an interface as a plugin in the simulation environment. This led to a substantial debugging and coordination effort for the interface between Adaptricity.Sim and the GridSense algorithm. It had to be ensured that the simulation data sent to and the control signals sent by the GridSense algorithm corresponded to the interaction of measurements, devices, and GridSense in reality. The effort was further increased because three parties (IDSIA, InnoSense, and Adaptricity) were involved. It is an important demonstration that we were able to successfully integrate the algorithm, while the learning is that a substantial effort was necessary to get there.

5. Results II: Measurement data analysis

5.1. Measurement data overview

The following paragraph reports an overview of the available data sources and the necessary treatments needed to get the data ready for analysis.

5.1.1. Available data sources

The performance assessment of GridSense in Riedholz' area exploited several datasets.

1. **Grid:** the grid model of the SoloGrid study area.
2. **Transformer measurements:** values of active and reactive power, voltage and current. Time resolution of 1 min.
3. **GridSense Units measurements:** measurements at household-level provided by the GridSense metering devices. The dataset contains values of active and reactive power, as well as voltage and current. Time resolution of 1 minute.
4. **Customer metadata:** customer metadata, IDs used to locate the customer at the appropriate grid bus. Annual consumption is reported for each and every customer, and it was used in the analysis to generate load profiles for unmetered (non-GridSense) households.
5. **GridSense test plan:** over the year-long test period, GridSense has been regularly switched on and off to compare the effects on the grid. The test plan reports the schedule of activation periods, including the different operation modes in which each household was controlled.

5.1.2. Data quality

Before any analysis or simulation could start, the data underwent a process of data cleaning. In particular, GridSense unit measurement data presented some unique challenges that needed to be addressed. A thorough cleaning was carried out to ensure that as little noise as possible could enter the further stage of analysis and simulation. This phase that accounted for a considerable share of the total time led to the development of useful diagnostics algorithms, visualization techniques, and data cleaning tools. The main issues to be addressed were:

- **Outlier detection:** within the data, extreme values can occur as a consequence of errors occurring because of random reasons or temporary malfunctioning of the metering device. If not properly identified and addressed, they can cause convergence problems in simulations and introduce biases in the statistical analysis. Algorithms have been developed for identification and proper treatment of outliers.
- **Missing data:** Simulation require complete information about the system but missing data are unavoidable. Each measurement time series presented a variable share of missing data. Algorithms for imputation have been developed and deployed to fill in the gaps.
- **Detection and handling of corrupted time series:** some time series presented a poor signal-to-noise ratio. These time series underwent separate treatment and were, at need, discarded.
- **Synthesis of missing time series:** around a third of all customers in Riedholz were not metered. In addition, as just pointed out, some time series for metered customers had to be discarded. Algorithms had been developed to allocate synthetic and realistic profiles to feed simulations.

5.2. Data insights

5.2.1. **Transformer data**

The transformer powering Riedholz' low voltage grid is equipped with a metering infrastructure that delivers data of active and reactive power, current and voltage. In the following paragraph, a qualitative analyis of transformer data will provide an overview on the prominent dynamics of the grid and the effects of exougenous factors at play. This will bring additional meaning to the rest of the analysis. Whenever of interest, plots display 3-phase values. Else, the average of the three phases is shown.

Violations at transformer station

Under normal load conditions, voltage at households is lower than at the transformer station, due to the natural voltage drop along the distribution line. Depending on the impedance of the cables and the load conditions, the drop can range from almost zero to many tens of volts. To compensate for the drop, voltage at transformer station is preferably kept above 230V. On the other hand, under-voltage conditions at the transformer amplify downstream.

Figure 16 displays a voltage map of minimum and maximum voltage values at the transformer. The data spans 2 years, between September 2015 and September 2017. The aim of the figure is to give a first snapshot of the grid's health, highlight possible systematic under/over-voltages. No criticalities at the transformer level are found, minimum voltage is constantly above 230V and maximum voltage is constantly within +6% p.u.. This ensures that the test area did not suffer from disturbances propagating from the higher voltage grid that could have biased the results. The actual benefits of GridSense will be evident once looking at the loading of the underlying low voltage grid (Section 5.3.1). However, this does not mean that there are over- and undervoltage effects in the individual feeder lines. GridSense became fully operational in Oct 2016, and as predicted this plot does not display any prominent difference after that date, suggesting that the impact of GridSense should be quantified not on the transformer data, but mostly on the basis of the data of individual households, located further away in the low-voltage grid.

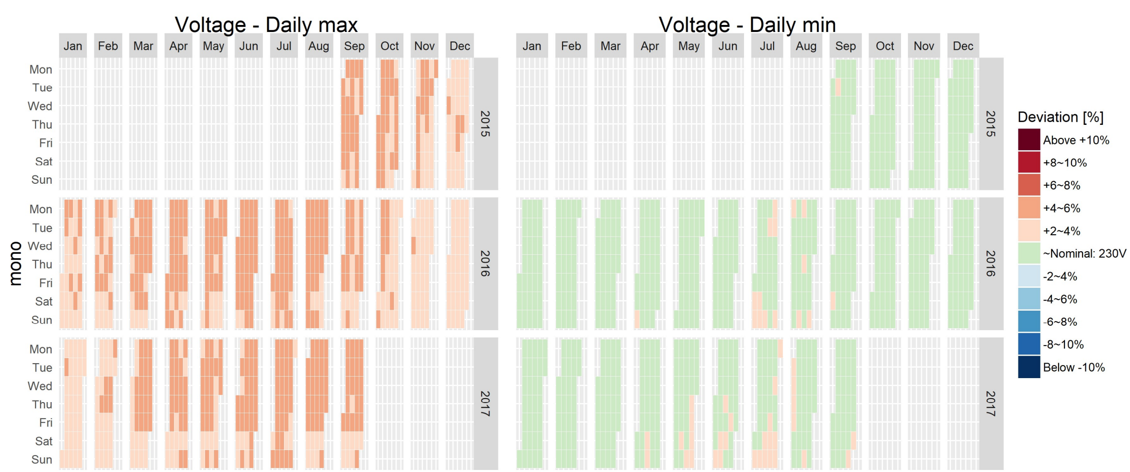


Figure 16 – Calendar map of daily max and min voltage at Riedholz' transformer.

Main impact factors: temperature, PV infeed, ripple control, disturbances from MV grid

A more granular look at the transformer data reveals which key external conditions influence the analysis and suggests the directions for investigation. Figure 17 displays the load at Riedholz' transformer. Load is represented through increasing shades of red. Reverse power flows are highlighted in blue. The upper orange-blue ribbon marks periods in which GridSense was active or inactive.

Two prominent effects take place:
1. In wintertime, load increases, due to a higher exploitation of heat pumps and boilers.
2. In summertime, PV production can exceed the residential load, causing an infeed of power into the transformer during daytime (blue areas).

GridSense was enabled and tested over cycles of roughly three weeks.
1. Week 1: GridSense ON, ripple control OFF: active control of devices.
2. Week 2: GridSense OFF, ripple control ON: devices are controlled with time-based schedule.
3. Week 3: GridSense OFF, ripple control OFF: pure observation mode.

Qualitative effects of control strategies:
1. GridSense smooths the load and shaves the peaks over the day. This is particularly evident in colder months. During GridSense ON periods (orange), the heatmap clearly displays a more homogeneous load pattern.
2. Ripple control generates load spikes: overnight, during periods of GridSense OFF and ripple control ON, dents of higher load regularly occur overnight. This is due to traditional ripple control, that simultaneously activates/deactivates boiler and heat pumps.

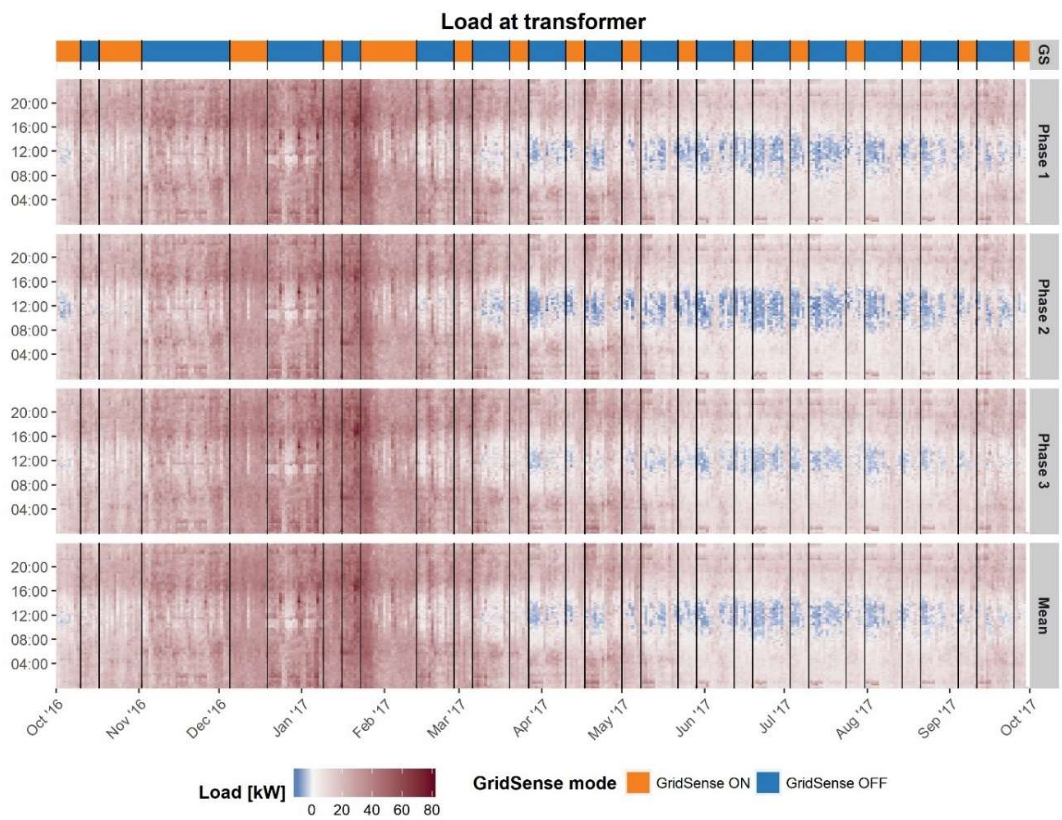


Figure 17 – Load at transformer during GridSense test period. Time in UTC.

Figure 18 is a heatmap visualizing voltage values at Riedholz' transformer. It helps appreciating the influence of the medium voltage grid on voltage values at the transformer station. Voltage magnitude in Riedholz' low voltage grid is significantly influenced by disturbances originated in the upper MV grid.

To demonstrate that, it is worth comparing the load pattern of Figure 17 with the voltage pattern of Figure 18 over the period of February 2016. Over that period, load at the transformer (Figure 17) remains sufficiently homogeneous within same days. Nevertheless, voltage pattern in the same period (Figure 18) still exhibits several well-defined spikes around 10:00 UTC.
This clearly suggests that the disturbance originated outside the test area. Recurrent spikes and dents in voltage are most likely caused by the combined action of ripple controlled appliances located outside Riedholz' low voltage grid but within the same MV grid.

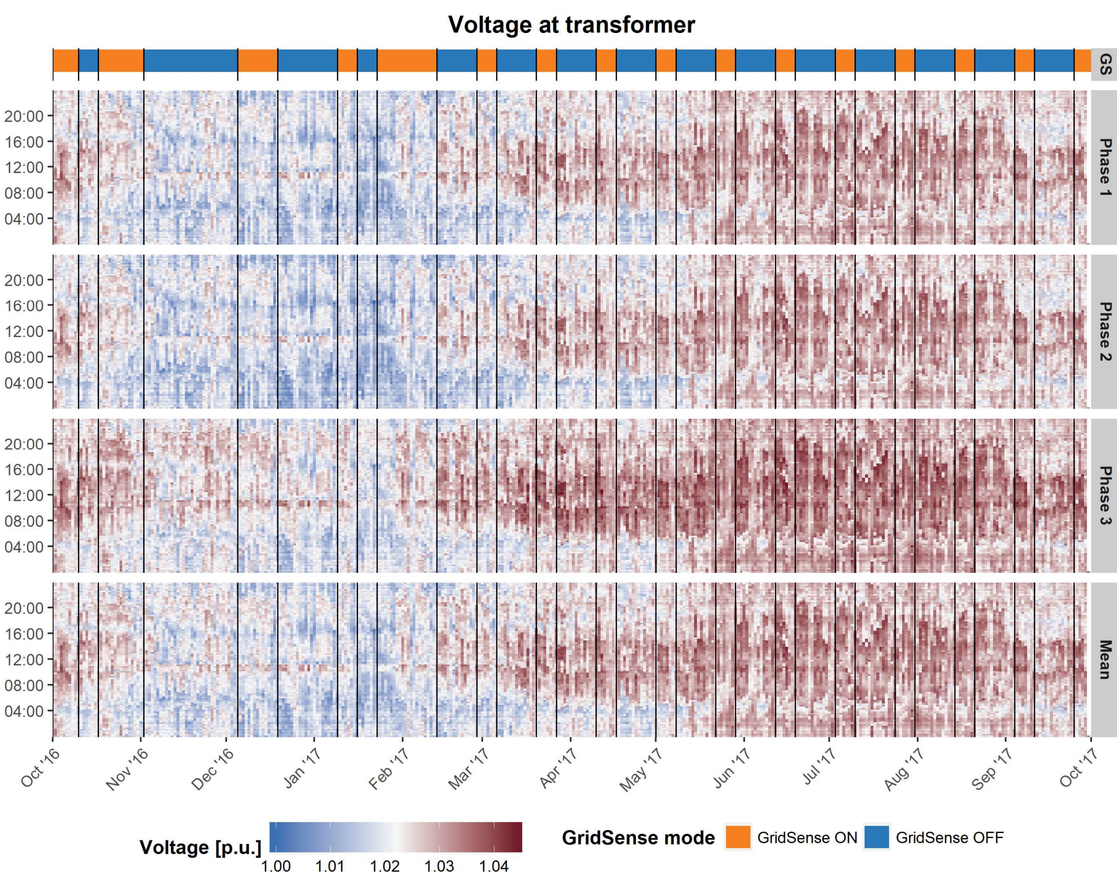


Figure 18 – Voltage at transformer during GridSense test period. Time in UTC

The beneficial effect of GridSense on the voltage will be more evident when analysing voltage drops within the LV grids and daily voltage fluctuations at the household level. This will be the purpose of the following paragraphs.

5.3. GridSense Effectiveness

GridSense helps smoothing the aggregated load over the day. Energy requirement can be shifted in time and rearranged on a time scale of minutes to hours to obtain a more homogeneous load. Clearly, load can be shifted but cannot vanish: it is not possible to reduce the global energy requirement, because households would still require the same amount of energy to maintain the comfort setpoint. In other words, GridSense does not have energy savings effects, but it acts in fact as a power smoothing algorithm. In the following, the smoothing effects will be presented more in detail.

5.3.1. **Comparison of representative days**

To qualitatively assess the load shifting capabilities of GridSense, it is worth to compare the transformer load and the average voltage drop[1] within Riedholz' grid on two representative days. On one day, GridSense is activated, on the other, only ripple control is active on the grid. One couple of days is compared for winter and one for summer. In order to minimize the influence of exogenous factors such as human activities, temperature and PV production, all days chosen for comparison are Wednesdays, and they must exhibit comparable photovoltaic production and temperature profile. The chosen winter days are Dec 21st 2016 (GridSense OFF) and Dec 14th 2016 (GridSense ON), for summer the dates are May 24th 2017 (GridSense ON) and May 31st 2017 (GridSense OFF).

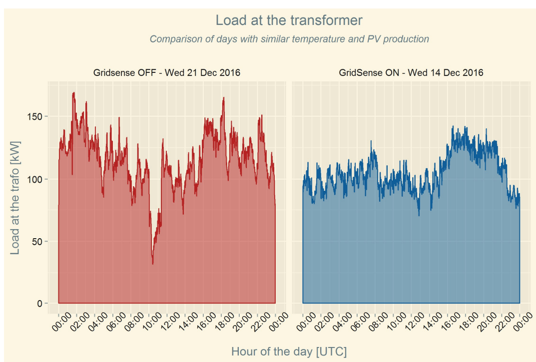


Figure 19 – Winter comparison: load at transformer

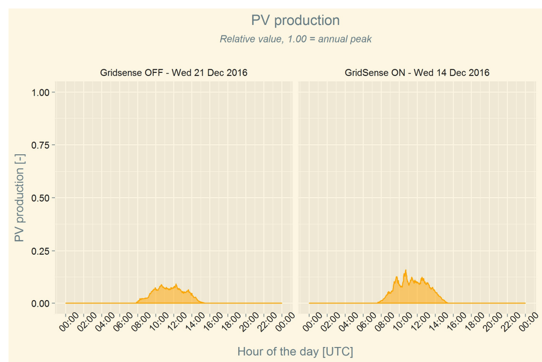


Figure 20 – Winter comparison: PV production

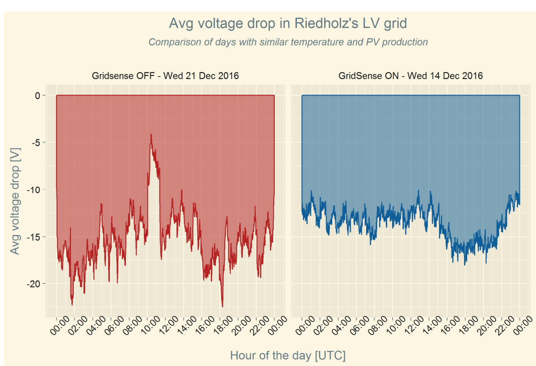


Figure 21 – Winter comparison: avg voltage drop

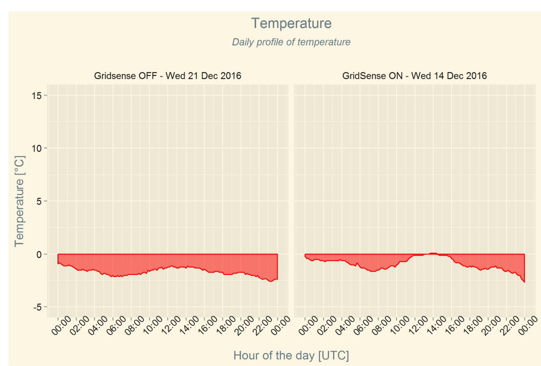


Figure 22 – Winter comparison: temperature profile

[1] The average voltage drop at a given point in time is here defined as the mean of voltage drops among GridSense households.

Notice that the load at transformer (Figure 19, Figure 23) has an indisputable negative correlation with the average voltage drop (Figure 21, Figure 25). Therefore, a smoother load at the transformer enhances the conditions downstream by reducing the maximum voltage drops. Spikes and dents of load at transformer during days of GridSense OFF are a direct consequence of ripple control and heavily affect the magnitude of the average voltage drop. As an example, the maximum voltage drop of Figure 25 is 50% higher during GridSense OFF.

These examples are a showcase of GridSense effectiveness: aggregated load is smoothed, yielding lower voltage drops within the low voltage grid.

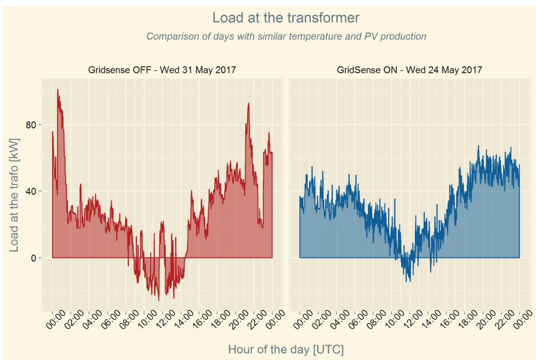


Figure 23 – Summer comparison: load at transformer

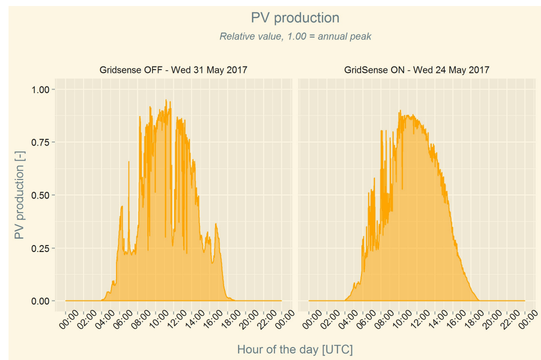


Figure 24 – Summer comparison: PV production

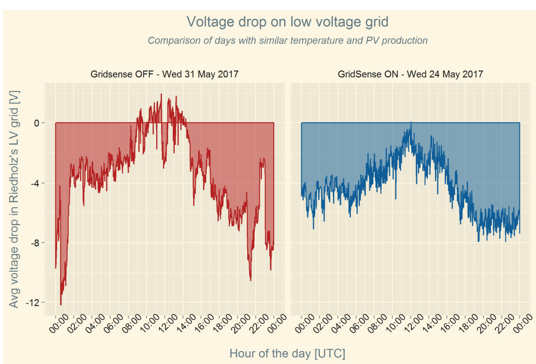


Figure 25 – Summer comparison: avg voltage drop

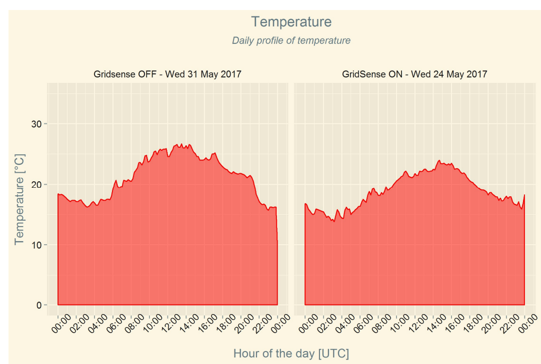


Figure 26 – Summer comparison: temperature profile

5.3.2. Ensemble comparison of voltage daily fluctuations

The previous paragraphs unveiled the potential benefits and limitations of GridSense in a qualitative fashion. Paragraphs 5.2 and 5.3.1 depicted how GridSense helps reducing voltage fluctuations within the grid. This paragraph reports a more quantitative analysis. To quantitatively asses the reduction in voltage fluctuation at the household level, it is worth to plot the daily voltage fluctuation[2] against the temperature and compare the situations for GridSense ON/OFF. In fact, temperature heavily influences the voltage drop. Lower temperature leads to higher load and higher load fluctuation, which in turn generate higher voltage drops and higher voltage fluctuations within the LV grid.

Figure 27 highlights that GridSense reduces the daily voltage fluctuation at the household level on average by ~4 volts, with the highest recorded drops reduced by ~6 volts (95th percentile). As expected, voltage fluctuations are higher for colder days. Notice that voltage fluctuation increase with colder temperature (blue trendlines), but the increase is milder when GridSense is active.

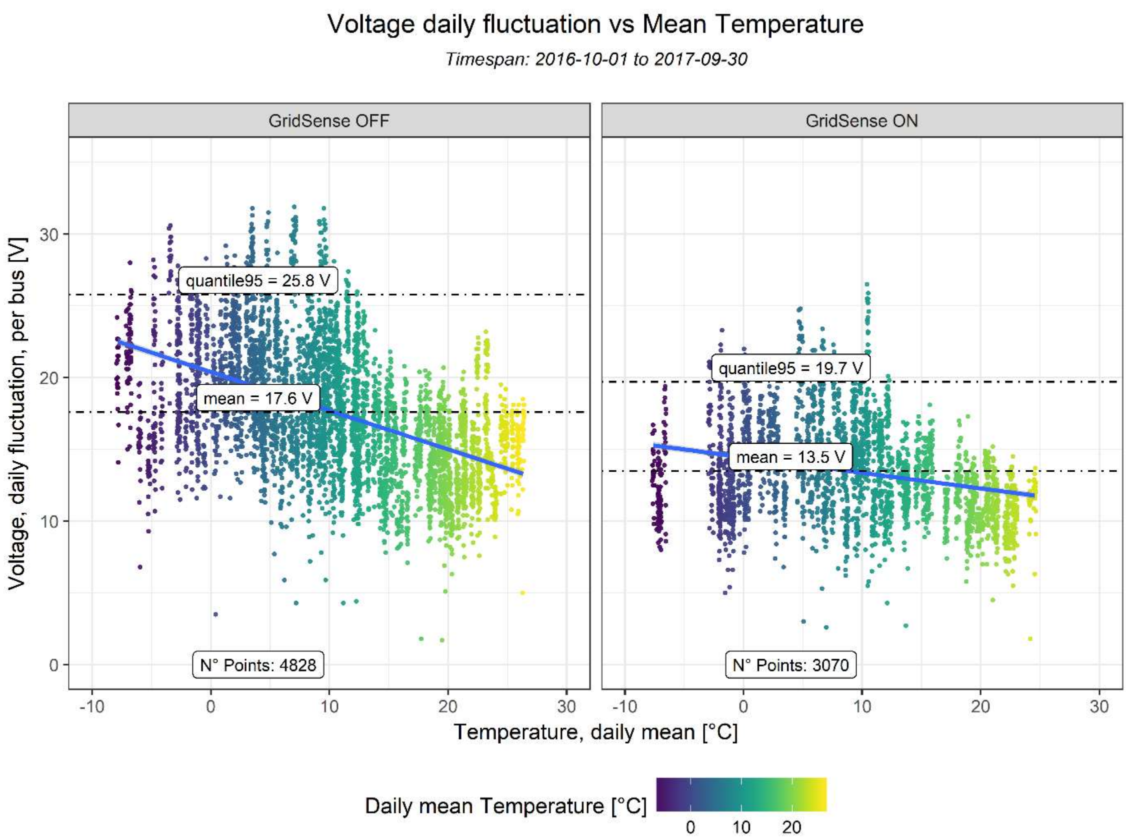


Figure 27 – Trends of daily voltage fluctuations vs temperature

[2] The daily voltage fluctuation of one household is defined as the difference between the max and the min 10-minutes voltage, within a same day. In one year, this yields to 365 values for each household.

5.3.3. Ensemble comparison of voltage values

It is valuable to compare the distribution of the bare voltage magnitude. In Figure 28 it is evident that during periods of GridSense activation the minimum recorded voltage values are higher than durig ripple control or observation mode. During observation mode and ripple control periods, for some devices the voltage dropped even below 0.85 p.u.. In observation mode, voltage was below 0.9 p.u. more than 4 times more frequently than during GridSense activation (0.37% of time vs 0.08%)

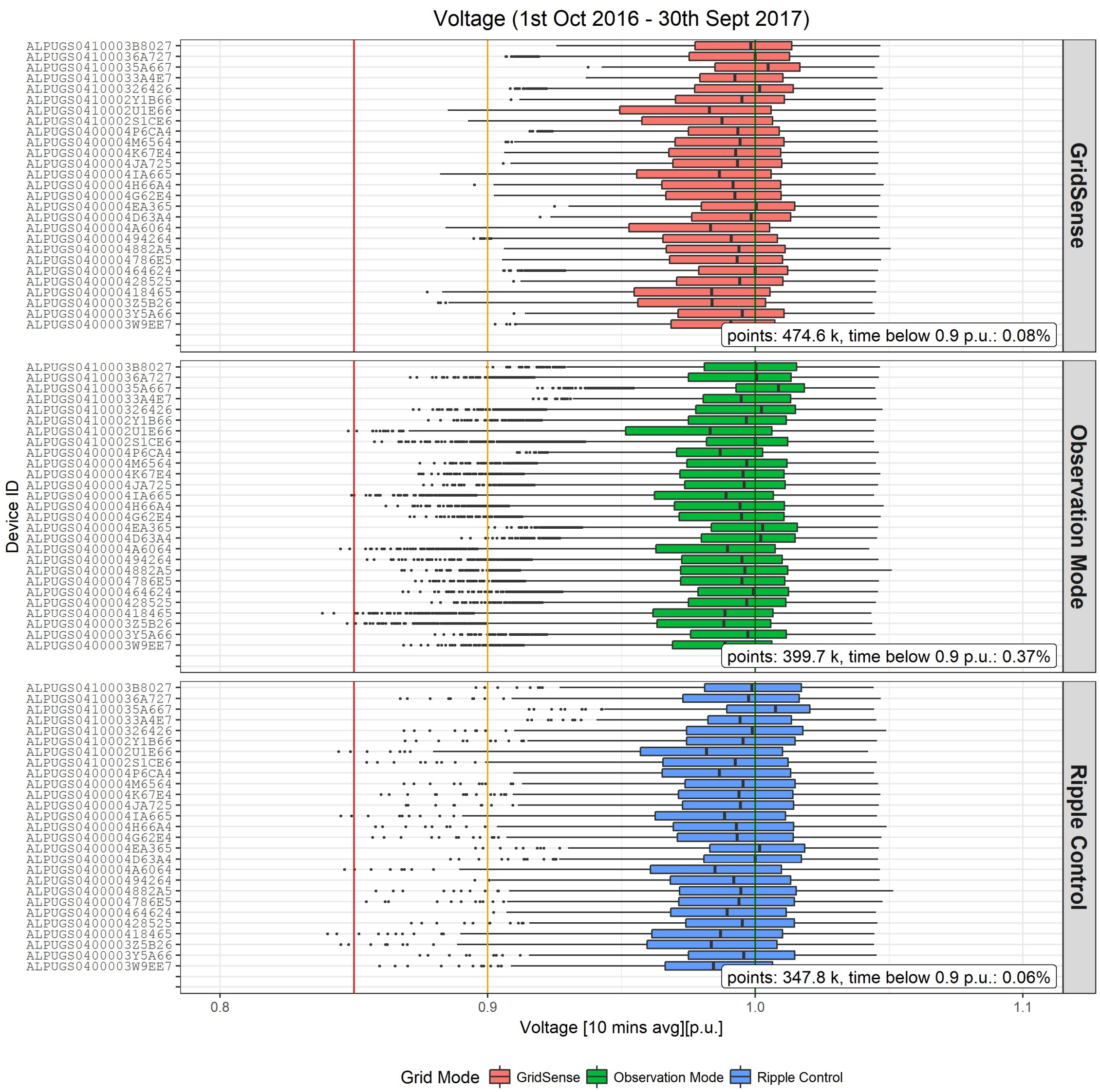


Figure 28 – Boxplot of voltage values

6. Results III: Simulations

6.1. Introduction

Simulations are a powerful way to complement the measurement results because they cover analysis aspects where the measurement analysis has limitations. The following four main advantages cover important limitations of the measurement analysis:

- grid, household, and boundary situations that do not occur during the test period can be simulated,
- the simulation time period can be arbitrarily shifted with limited additional effort needed,
- simulations can be repeated with identical boundary conditions that influence the local grid and the prosumers, thus enabling a totally fair comparison between times with activated and deactivated GridSense,
- the value of every variable associated with any component that is part of the simulation is known for every time-step of the simulation (grid transparency).

We thus made use of the simulations to create fair comparisons between a grid with households where GridSense is activated and one without GridSense being active. Such comparisons also include alternative ways to keep the status of the grid in acceptable conditions or to minimize costs for prosumers. Several components of the households and of the grid model were varied in the simulations. This was carried out to analyze future scenarios, to assess the impact of GridSense with various system configurations and differing GSU penetrations, and to gain more insights about the interplay of GridSense with different unit categories (heat pumps, boilers, batteries, PV units, and electric vehicles).

The simulation platform of Adaptricity, Adaptricity.Sim, offers a versatile and potentially mixed approach for simulations: it is possible to combine smart meter measurements, statistically generated data, and models for different household applications. Different control strategies and tariffs can be modelled and applied. In order to use the simulation platform for this project, the GridSense algorithm needed to be integrated in the simulation platform as a plugin. In the view of Adaptricity.Sim, this GridSense algorithm plugin then behaved like a special type of a controller for the GridSense controlled household appliances: boilers, heat pumps, electric vehicles, and batteries (PV units are measured for the GridSense algorithm but not controlled by it).

The simulation work tasks were approached in a two-stage process. In the first stage we made use of the smart meter active and reactive power measurements by using them as an input for simulations. These simulations were carried out with the grid model supplied by AEK (GIS export, used for all simulations) that represents the current status in the test area and with one that represents a realistic classic grid reinforcement. In this simulation we were able to compare the grid voltages when GridSense was “ON”, with the grid voltages with a classically reinforced grid (without GridSense). Since the simulation was fed with actual active and reactive power measurements there was neither need for models for the components of the system nor utilization of the GridSense algorithm as a controller for these models. With this approach we were able to overcome the limitation of the measurements that they only represent the real configuration in the current grid. However, since GSU measurements were used, we still suffered from the limitations that the boundary conditions were not stable and that we were bound to the measurement time window.

In the second stage we went from a measurement-powered simulation scenario to a fully model-driven scenario. This means that in principle no household measurements were needed anymore because all components of the system were represented by suitable models. Measured weather data was used as an input in order to create realistic circumstances for the heating and PV models. The GridSense algorithm plugin or in the comparison simulations a classical device control rule were used to define the behavior of flexible devices like boilers, heat pumps, batteries, and electric vehicles. This kind of simulation provides full flexibility for variations of every aspect of the system configuration, be it grid model, control strategies, number and parameters of flexible devices, or settings of and penetration with the GridSense algorithm.

Before the start of the simulations, an evaluation of the one-to-one applicability of their results to the Riedholz test area was carried out. To this end, GSU power measurements were used as inputs for the simulations and the simulated voltages were then compared with measured voltages.

The simulations in the SoloGrid project are performed on the SmartGrid simulation platform Adaptricity.sim, developed and maintained by Adaptricity. The time-series-based simulation platform for active distribution grids (Figure 29) allows the evaluation of operational performance of SmartGrid elements, such as controllable Renewable Energy Sources (RES), dynamic Demand Response schemes, energy storage, SmartMetering, and within the scope of the SoloGrid pilot project of the GridSense solution for all grid operation and grid planning aspects. The simulation platform is server-based and amenable to cloud computing and massive parallelization of simulation and optimization tasks, as is needed for simulating large numbers of prosumer households dispersed in fine-grained electricity grid models [2-3].

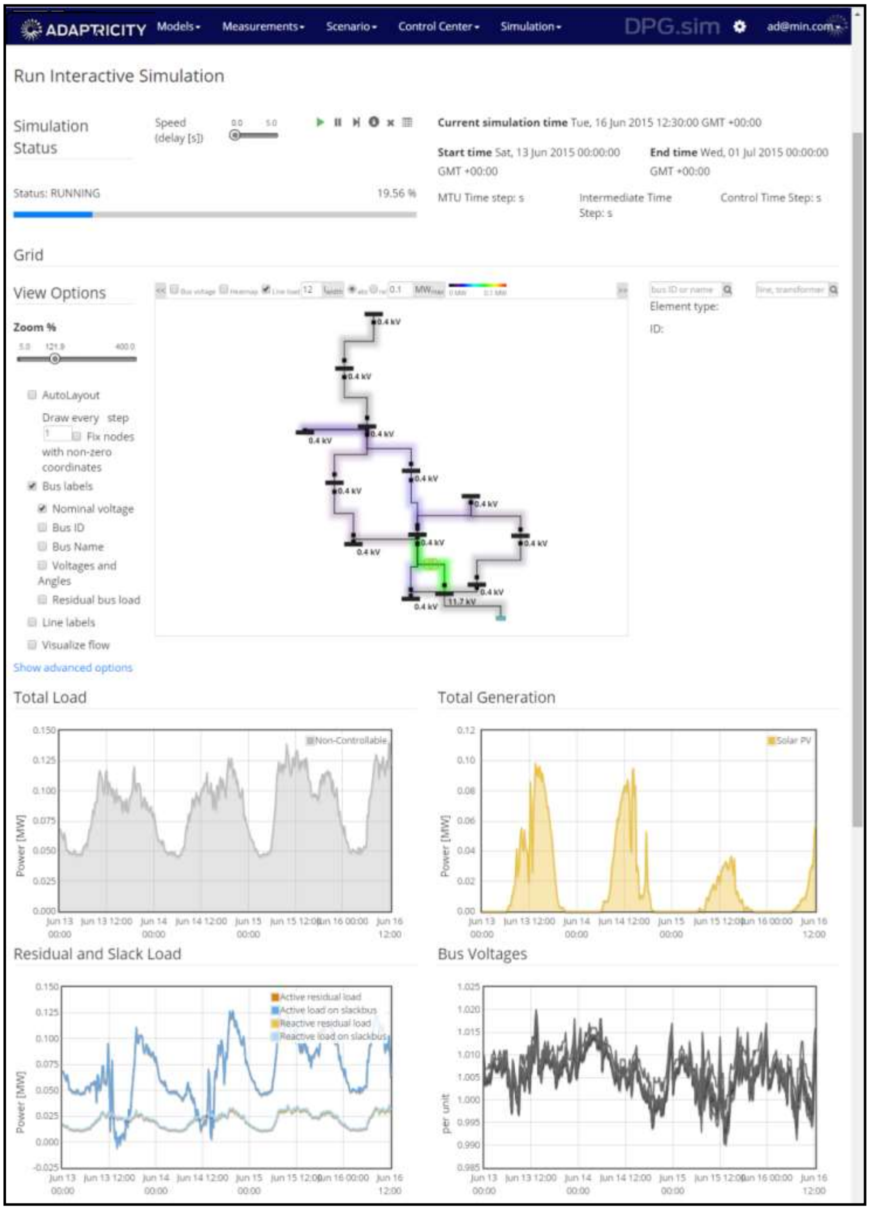


Figure 29 – Simulation Plattform Adaptricity.Sim (snap-shot).

6.2. Voltage validation

6.2.1. **Approach**

Several simulations were performed to assess the one-to-one applicability of the simulation results to the real test system. To this end, the GSU active and reactive power measurements were used as time series inputs with a resolution of one minute for a simulation. In order to take into account the voltage effects from the medium voltage grid on the distribution grid, the voltage measurements at the transformer were also used as an input for the simulation. The simulation then provided voltage results with a time resolution of one minute for every bus in the distribution system. These voltages were then compared to the ones that were actually measured at households that were equipped with GSUs. This comparison was carried out for a representative period in winter.

The major challenge for this comparison proved to be the unmeasured households, i.e. the households without GSUs. The only information available about these households were their yearly electricity consumptions. By comparing the aggregated household power measurements with the transformer power measurements, it was possible to estimate the share of measured consumption in the test area of Riedholz: it proved to be around 60 %. Factoring in grid losses of about 5 % this translates roughly to a mean share of 35 % unmeasured power of total power in the test system. Several different statistical approaches to estimate the power time series of these households were applied.

For example, an advanced statistical process [5] to create realistic profiles that resembled the measured time series and applied a differential rescaling to match the profiles at every time step to the residual between measured transformer power and measured aggregated GSU powers at the households was applied. The matching was carried out so that the electricity consumption of these households with estimated power time series in the simulation time window was in proportion to their annual electricity consumption. This is an advanced method to create realistic time-series with a given aggregated value. Realistic single household power consumption time series are typically not smooth but feature periods of very low consumption abruptly interrupted by periods of higher consumption. However, using the described method to approximate the inputs for the simulation resulted in an increase of noise in the results. This was due to the nature of this specific situation where the exact curves of unmeasured household power values needed to be approximated.

The goal was thus to minimize the differences between approximated and unmeasured time series. Although these realistic time series, generated with an advanced method, had similar properties like the real-time series, there was a high likelihood for mismatches between the periods of high and low demand on single household level. These mismatches then lead to increased noise in the simulated voltages at household level even though the aggregated household power consumption was matched with the transformer power.

It therefore proved to be advantageous to use a much simpler approach. It consisted of matching the power time series of unmeasured households with the residual between the transformer power and the aggregated measured household power values. This was done both for the shape of the profiles and the power level which was divided proportionately to the yearly electricity consumption of the respective households. In the end, every unmeasured household featured power time series with identical shape and a magnitude according to its yearly electricity consumption. This procedure was carried out for both active and reactive power. These smooth time series lack the typical properties of a single household power curve but feature smaller maximal deviations. This leads to less noise in the simulations.

6.2.2. Presentation and discussion of results

The results of this voltage validation are directly shown and discussed in this chapter because these are not results that are related to the questions about the performance of GridSense. They serve as an indication for measurement data consistency as well as simulation grid model conformity with the existing grid. The outcomes should provide a qualitative impression how well the simulation results can be directly applied to the real electric distribution system in the test area of Riedholz.

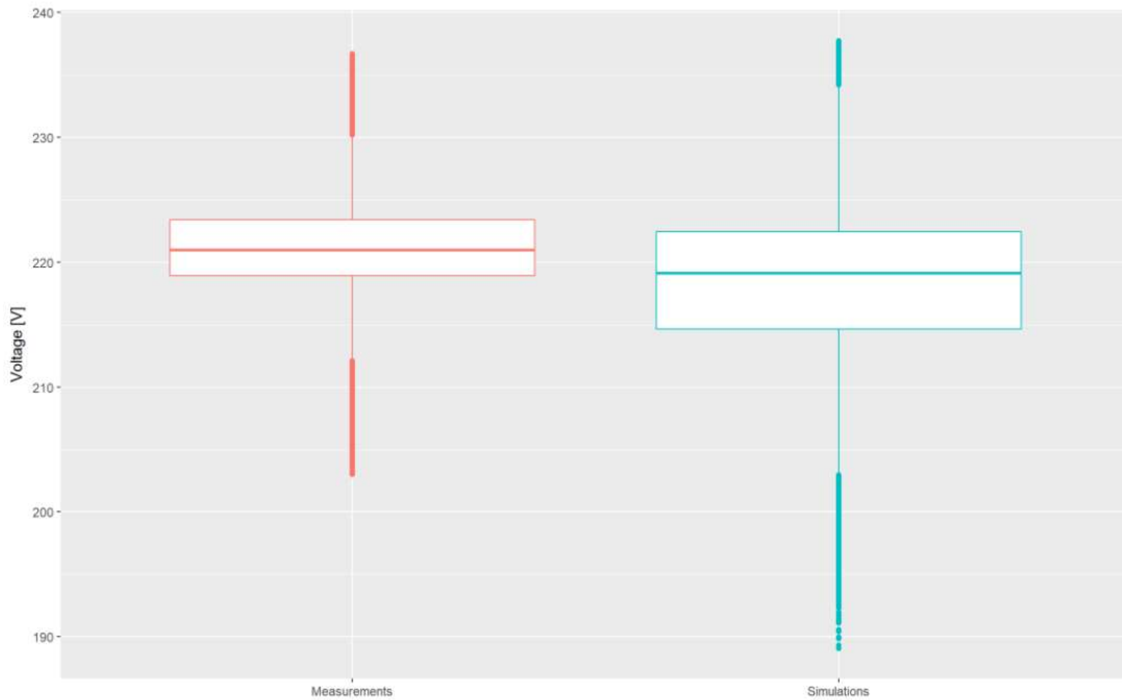


Figure 30 – Boxplot comparison of simulated and measured voltages at households.

In Figure 30 and Figure 31 it can be seen that the simulated voltages are in general comparable to the measured ones. An analysis of their similarity at a single, exemplary household over the passage of time, presented in Table 2 and Table 3, reveals very high correlation and also low root mean square errors (RSME). This analysis also tests for problems with lagging or leading time series (wrong time stamps). No problems were detected in these tests as is evident: the best results are observed when the compared time series are not shifted in the time domain. The results presented in Table 3 indicate that the simulations resulted at a voltage that was on average ca. 1 V lower than the measurements (because that is when the RSME is at the minimum).

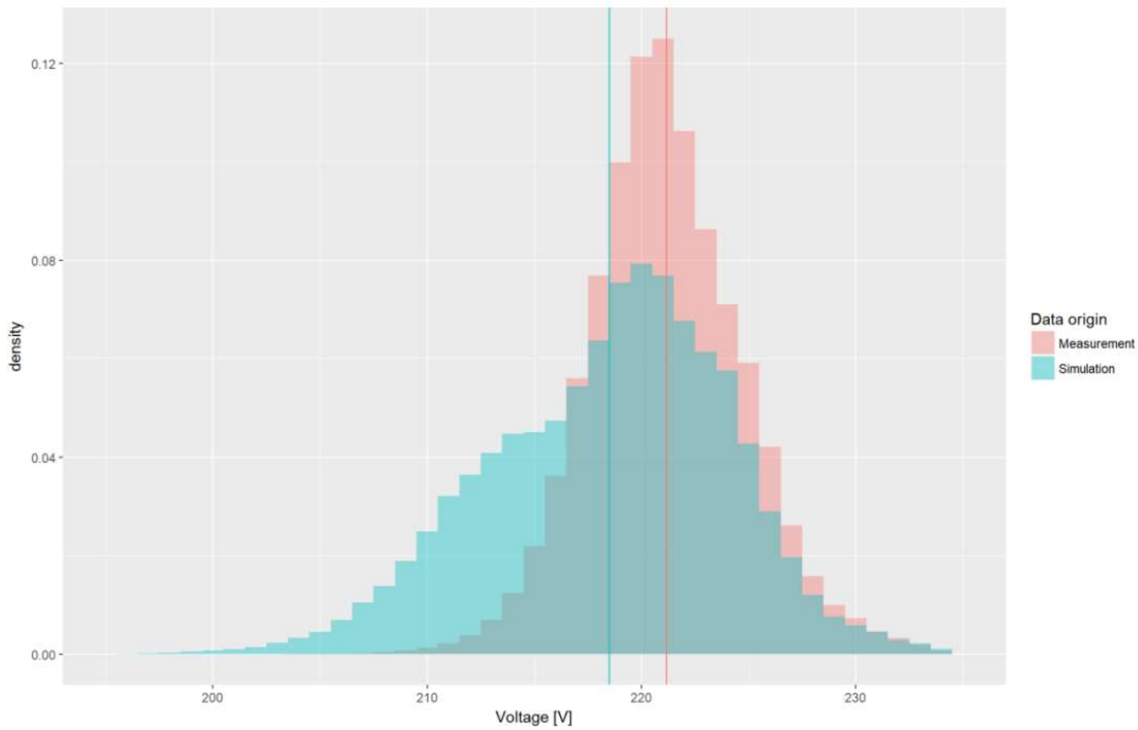


Figure 31 – Histogram comparison of simulated and measured voltages at households.
Mean values are indicated by vertical, colored lines.

Table 2 – Correlation between simulated voltages and measured voltages at exemplary household AEK 11 including tests for lead/lag of the simulated voltage time series. Note: the correlation is invariant to vertical shifting of time series.

Lag 2	Lag 1	Original	Lead 1	Lead 2
0.93	0.96	0.99	0.98	0.95

However, it can also be seen that some of the simulated voltages are lower than was measured in the field. Figure 30 and Figure 31 indicate that this is true for extreme values but also for a sizeable share of results below ca. 216 V where the two areas in the histograms start two heavily deviate. An analysis of the voltages grouped by time of the day, presented in Figure 32, proves that this is a time invariant feature of the data in that it does not seem to be dependent of the time of the day.

Table 3 – RMSE of simulated voltages and measured voltages at exemplary household AEK 11 including tests for lead/lag and vertical shifts of the voltage time series. The shifts give an indication by how many volts the simulated voltage time series should have optimally been different to minimize the RMSE.

Shift by [V]	Lag 2	Lag 1	Original	Lead 1	Lead 2
2	1.66	1.48	1.29	1.37	1.58
1.5	1.36	1.15	0.88	1.00	1.27
1	1.22	0.96	**0.62**	0.79	1.11
0.5	1.26	1.02	0.71	0.86	1.16
0	1.49	1.29	1.06	1.16	1.40
-0.5	1.83	1.67	1.50	1.57	1.75
-1	2.22	2.10	1.96	2.02	2.17

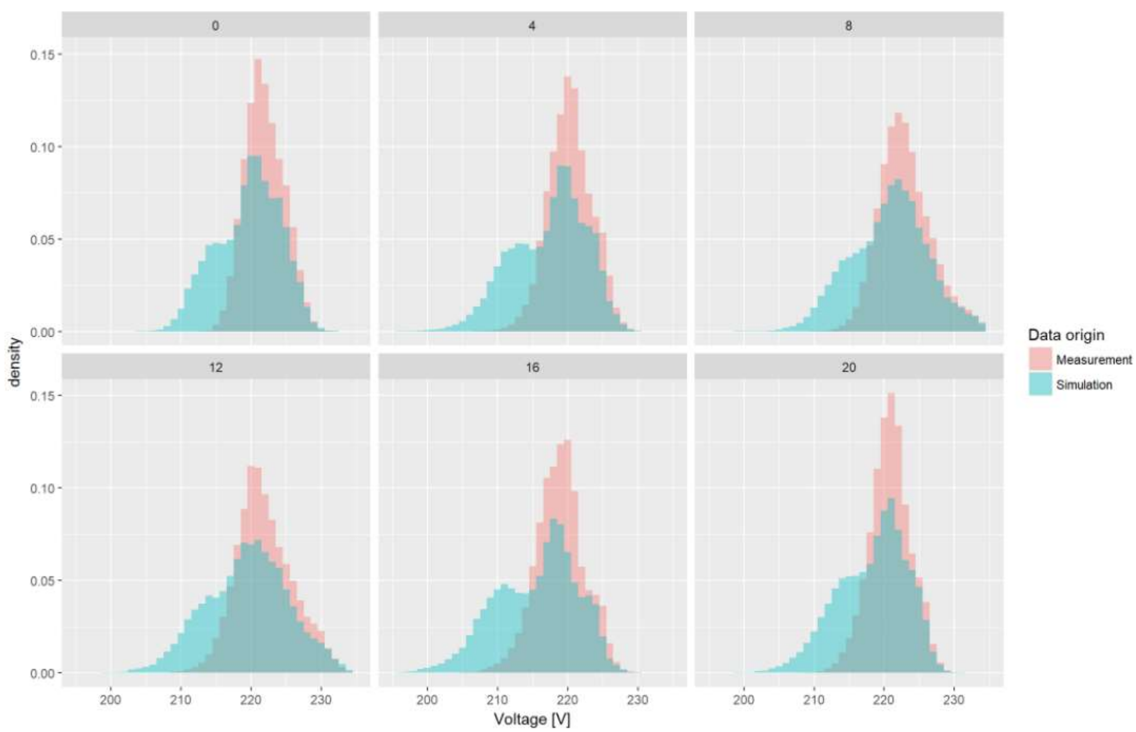


Figure 32 – Comparison of simulated and measured voltages at households by time of the day.

A closer inspection of the results revealed that the voltage deviations between the measured and simulated voltages is mostly caused by households along Hofmattweg which is the distribution grid region which is furthest away from the transformer (see Figure 33). It is also notable that this region of the grid has the lowest penetration with GSUs i.e. for a substantial share of households along this street there are no measurements available.

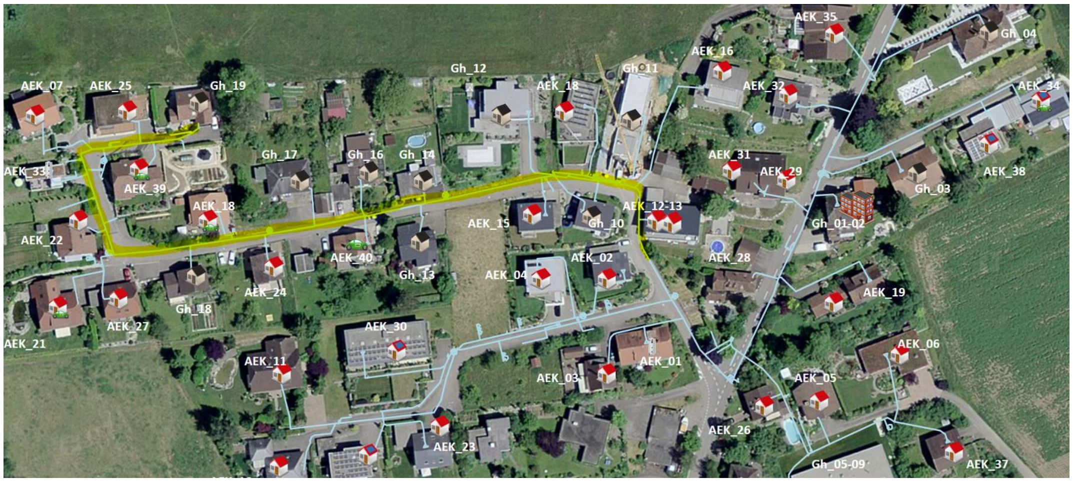


Figure 33 – Overview test area Riedholz with Hofmattweg highlighted in yellow.
Red house symbols designate households with GSUs, black house symbols those which are not measured.
Along Hofmattweg the share of households without measurements is substantially higher than in rest of test area.

If the data of those households are excluded from the comparison the deviations decrease dramatically as shown in Figure 34. However, it must be stated that the simulated voltages are in tendency still lower than the measured ones, a phenomenon which is accentuated at lower voltages. In general, the simulated voltage data have a higher variance than the measured ones.

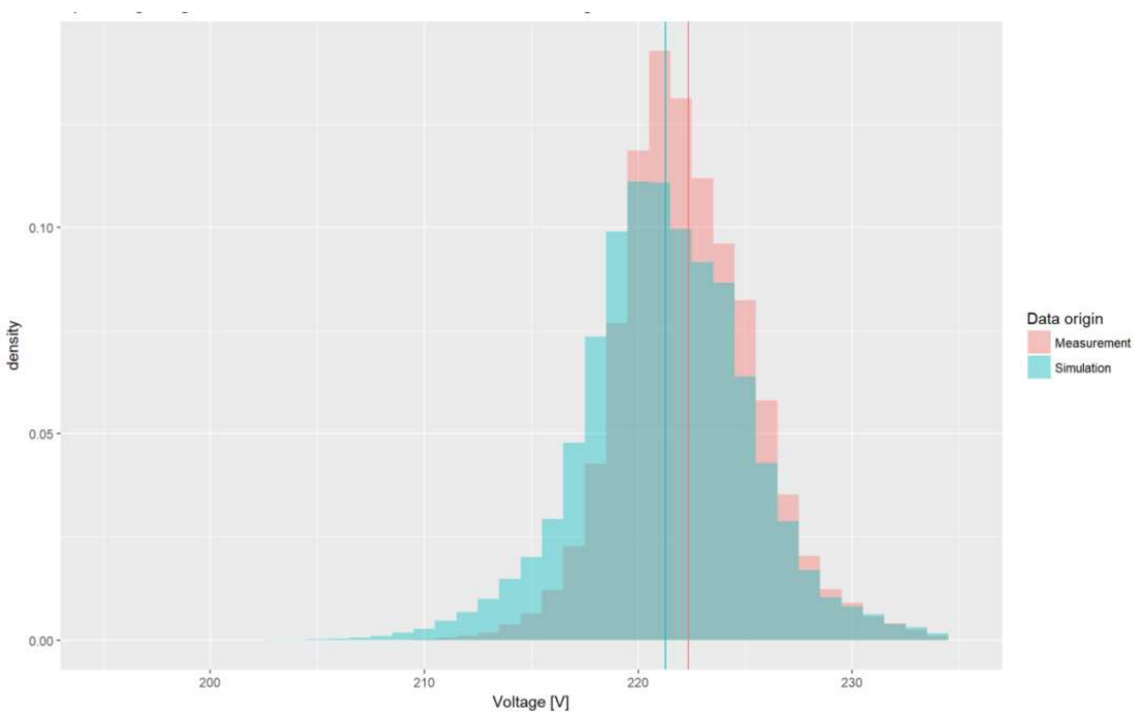


Figure 34 – Histogram comparison of simulated and measured voltages at households without Hofmattweg. Mean values are indicated as vertical, colored lines. Hofmattweg is the longest branch of the local grid and also the one with most severe voltage problems. In this plot the data from Hofmattweg were removed so only data from the rest of the grid were used for the comparison.

To find the source of the deviations, an in-depth analysis of the active and reactive power measured at the transformer in comparison with the ones measured at and synthesized for households was carried out. It is striking that the biggest voltage mismatch occurs in the part of the grid which is furthest downstream of the transformer station and also features the biggest share of non-measured households. Voltage problems in the grid are intensified in such regions of radial distribution grids so this might only be the location where overall problems with the grid model arise most prominently. A single reason for the voltage deviations was not found but there is evidence for a combination of reasons: the estimation of the power consumption of unmeasured houses is bound to contain errors. Then there might be totally unknown/unconsidered sources of consumption or generation. In addition, the possibility of inaccuracies in the available grid parameters or the transformer measurements cannot be completely excluded.

In addition to the general voltage deviations, there are small but still measurable voltage deviations between measurements and simulation which occur regularly and have a length of about 30 to 120 minutes. These deviations were found to be tightly linked to associated mismatches in reactive power consumption during the same time intervals. During those time intervals the measurements of reactive power consumption at households and transformer show a substantial mismatch. The reason for this mismatch could not be detected.

For completeness, the comparison of power measurements at the transformer and aggregated measured and synthesized power values at households are given in Figure 65 and Figure 66 in the appendix.

Concluding this chapter, it must be stated that deviations occur between measured and simulated voltages. This is especially the case in times of strong under-voltages and for the households along Hofmattweg. On the other hand, it can be said that the general match of measured and simulated voltages is good. This conformity applies both to the absolute values (shown in boxplots and histograms) and to the shapes of the time series (as given with the correlations in Table 2). In summary, this means that the simulations to assess the performance of GridSense will provide results that can serve as a good indication for the real world. The simulated voltages will in tendency be a bit too low, especially for households at Hofmattweg so they should be taken with a grain of salt. However, it is very important to state that the subsequent simulations to compare the state of the grid with and without activated GridSense are going to be completely fair. Unlike when comparing simulated with measured voltages, the underlying electricity system components are going to be absolutely identical in those comparisons.

6.3. Scenario Overview

Simulations can be broadly classified into the aforementioned two stages: the simulations of the first stage are purely measurement-powered and allow for limited variation of the system. Only grid model-related changes can be applied. This scenario was thus used to simulate a potential classic grid reinforcement. Simulations of the second stage are then model-based and provide much more flexibility. The majority of simulations fall therefore in that category.

6.3.1. **Measurement based simulations**

Simulations based on measurement inputs do not depend on any models of units. They only depend on the grid model, an input time series of the voltage measurements at the transformer, and the power time series at all households. These active and reactive power time series consist of measured data wherever possible. Transformer and household measurements originate from the data sources described in paragraph 5.1.1. There are values within time series and whole time series that needed to be approximated because they were missing (see paragraph 5.1.2 for reasons and measures taken).

Again, the challenge of synthesizing power measurements that deviate as little as possible from what happened in reality needed to be addressed (see paragraph 6.2.1 for details).The used approach was therefore in line with previous experiences. The deviations between the power time series at the transformer and aggregated measured powers at households were calculated. The resulting power value at every time step represented the aggregated power of the households without measurements (line losses were considered). Each household with missing measurements was apportioned a share of this time series according to the households' relative shares of annual energy consumption which was known. This was done for both active and reactive power.

With the full year of measurement data (October 2016 to September 2017) yearly simulations are possible. While the transformer voltage and household power measurements are given, the underlying grid model of these simulations can be varied. It is thus possible to simulate the effect of potential grid reinforcements on the voltages with currently observed power measurements. To that end, two scenarios with varying grid model were defined:

- Scenario "status quo" with the original Riedholz grid model.
- Scenario "classical grid reinforcement" which features a grid model where the long cable section between transformer and neighborhood is replaced with a cable with doubled cross section (corresponds to a halving of the cable resistance).

Apart from the described difference in the underlying grid model the two simulation scenarios are identical.

6.3.2. **Model based simulations**

The current real system configuration of the test area in Riedholz served as a realistic inspiration for the model based simulations. This also ensures that certain simulated comparisons can be used as an indication for the outcome of corresponding real-world comparisons. However, it must be mentioned that these simulation results should not be compared one-to-one to the current situation in the Riedholz test area. There are two reasons for this: firstly, the purpose of the simulations is to assess the functionality of GridSense in universal situations, not only particularly applied to the Riedholz test area. The simulation scenarios therefore deviate from the test area for the sake of optimal inter-scenario comparability. Secondly, structural household information and measurements were missing, so it would not have been possible to create a simulation scenario that matches one-to-one with the measurements even if this had been a goal in the context of this project.

In the following, details about the base case simulation scenario are given. The other simulations are variations of the base case, so we only describe in what way they differ from the base case simulation. Table 5 is a summary about all model-based simulations that were carried out with information in what way they differ from the base case simulation. In total, 38 different scenarios were simulated. All simulations feature 56 households which are always attached to the same nodes of the electric distribution system. In all scenarios there are no households that own two units of the same kind. We use the following definition for GSU penetration: Percentage of potentially GridSense-controllable devices (boilers, heat pumps, batteries, and electric vehicles) that are controlled by GridSense. The grid topology and the distribution of households in the simulation scenarios are shown in Figure 35.

Figure 35 – Overview of household position and names for model-based simulations. The light blue color represents the single-phase representation of the electric distribution grid in the test area. Note that the abbreviations in the names of the households were varied according to the devices that were installed. The numbers with which each name starts stays the same during all simulations and serves as identifier. Abbreviation explanation: BOI (boiler), BAT (battery), HP (heat pump).

In the base case scenario, the electric distribution grid model is identical to the real distribution grid in the test area in Riedholz. As listed in Table 4 the base case scenario features 39 electric boilers, 25 heat pumps, 7 PV units, 3 batteries and 5 electric vehicles distributed among the households (see Table 9 in the Appendix for exact connection nodes and household details). Detailed specifications such as rated powers, battery capacities, or assumed usage patterns of the unit models can be found in the Appendix in paragraph 13.1.2.
54 out of a total of 72 flexible devices are GridSense-controlled in the base case scenario. This is equivalent to a GSU-penetration of 75 %. Please take note of the difference between the share of households that is equipped with GridSense of 52 % (see Table 4) compared to the GSU penetration of 75 % in the same scenario. The deviation exists because several households have no units that are potentially GridSense-controllable and due to the principle that households with a high number of GridSense-controllable devices are more likely to be equipped with the GridSense system.

Table 4 – Overview of system configuration of the base case simulation scenario (deviates slightly from the reality in Riedholz). Household share represents the relative amount of households which feature a certain device type. Not all households have flexible electric devices that can be controlled by GridSense. Batteries are only present in households with a PV unit. If a household is equipped with the GridSense system all of its controllable devices are equipped with GSUs. In the context of this report the terms household and prosumer are used interchangeably.

	Households	Boilers	Heat pumps	PV	Batteries	EVs	GS households
Absolute number	56	39	25	7	3	5	29
Household share	-	0.7	0.45	0.13	0.05	0.09	0.52

The definition of the scenarios was based on the following list of research questions (the individual scenarios are listed, described, and linked to research questions in Table 5):

0. **Base case comparison GridSense activated/deactivated**
   The base case comparison features three simulations which all consist of the described physical system configuration. The only difference lies in the way how the household devices are controlled: in the scenario *Base Case GS off* only the standard internal controllers are in use. *Base Case Grid-mode* is a simulation in which devices are GridSense-controlled with the grid-mode to support the grid. The third simulation scenario in this simulation package is one with ripple control for boilers (*Base Case ripple control GS off*). These scenarios are used to analyze the general effects of GridSense in a basic electric distribution system.

1. **Penetration with GridSense-Units**
   To analyze the effect of varying GSU penetration levels the share of flexible units which are controlled by GridSense is varied in 25%-steps. The scenario *Base Case GS off* can be used as a base line comparison for the identical system without any control by GridSense.

2. **Alternatives to GridSense (benchmark)**
   It is important to compare GridSense's performance with alternative, well-known measures that are deployed to support the grid. These are namely classic grid reinforcement (replacing existing conductors with conductors with less resistance, i.e. in this case using thicker cables), installing an on-load tap-changer (OLTC) which is in our simulation equivalent to a line voltage regulator, or introducing a system for PV curtailment. Out of these three measures the two first-mentioned ones help in case of under- or overvoltages. However, PV curtailment obviously only has the potential to reduce overvoltages that originate from PV infeed. Since PV infeed is not problematic in the base case scenario, PV curtailment is applied in a scenario with an increased number of PV units. It can then be compared to the GridSense performance in another scenario with the same elevated level of PV penetration. Also part of this question are scenarios that are combinations of two other scenarios. One motivation for this is to test alternative measures under the conditions of a grid with higher loadings. The other motivation is to test the viability of combining GridSense with a classic grid reinforcement.

3. **GridSense performance in different seasons**
   GridSense's performance in different seasons is assessed by separately analyzing the results of the base case simulation by meteorological season.

4. **Impact of installed household units on performance of GridSense**
   Different questions related to the performance of GridSense in the context of varying different types of units were examined. It is of interest, how GridSense performs with varying prevalence

of different unit types. Also, the effect on GridSense performance by an increased amount of distributed generation by PV units was evaluated. Another aspect of importance is the comparison of GridSense's effectiveness between different unit types. To achieve those goals, the prevalence of unit types was varied one at a time in order to maintain cross-comparability of scenarios.

5. **Electricity bill analysis**
   Apart from the grid-mode GridSense also features a hybrid-mode. The hybrid-mode reduces household electricity bills while still operating devices grid-friendly. One key aspect of ripple control is also the reduction of household electricity bills by limiting boiler run-time to off-peak tariff hours. We thus simultaneously compare the electricity bills and the status of the grid in simulation scenarios with GridSense in grid- and in hybrid-mode with the base case scenarios with and without ripple control for boilers.

6. **Influence of grid topology on the performance of GridSense**
   In this question it is assessed if the GridSense performance is dependent on different grid topologies. We analyzed the effect of varying lengths of the main, ca. 250 m long cable which connects the transformer with the test area neighborhood. With a reduced cable length the grid corresponds roughly to an urban residential grid where transformers are usually located close to the densely populated supply region.

Table 5 – Overview of model based simulations in SoloGrid project. The principal design of the simulation scenarios optimized the opportunities for cross-comparisons while keeping the number of simulation scenarios as low as possible. There is therefore a base case with and without GS and all subsequent simulations are modulations of that base case. The first two entries in the table are the base cases which are in detail described in this report. Of the other simulations, only differing components or grid configurations from the base case are listed. Not explicitly listed aspects of simulations are identical to the base case (BC). Batteries are reactively controlled when GS is off and always in self-consumption-mode with activated GS (even though all the other devices are in grid- or hybrid-mode). Reactive control means that one tries to bring the household net power to zero: the battery is charged when there is net production and discharged when there is net consumption within a household. The tap-changing transformer has seven levels, it is activated when the voltage at the reference bus exceeds the [0.925, 1.075] p.u. voltage band, and it has uniform tap-sizes of 2.5 %. The reference bus is one of the buses furthest downstream from the transformer and a good representative for the area of the grid with voltage problems. Ripple control is carried out with three randomly assembled boiler groups which each are activated in two shifted 2-hour time windows overnight. PV curtailment is activated when the voltage at a reference bus exceeds a voltage of 1.1 p.u. In that case all PV units are curtailed to 60 % of their rated power. The reference bus is again one of the buses furthest downstream and representative for the, voltage-wise, most problematic area in the grid. In the unit variation related scenarios, the units whose amount was varied were all controlled by GS, hence the slightly higher number of GS controlled units compared to the BC.

Name	GS status	GS controlled units (share of controllable devices)	Components	Control strategies	Research question	Comments
Base Case GS off	**off**	**-**	**BC**	**-**	**all**	**BC without GridSense**
Base Case grid-mode	**on**	**75%**	**BC**	**GS grid-mode**	**all**	**BC with GridSense**
Base Case ripple control GS off	off	75%	BC	Ripple control for boilers (3 groups)	0, 5	-
Base Case hybrid-mode	on	75%	BC	GS hybrid-mode	5	-
Alternatives tap-changing transformer GS off	off	-	Tap-changing transformer with 7 levels	Tap-changing voltage control	2	-

Alternatives thicker cable GS off	off	-	Main cable with a doubled cross-section	-	2	-
Alternatives PV curtailment GS off	off	-	28 PV-units	PV curtailment vs. overvoltages	2	-
GSU penetration 25% grid-mode	on	25%	BC	GS grid-mode	1	-
GSU penetration 50% grid-mode	on	50%	BC	GS grid-mode	1	-
GSU penetration 75% grid-mode	on	BC	BC	GS grid-mode	1	≙ BC grid-m
GSU penetration 100% grid-mode	on	100%	BC	GS grid-mode	1	-
Unit variation battery 50% GS off	off	-	28 batteries, 28 PV-units	-	4	-
Unit variation battery 50% grid-mode	on	> 75%	28 batteries, 28 PV-units	GS grid-mode	4	-
Unit variation boiler 100% GS off	off	-	56 boilers	-	4	-
Unit variation boiler 100% grid-mode	on	> 75%	56 boilers	GS grid-mode	4	-
Unit variation EV 50% GS off	off	-	28 electric vehicles	-	4	-
Unit variation EV 50% grid-mode	on	> 75%	28 electric vehicles	GS grid-mode	4	-
Unit variation heatpumps 66% GS off	off	-	37 heat pumps	-	4	-
Unit variation heatpumps 66% grid-mode	on	> 75%	37 heat pumps	GS grid-mode	4	-

Unit variation heatpumps 100% GS off	off	-	56 heat pumps	-	4	-
Unit variation heatpumps 100% grid-mode	on	> 75%	56 heat pumps	GS grid-mode	4	-
Unit variation PV 12.5% GS off	off	-	BC	-	4	≙ BC GS off
Unit variation PV 12.5% grid-mode	on	BC	BC	GS grid-mode	4	≙ BC grid-m
Unit variation PV 25% GS off	off	-	14 PV-units	-	4	-
Unit variation PV 25% grid-mode	on	BC	14 PV-units	GS grid-mode	4	-
Unit variation PV 37.5% GS off	off	-	21 PV-units	-	4	-
Unit variation PV 37.5% grid-mode	on	BC	21 PV-units	GS grid-mode	4	-
Unit variation PV 50% GS off	off	-	28 PV-units	-	4	-
Unit variation PV 50% grid-mode	on	BC	28 PV-units	GS grid-mode	4	-
Grid topology line 0% GS off	off	-	Main cable 0 % orig. length	-	6	-
Grid topology line 0% grid-mode	on	BC	Main cable 0 % orig. length	GS grid-mode	6	-
Grid topology line 50% GS off	off	-	Main cable 50 % orig. length	-	6	-
Grid topology line 50% grid-mode	on	BC	Main cable 50 % orig. length	GS grid-mode	6	-
Grid topology line 100% GS off	off	-	BC	-	6	≙ BC GS off

<table>
<tr><td>Grid topology line 100% grid-mode</td><td>on</td><td>BC</td><td>BC</td><td>GS grid-mode</td><td>6</td><td>≙ BC grid-m</td></tr>
<tr><td>Combinations HPs 66% | tap-changing transformer GS off</td><td>off</td><td>-</td><td>37 HPs, OLTC 7 levels</td><td>-</td><td>2</td><td>-</td></tr>
<tr><td>Combinations HPs 66% | thicker cable GS off</td><td>off</td><td>-</td><td>37 HPs, main cable doubled cross-section</td><td></td><td>2</td><td>-</td></tr>
<tr><td>Combinations HPs 66% | thicker cable grid-mode</td><td>on</td><td>> 75%</td><td>37 HPs, main cable doubled cross-section</td><td>GS grid-mode</td><td>2</td><td>-</td></tr>
<tr><td>Combinations PV 50% | tap-changing trans-former GS off</td><td>off</td><td>-</td><td>28 PV units, OLTC 7 levels</td><td>-</td><td>2</td><td>-</td></tr>
<tr><td>Combinations PV 50% | thicker cable GS off</td><td>off</td><td>-</td><td>28 PV units, main cable dou-bled cross-section</td><td>-</td><td>2</td><td>-</td></tr>
<tr><td>Combinations PV 50% | thicker cable grid-mode</td><td>on</td><td>BC</td><td>28 PV units, main cable dou-bled cross-section</td><td>GS grid-mode</td><td>2</td><td>-</td></tr>
</table>

6.4. Simulation Results

The presentation of simulation results is structured into two parts: first the results of the simulations with measurements inputs are shown and discussed and in the subsequent chapters the model based simulation results are presented and analyzed.

It is important to keep in mind that not the same analyses were applicable for the two different types of simulations. For the simulations with measured active and reactive power inputs the analyses had to take into account the boundary conditions and be thus more based on statistics. For the purely modelled simulations an exact same copy of the system with identical boundary conditions could be simulated once with and once without activated GridSense. These results can be directly compared because one does not have to take into account differing boundary conditions like the weather or the influence of the medium voltage grid on voltages.

6.4.1. **Simulations with measurement inputs**

Low ambient temperatures can be associated with under-voltages in distribution grids with substantial prevalence of electric boilers, heat pumps, or even direct electric heating. Indirectly, low temperatures can in addition be a proxy for nighttime, during which voltages in residential distribution grids tend to be lower because of electric lighting, ripple controlled activation patterns, and the lack of any power generation by PV units. This makes temperature an important boundary condition which should be taken into account when household measurements are analyzed. This is relevant here because the simulations were run with measurements as inputs so the results must be treated accordingly.

The measure which is used as an indicator for grid voltage status is the daily voltage range. The daily voltage range is defined as the difference between the highest and lowest 10-minute mean voltage at a household over a day. It is desirable to keep the voltage within a stable voltage band. Therefore, big variations of the voltage should be avoided. Figure 36 depicts the corresponding analysis for two measurement powered simulations, one with the grid model as a reflection of the current distribution grid and the second one with a grid model which represents a classical reinforcement in that the main cable has a doubled cross-sectional area. This roughly equals to a halved resistance of that cable.

The first important take-away is the difference in the means of plot A. On average, a 4.5 V lower daily voltage range is observed during times when GridSense is active compared to times of inactivity. The second important message is derived by comparing GridSense ON of part A. with GridSense OFF of part B. By using a reinforced grid model the mean daily voltage range during times of GridSense OFF was decreased from 19.9 V to 15.4 V. This is in the same range as the mean daily voltage ranges are with the original grid when GridSense is active. Our conclusion is thus that the positive effect of GridSense on the mean daily voltage range is comparable to the effect of a classical grid reinforcement.

The same figure type but with data from only the colder half of the year (October 2016 to March 2017) is shown in Figure 37. During that time the daily voltage ranges are larger and the positive influence of activated GridSense is so, too. Compared to classical grid reinforcement the effect of GridSense seems to be at least comparable if not superior. Please note that the data of the colder part of the year are a subset of the whole year. However, the color scale of the figures is adjusted to the temperature range so the coloring does not match exactly.

In addition to the visual and calculated mean difference shown in Figure 36, a multiple linear regression can be run to test for statistical significance of the GridSense status. Such an analysis also yields an estimation of the relevance of different predictor variables given by their coefficients (estimate). Three predictor terms were used for the regression: the GridSense status, the daily mean temperature, and an interaction term of GridSense status and daily mean temperature.

In Table 6 the regression results are listed. All predictors are highly significant and should therefore remain in the model. The continuous variable *Daily mean temperature* has a negative estimate of -0.6 V. In practice this means that an increase of the daily mean temperature by 10°C will generally lead to a decrease of the daily voltage range by 6 V. *GridSense status* is a binary categorical variable with entries either ON or OFF. The estimate for this predictor show that in general the daily voltage range is reduced by 7.2 V if GridSense is active. This difference is larger than what was observed when comparing the means of the data. However, it comes as no surprise because GridSense was proportionately more often active during cold times when the daily voltage range is normally larger. In the regression this comparative disadvantage is taken into account by using temperature as a separate predictor. An interesting result is the estimate for the interaction term of *Daily mean temperature* and *GridSense status*: the positive value of 0.24 V mean that the temperature dependency of the daily voltage range decreases when GridSense is active. In practice this means the increase in voltage range when the temperature goes from 0°C to -10°C is generally observed to be 6 V without GridSense and only 3.6 V when it is active (this is on top of the general daily voltage range reduction which was observed to occur when GridSense is active). This result can be qualitatively observed in Figure 36 with the blue trend lines which have smaller slopes when GridSense is active.

Table 6 – Multiple linear regression output for mean daily voltage range as response variable with the *daily mean temperature*, the *GridSense status*, and the interaction term of daily mean temperature multiplied with GridSense status as predictors (denoted as *Daily mean temperature:GridSense status ON*).

Coefficients	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	25	0.084	310.5	<2e-16 ***
Daily mean temperature	-0.6	0.006	-93.2	<2e-16 ***
GridSense status ON	-7.21	0.13	-55.8	<2e-16 ***
Daily mean temperature:GridSense status ON	0.24	0.010	24	<2e-16 ***

Such a regression was run for both simulation scenarios, the one with original grid model and the one with a reinforced grid. The results with a reinforced grid are not shown here because they are analogous to the case with the original grid model in that all predictors are highly significant. Not surprisingly, given generally smaller voltage ranges, the magnitude of effects given by the estimates is smaller.

In conclusion, a clear positive effect of GridSense on the daily voltage range is visually shown and statistically quantified. The daily voltage range is shown to be reduced by more than 7 V with GridSense being activated and on top of that it is observed to be less negatively impacted by low temperatures while GridSense is active. The comparison between the results with the original grid model and the reinforced grid model indicate that the effect of GridSense on the daily voltage range is comparable to the effect of a classic grid reinforcement.

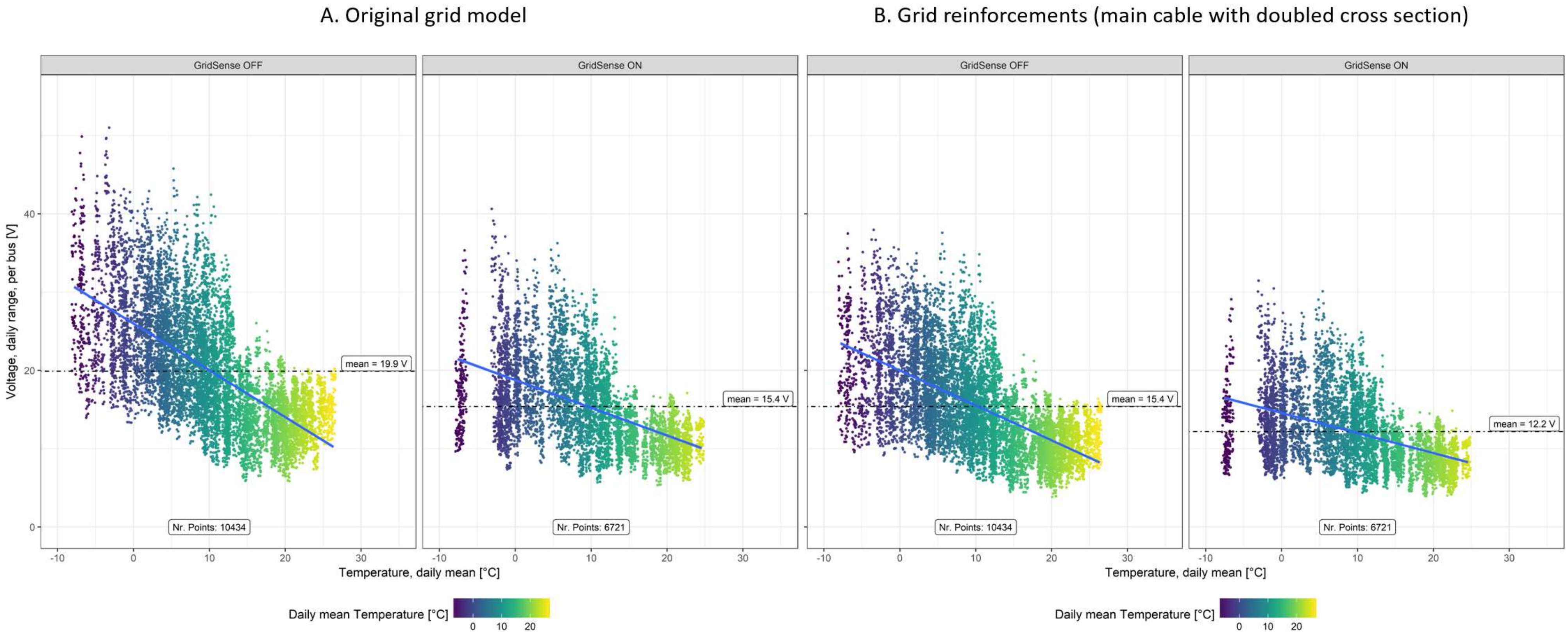


Figure 36 – Daily voltage range vs. daily mean temperature – comparison between GridSense and grid reinforcements (measurement period: 01.10.2016 – 30.09.2017). GridSense OFF includes times when ripple control was activated and times when no control schemes were active. The daily voltage range is defined as the difference between the highest and lowest 10-minute mean voltage at a household over a day. The blue lines serve as a trend indication, they were obtained with a least squares regression. The time periods without GridSense were longer than when GridSense was activated, hence the higher number of points. The hole in GridSense ON data between -2.5°C and -6°C is due to a lack of days with these temperatures during the observation period when GridSense was active. The temperature measurements were conducted 2 m above ground in Riedholz. Measured and synthesized active and reactive power values at households were used as input for the simulations. Input data for simulation A and B are identical. The only difference is the grid model which was changed for Simulation B: a classic grid reinforcement was simulated by halving the resistance of the main cable of the grid model (this corresponds to a replacement by a cable with doubled cross-sectional area).

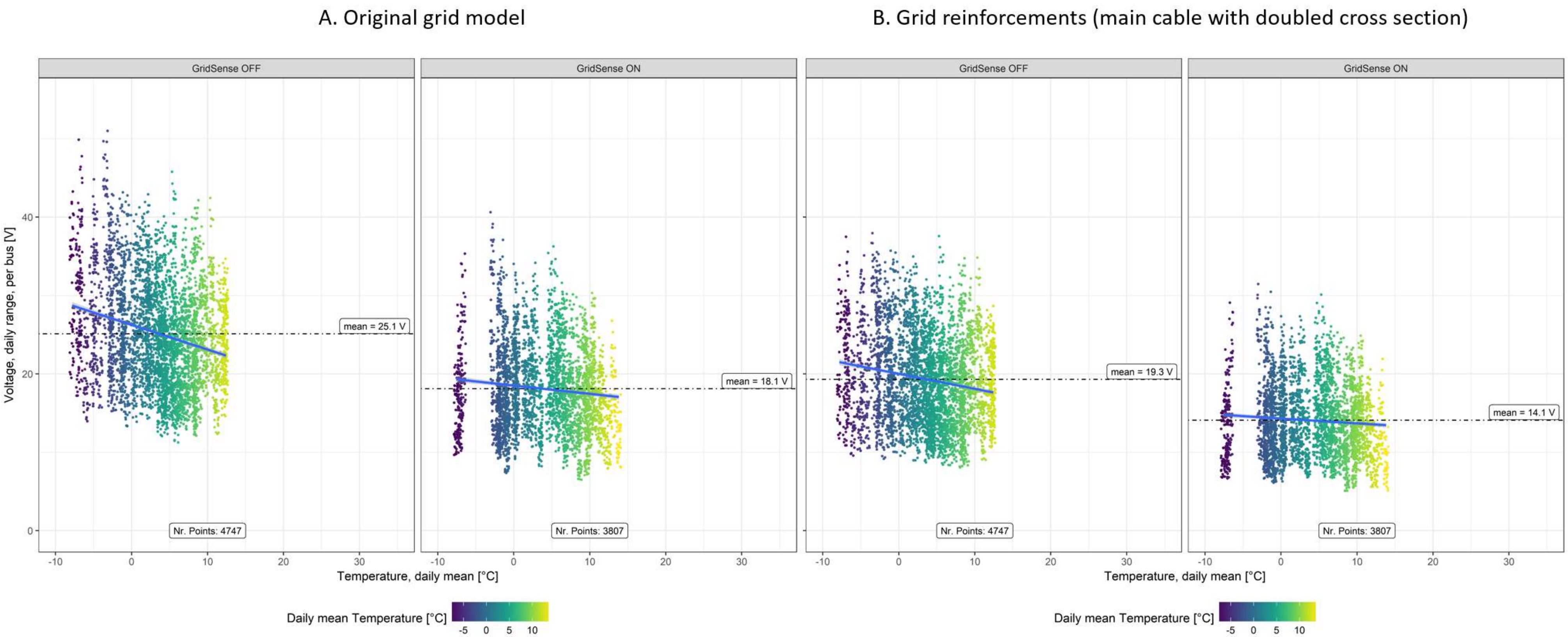


Figure 37 – Daily voltage range vs. daily mean temperature – comparison between GridSense and grid reinforcements (measurement period: 01.10.2016 – 31.03.2017). GridSense OFF includes times when ripple control was activated and times when no control schemes were active. The daily voltage range is defined as the difference between the highest and lowest 10-minute mean voltage at a household over a day. The blue lines serve as a trend indication, they were obtained with a least squares regression. The time periods without GridSense were longer than when GridSense was activated, hence the higher number of points. The hole in GridSense ON data between -2.5°C and -6°C is due to a lack of days with these temperatures during the observation period when GridSense was active. The temperature measurements were conducted 2 m above ground in Riedholz. Measured and synthesized active and reactive power values at households were used as input for the simulations. Input data for simulation A and B are identical. The only difference is the grid model which was changed for Simulation B: a classic grid reinforcement was simulated by halving the resistance of the main cable of the grid model (this corresponds to a replacement by a cable with doubled cross-sectional area).

6.4.2. **Model based simulations**

The description and discussion of the model based simulation results is structured according to the investigated questions related with the performance of GridSense:

- Base case comparison GridSense activated/deactivated
- Electricity bill analysis
- Penetration with GridSense-Units
- Alternatives to GridSense (benchmark)
- GridSense performance in different seasons
- Impact of installed household units on the performance of GridSense
- Influence of grid topology on the performance of GridSense

The conducted analyses of every simulation follow the same structure. The base case results are in the following in detail reported and discussed. Aggregated measures will be used to cover the remaining simulations in order to keep the results overseeable.

The reduction of voltage violations is one of the core targets of GridSense. In Figure 38 there is thus an overview with the voltage violations according to norm EN 50160 [4]. In this norm it is defined that during every week at least 95 % of the 10-minute mean voltage values at individual households need to be within the voltage band of reference voltage ±10 %. If this is not the case the voltage is violated for the household and week in question. This voltage violation norm is a good measure to compare different simulation scenarios because problems associated with voltage were nearly the only cause of grid problems in the simulation scenarios presented here.

Line loadings only become a relevant matter in the most extreme scenarios examined as part of this report and also transformer loadings are not problematic. Additionally, reducing voltage violations according to norm EN 50160 has always been one of the core targets in the development of GridSense.

Detailed simulation results

Many more detailed figures and tables were produced and used to support the analysis of every simulation mentioned in this report. These detailed simulation reports are available in digital format upon request[3].

[3] Please get in contact with Adaptricity via contact@adaptricity.com.

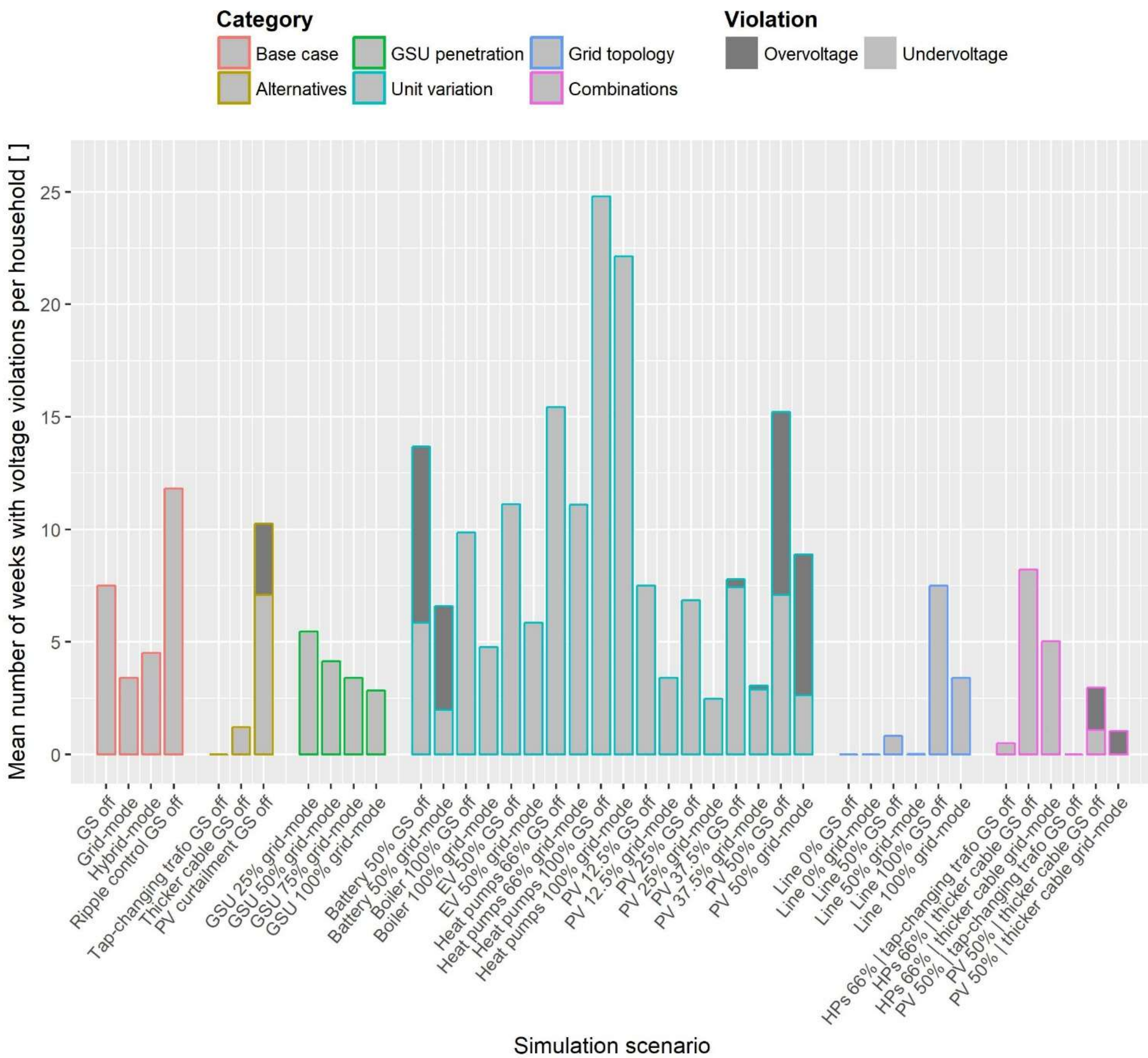


Figure 38 – Mean number of weeks with a voltage violation (norm EN 50160) per household over one year by simulation scenario. The detailed settings for every depicted simulation can be found in Table 5 where all model based simulations are listed by name. At the PV levels in the base case no over-voltages occur. Small differences observed in the category "unit variation" should not be treated as significant because the variation of devices had a (limited) influence on the fixed master seed. It thus created a small variability that is not solely caused by the variation of the unit under investigation. This only applies to scenarios with a unit variation and even there the device parameters in comparative simulations with and without activated GridSense are still identical. Please note that these results are generated with fully model based simulations (without measurements as inputs). It is therefore possible that these results slightly deviate from the findings that were obtained with measurements.

Base cases
As described, the base case simulations consist of identical electric distribution systems with identical prosumer features. The only difference lies in the way how flexible household devices are controlled.

Base Case GS off and *Base Case Grid-mode* are the two neutral base cases which are in the following in detail compared with each other. For interesting measures, they are compared to a scenario with ripple-control because this is a control strategy that is widely applied today. In fact, the test area in Riedholz would normally also feature ripple control for several device types.

One way to verify that the simulations featured components with identical parameters, is via checking the yearly consumption and output of their modelled devices. Figure 67 in the appendix depicts the energy consumption over a year of simulation of all devices. There are small differences in the energy consumption of batteries. Since they do not have any inherent demand that needs to be fulfilled, the way how they are controlled has an influence on how much energy they cycle. All batteries in the simulations are only allowed to be charged with excess PV generation at the same household. There might also be very small differences in the consumption of boilers and heat pumps that might arise when the thermal buffer of these devices is regularly exploited by GridSense to shift the charging phases. The outputs of PV units, however, is identical because there is no PV curtailment applied in the base cases as can be seen in Figure 68 in the appendix. Again, the output of the batteries differs slightly because of different control schemes.

The following detail plots of the base cases all consist of data from year-long simulations with a data sampling rate of 2.5 min. One figure always includes the comparison between the base case without GridSense (*Base Case GS off*) shown in the upper plot and its counterpart with activated GridSense (*Base Case grid-mode*) in the lower plot.

For convenience, the simulation household number is used as legend for voltages at households. These voltages are in fact the calculated voltage for the node in the grid to which the respective household is connected. Some households are connected to the same node in the grid, in such cases only the lower household number is displayed in the plot. This applies to the following groups of households: 10 and 11; 26 and 28; 27, 55, and 56; 37 and 38; 41, 42, 43, 44, and 45.

Due to the moderate PV penetration in the base cases they do not suffer from problems with over-voltages as evident from Figure 39. However, there are problems with severe under-voltages with values going down to about 180 V. When GridSense is activated these under-voltages are reduced. This can be seen in the histogram which features less observations at the lower end with GridSense on.

These observations are confirmed by the number of voltage violations according to norm EN 50160 which are shown in Figure 38. GridSense manages to halve the voltage violations in comparison with the base case without GridSense. It must also be stated that with GridSense activated, the voltage violations are only about a third in comparison with the base case system including ripple control for boilers. Ripple control is a widely applied way to control flexible devices like boilers so that they only run at night. These simulations, confirming the previously presented measurements, demonstrate clearly that ripple control has detrimental effects for the grid status. In this report, we thus compare the GridSense base case scenario in detail with the base case scenario without GridSense and without ripple control. This is a more neutral (and more conservative) benchmark. Otherwise, the design of the ripple control scheme, which is not equally implemented in different distribution grids, would have affected the outcome of the comparison. However, it must be stressed that since ripple control is widely applied, the benefits for the grid by using the GridSense system could in practice be as big as the difference between scenarios *Ripple control GS off* and *Grid-mode.*

The week-wise analysis of voltages outside ±10 % the reference presented in Figure 40 shows that the voltage norm violations occur during the cold periods of the year which is not surprising considering that we are talking about under-voltages in these scenarios. The figure further indicates that the reduction in voltage violations by GridSense is not uniform: the relative reduction in share of time with a voltage violation is in tendency bigger for weeks where the share of time with a violation is substantial but not extreme. This often applies to weeks during mid-seasons. It needs to be kept in mind that these are the results of the model based simulations where voltage violations occur more often than in the measurement analysis and in the measurement based simulations. First of all, the systems are by choice defined to be heavily stressed to unveil differences between scenarios. Additionally, result uncertainties increase the less measurement inputs are used for simulations. The model based time series might for instance feature more aggressive profiles than in reality which leads to more stress on the grid.

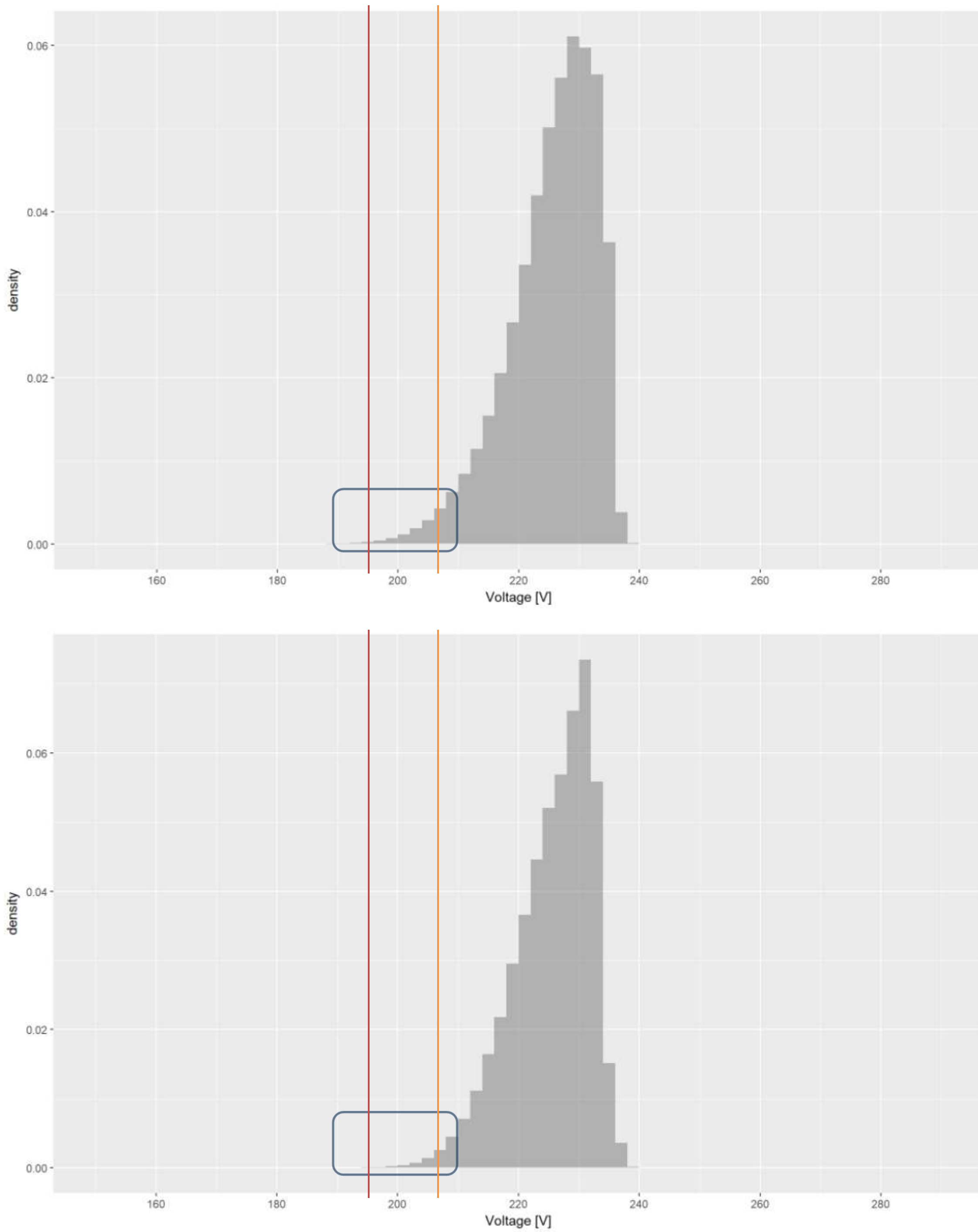


Figure 39 – Distribution of voltage values at households. In orange the soft limit of *207 V (0.9 p.u.) and in red the hard limit of 195.5 V (0.85 p.u.) stated in norm EN 50160 are designated. The rectangular shape is placed at identical positions in both plots to support the analysis by highlighting important differences.*
Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*

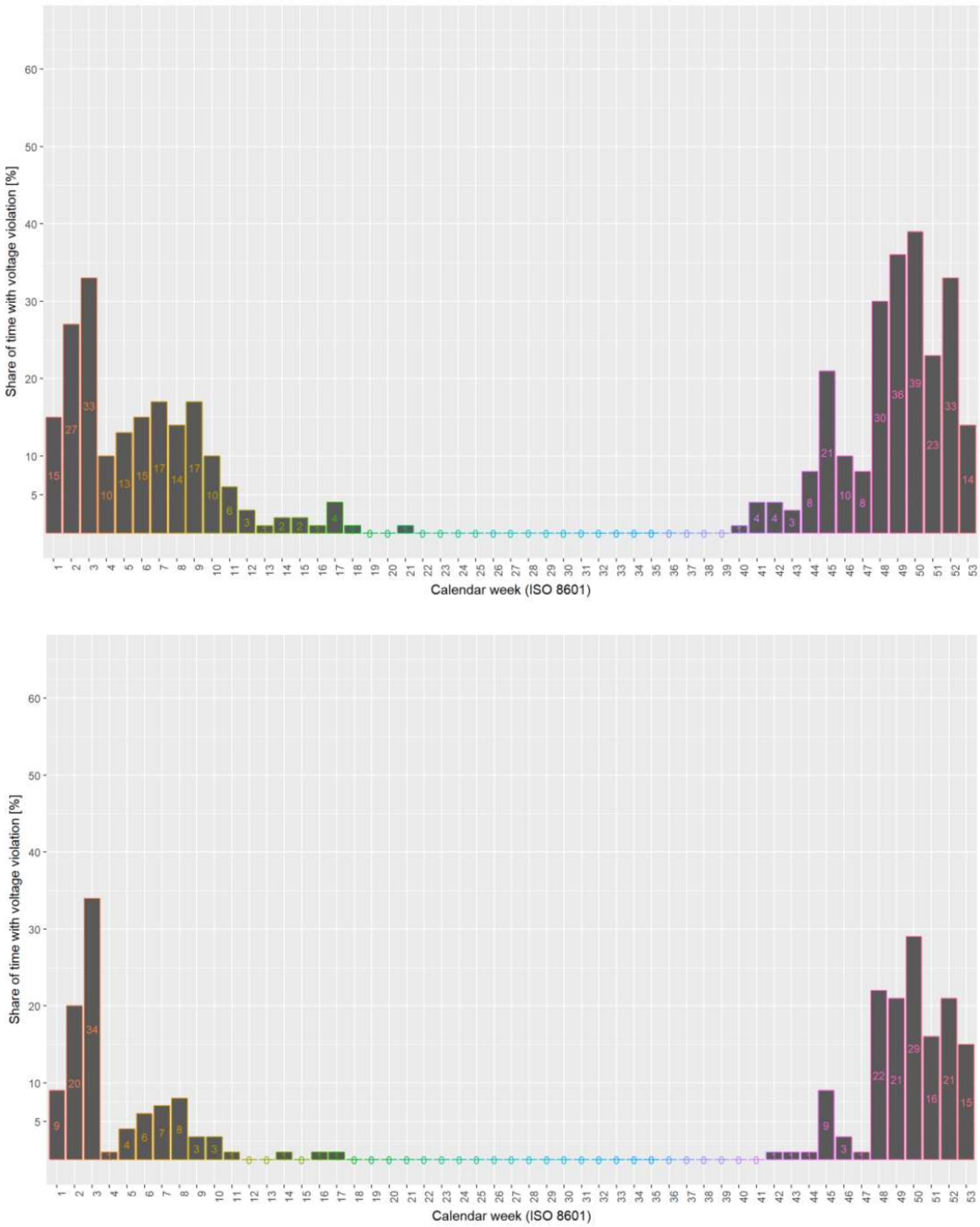


Figure 40 – Week-wise percentage of violations of voltage band of [0.9, 1.1] p.u. at reference household (Nr. 19). 10-minutes mean voltages were used for the calculations. These are results from the model based simulations which feature a highly stressed system. Simulation scenarios are intentionally defined to be in a stressed state to uncover differences between scenarios and partly it is a result of modelling uncertainty due to missing information. Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*

The frequency of extreme line loadings decreases when GridSense is active as shown in Figure 41. The effect is almost not visible at side branches but at the four most upstream cables where the effects are summed up a difference in line loadings is noticeable.

The visualization of the distribution of transformer power values confirms the previous statement that over-voltages due to PV infeed are not a problem in the base case scenarios: only small values of reversed power flows from the distribution grid to the middle voltage grid i.e. negative power at the transformer are observed. The shape of the power distribution clearly changes when GridSense is active. Moderate power values occur more frequently while the occurrence of extreme values decreases; the variance of the power distribution is reduced. This is a consequence of the way how GridSense supports the grid operation. By shifting the activation times of flexible devices from times of high demand to times of less demand, the loading of the system is evened out and therefore the stress reduced. This is also directly visible in Figure 43: it is rarer that the transformer loading is close to zero and the times of high loadings are in turn reduced. Another important take-away from this plot is that the transformer loading is rarely even above 50% so the transformer loading is not a problematic aspect in any of the simulations that were carried out for this report.

The breakdown of the power distribution by blocks of hour of the day presented in Figure 44 allows us to analyze which intra-day shifts of power took place when GridSense was active. Firstly, it solidifies the previous statements that the power distribution becomes narrower because of a reduction in extreme values on the upper end. The main difference in shape when GridSense is active is observed for the time-period between 00:00 and 05:59. The distribution of that time moves to the right and thus exhibits less times of power values close to 0. Importantly, this happens while there is a reduction in the frequency of very high-power values. GridSense causes this shift by pushing the activation times of devices to times of low power demand which are here mainly observed at night. By that, times of higher power demand are relieved. Reducing the (near) idle time of systems is a good strategy to increase their efficiency.

Considering the intra-day shifting of power consumption, scenario *Base Case ripple control GS off* offers an interesting comparison because it features a ripple control scheme for boilers. Ripple control is a way to shift power consumption from time of high demand to times of lower demand. It is widely applied in Switzerland to shift e.g. boiler activation to time windows at night and incentivized for end consumers by the lower power tariffs at night. The results presented in Figure 45 show that a substantial shift of power consumption occurs but it is also revealed that at least one of the original purposes is essentially not achieved: ripple control as it is implemented here leads to more idle times during the day which do not offer any advantage while creating times of overload at night. The fixed nature of the classical ripple control is a major disadvantage compared to GridSense which can flexibly react to the current situation in the grid.

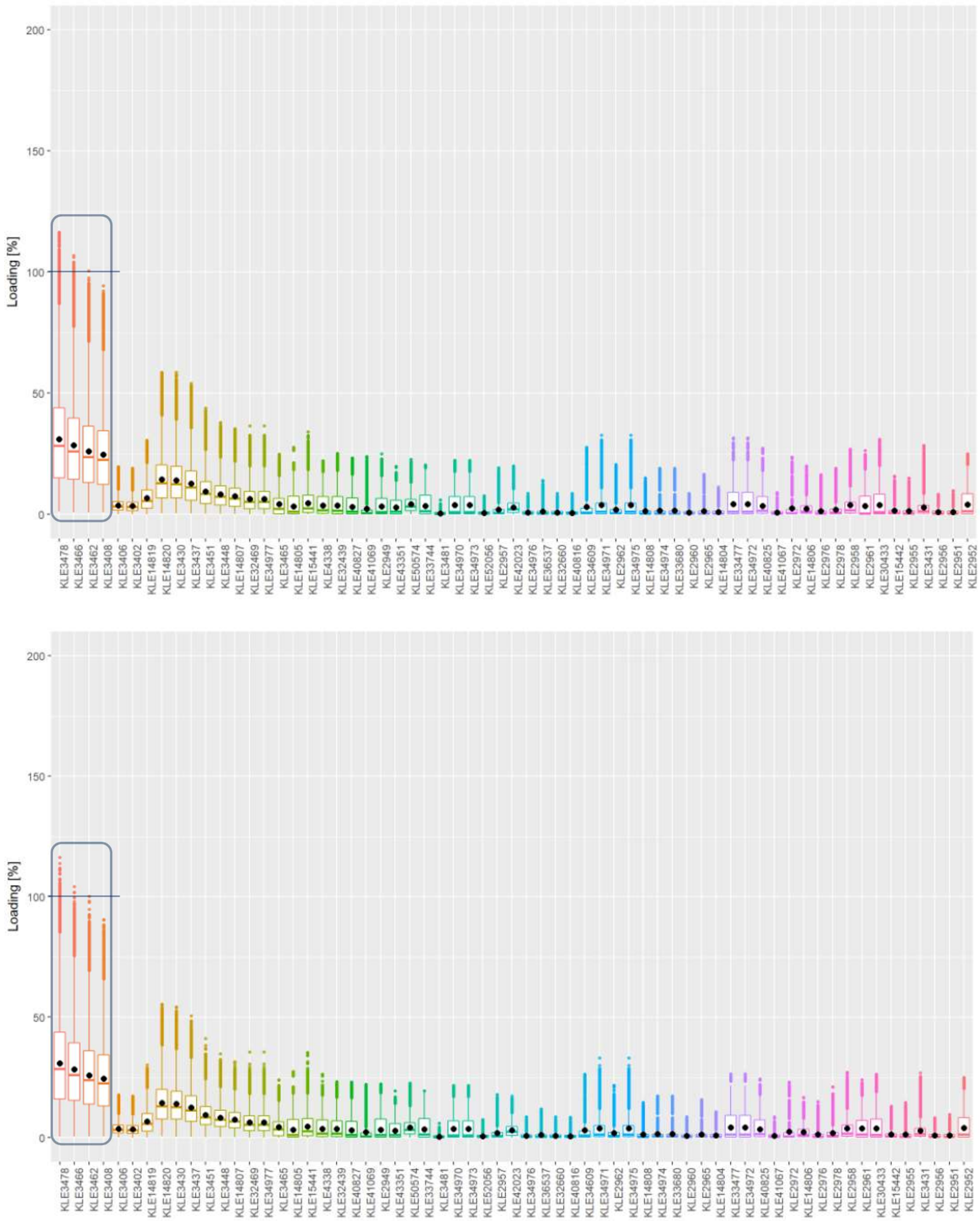


Figure 41 – Range of line loadings by individual line. Only line segments longer than 10 m were taken into consideration for this figure. The lines were roughly ordered from the transformer going downstream.
Lines in between with very low loadings are branch lines from the main connection. The rectangular shape highlights the lines where the loading is of interest because it reaches values around 100 %. These high loadings are where differences between the plots are visible.
Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*

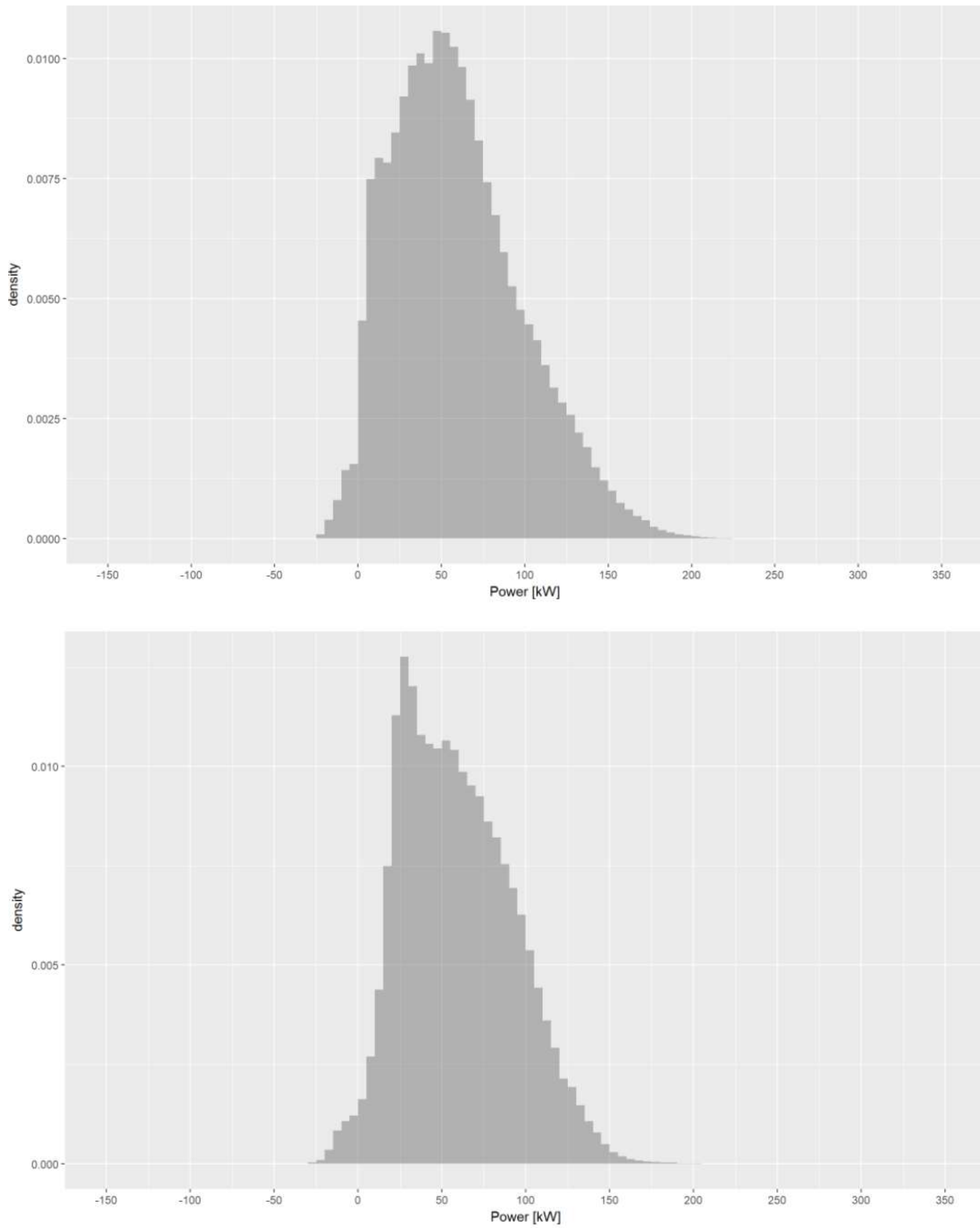


Figure 42 – Distribution of transformer power values.
Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*

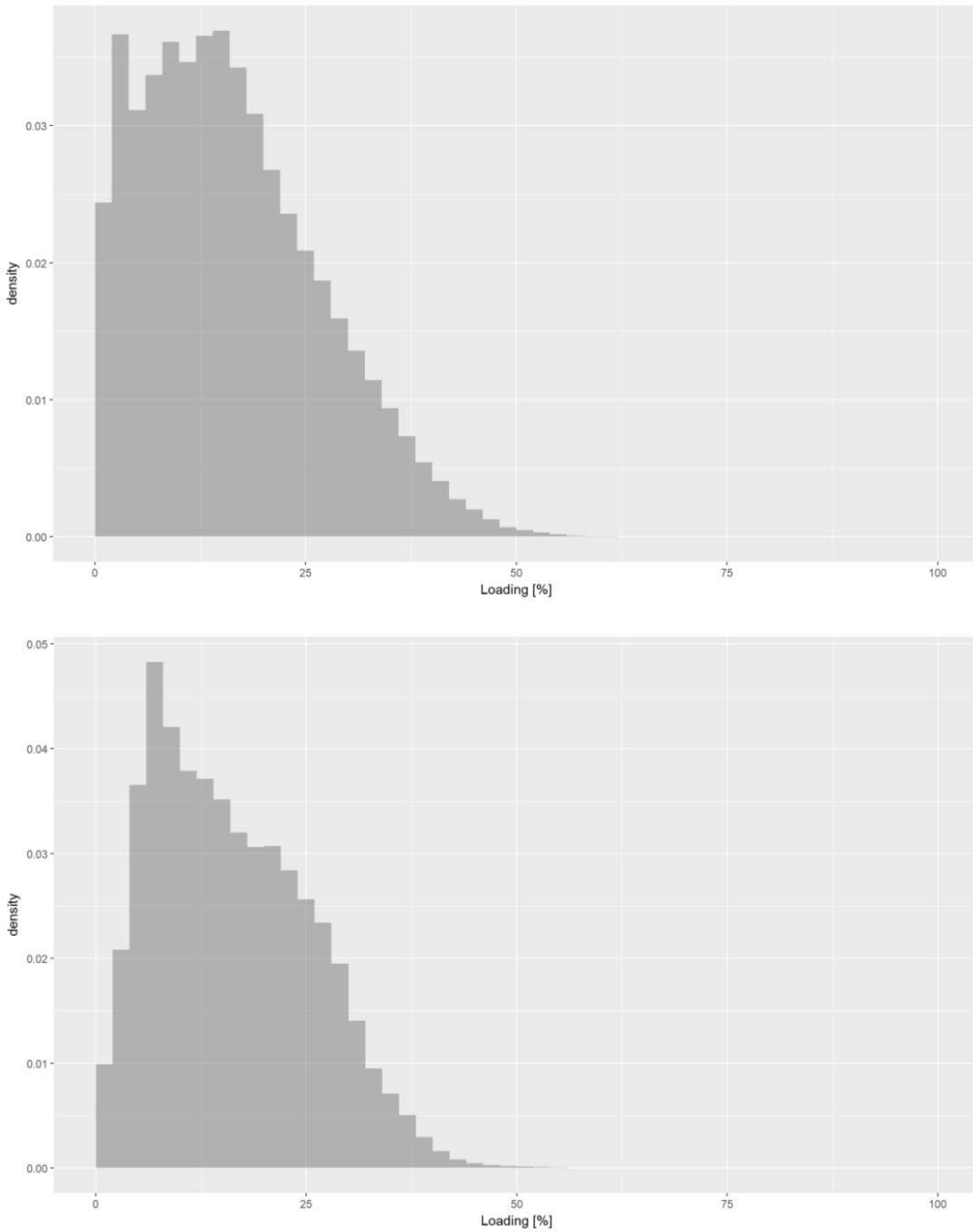


Figure 43 – Distribution of transformer loading.
Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*

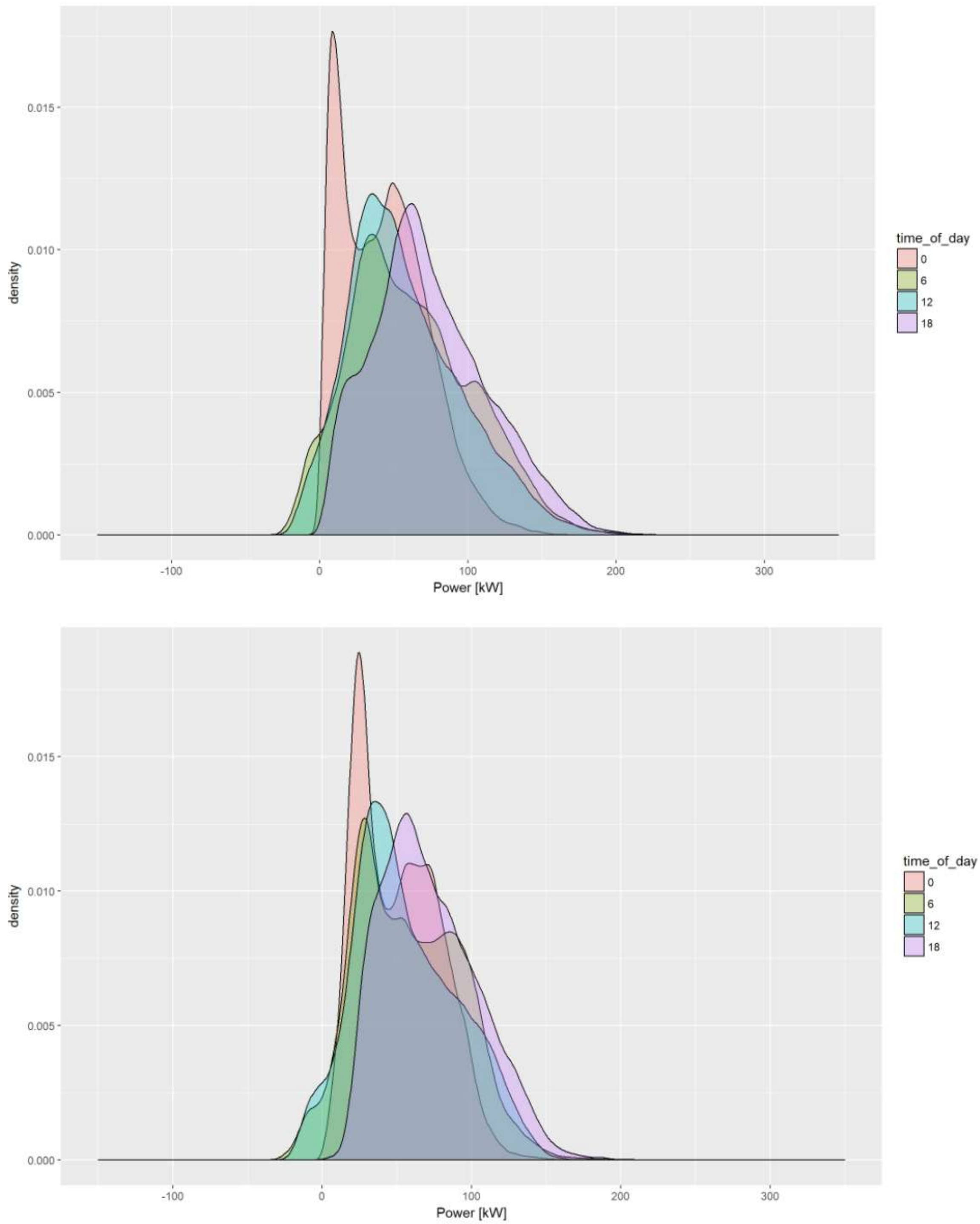


Figure 44 – Transformer power distributions by time of the day. The time intervals are 6 h long and start at the designated time in the legend, e.g. 0 stands for the time of the day from 00:00 to 05:59.
Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*

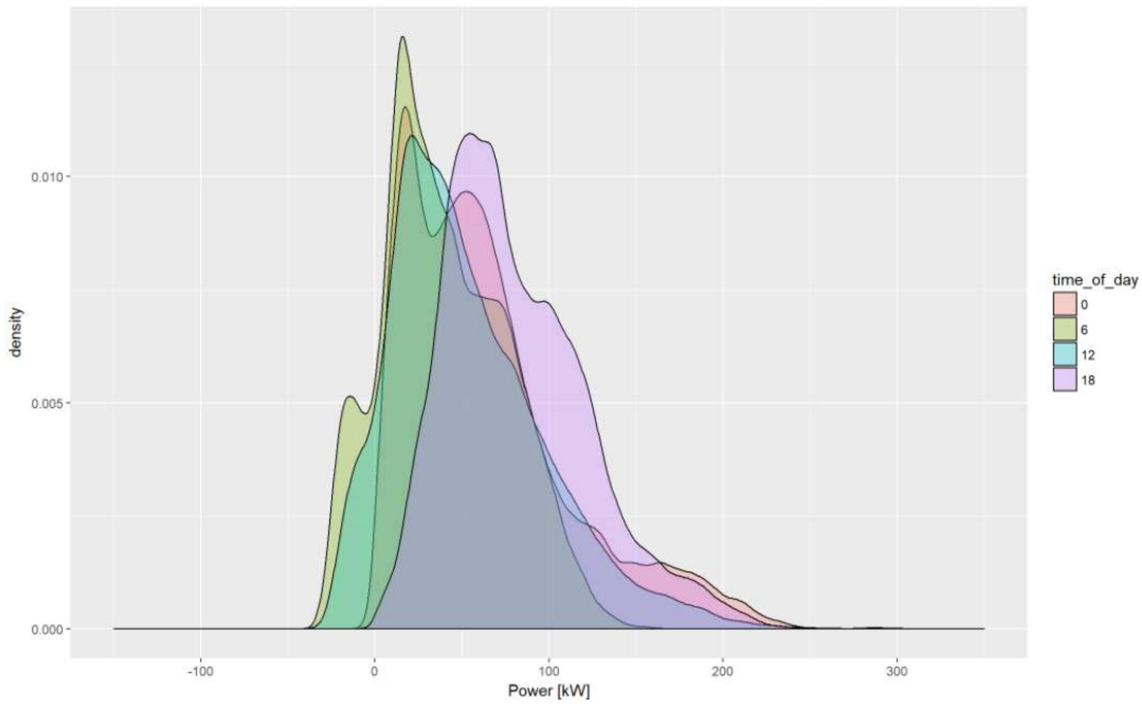


Figure 45 – Transformer power distributions by time of the day. The time intervals are 6 h long and start at the designated time in the legend, e.g. 0 stands for the time of the day from 00:00 to 05:59.
Simulation scenario: *Base Case ripple control GS off.*

At this point we conclude the analysis of the effect of GridSense on the status of the grid. In the grid-mode of GridSense an improvement of grid characteristics was observed. However, there is a second part which is important: while GridSense improves the grid situation, it is of outmost importance that there are no negative side-effects for participating prosumers. Thus, an analysis on the household level is needed to check for effects for individual prosumers.

The main factors that need to be examined are the durations and the number of times devices are active and the comfort level for users. GridSense needs to work in a way that no device-typical limitations on duration or number of status changes are exceeded and so that the user has no loss of comfort in using GridSense-controlled devices.

In the following figures a subset of devices is plotted. Namely only those devices that are controlled by GridSense in the scenario *Base Case grid-mode* are part of the plots. This measure was taken to ensure that the comparison involved only GridSense-controlled devices on one side and only devices without GridSense control on the other side.

Our analyses have shown that the average heat pump activation length is shorter when GridSense is activated compared to when it is not active. As expected, the heat pumps with GridSense were ca. 25 % times more often activated when GridSense was active. In summary, GridSense-controlled heat pumps have shorter but more activation phases. This is an expectable consequence when they flexibly react to current grid situations.

Without GridSense the heat pumps were on average active during 20 % of the total simulation time whereas they were on average active during 28 % of the time period they had clearance by GridSense (time where the unit has clearance is shorter than total simulation time, energy consumptions are nearly identical). This is for the full year, so the shares are significantly higher in winter where they go up to 42% and 58%. The analysis shows that the heat pumps were most likely not too constrained by Grid-Sense. The algorithm could have even been a bit more constraining on average. However, there were already individual heat pumps where that ratio went up to over 70 % when GridSense was active.

Figure 46 depicts the room temperatures of households that were heated by heat pumps. If the constraints by GridSense for heat pumps had been too strict we would see a decrease in temperature and thus end user comfort. However, there is no sign of any problems with comfort concerning the heat pumps. This is true for the base case but also for all the other simulations carried out for this project. The lowest observed temperatures for individual households with a GridSense controlled heat pump is around 19 °C and this applies to a household with a low temperature set point of ca. 20 °C.

An identical analysis was carried out for the boilers. The results that were observed with heat pumps are found to be more pronounced with boilers as the simulation results suggest. The median activation durations are clearly reduced while the number of activation phases is consequently substantially higher. GridSense-controlled boilers were on average 23 % of the time active when they had clearance by GridSense compared to 9 % of the simulation time that the boilers with conventional controllers were active (the energy consumptions are nearly identical). The number shows that boilers were time-wise not too constrained by GridSense. Constraining them more might have very well be possible and would have most possibly led to a better performance concerning grid support.

The state-of-charges of the boilers, an alternative way to represent the water temperature inside the boiler, are shown in Figure 47. It is evident that the internal hysteresis controller of the boilers is activated at a SOC of 70 % so they do not fall below that threshold when they are not GridSense-controlled. With GridSense, the SOCs fall further down to around 50 % and in the most extreme case even down to 40 %. The threshold where comfort decreases become noticeable is expected to be around those extremes values of 40 %. It can thus be concluded that there were no or extremely few comfort decreases due to boiler constraints. It must be noted that the results of the scenario *Base Case ripple control GS off* are strikingly worse in respect to low levels of boiler-SOCs (see Figure 48). This is a relevant comparison because of the wide-spread usage of ripple control for boilers.

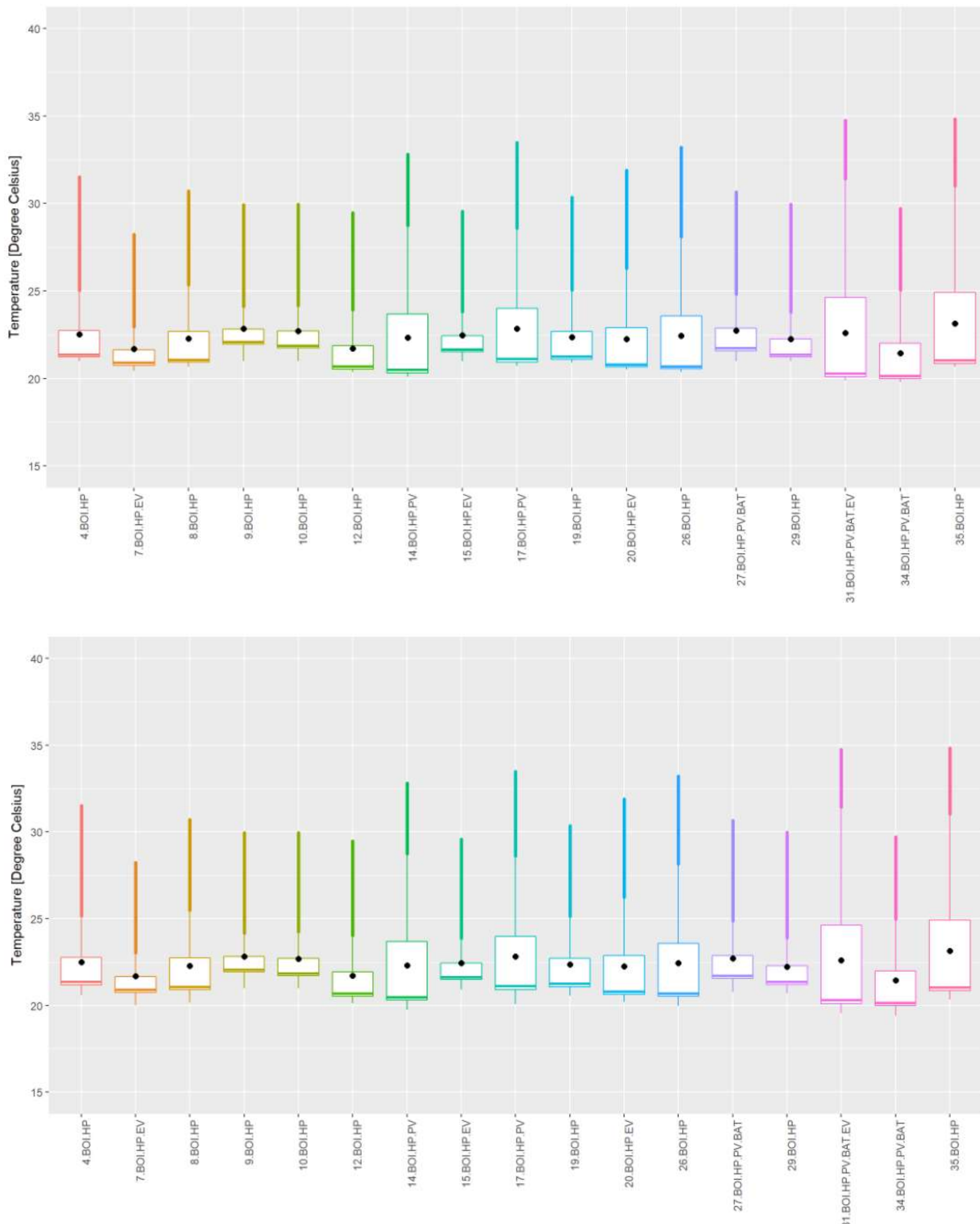


Figure 46 – Room temperature by individual household. The heat pump unit includes a thermal model of a building. In summer, the outside temperatures and the solar gains heat up the buildings without the heat pumps being active. The hysteresis controllers which govern the activation of the heat pumps have varied temperature set-points and dead bands as can be seen from the different lowest values.
Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*

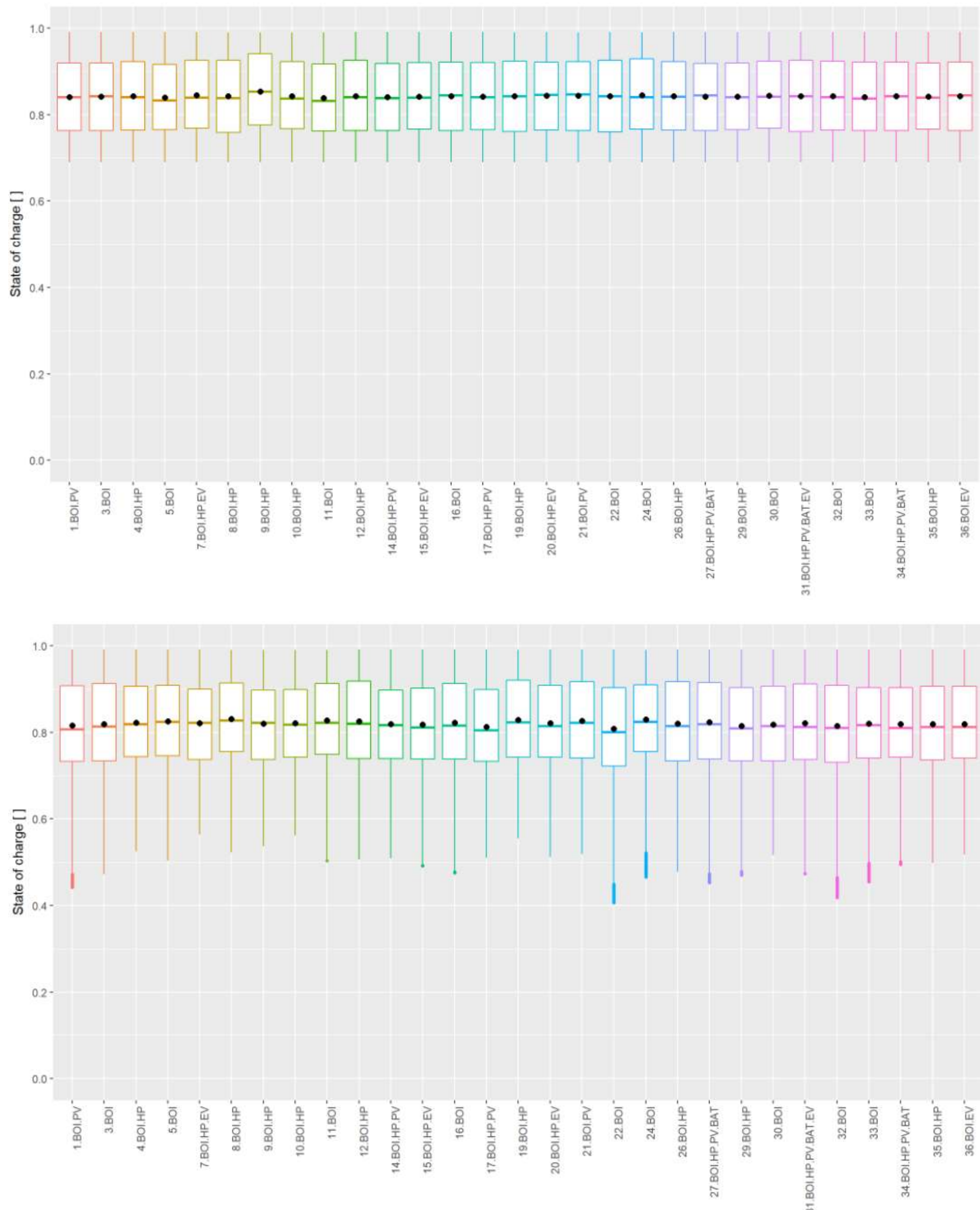


Figure 47 – State of charge by individual boiler. The state of charge directly translates to how much hot water remains in the boiler. The boilers' hysteresis controllers have fixed setpoints and dead bands state of charge-wise. However, the boilers have different settings for cold and hot water so in terms of water temperature, identical state of charges translate to differing values.
Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*

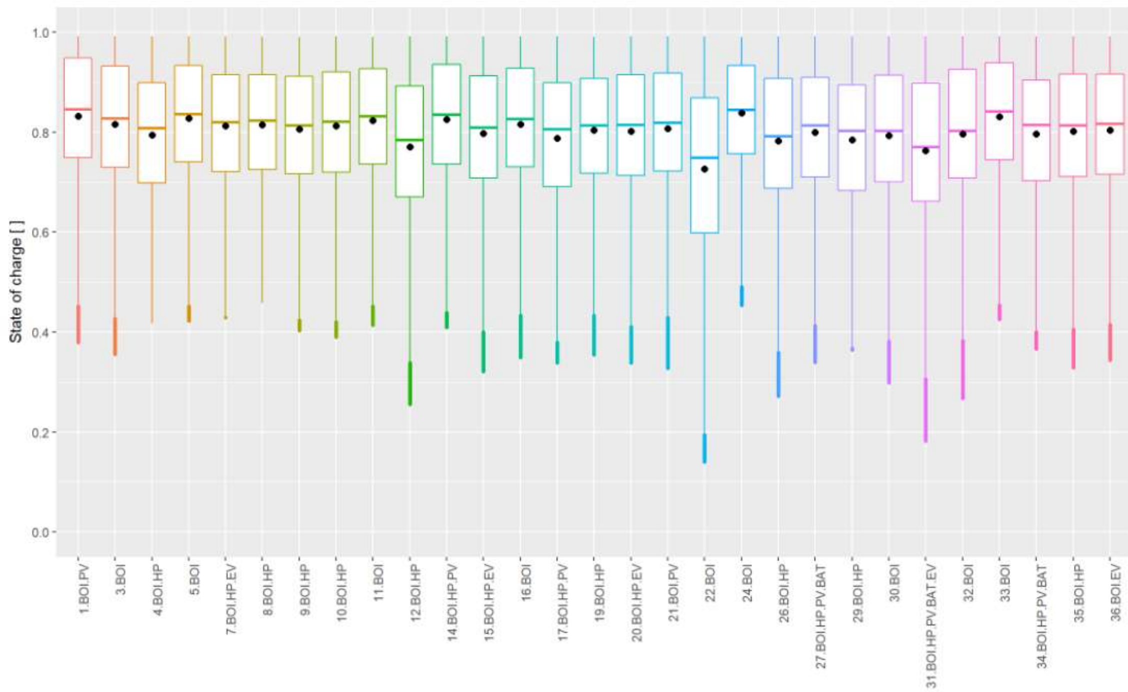


Figure 48 – State of charge by individual boiler. The state of charge directly translates to how much hot water remains in the boiler. The boilers' hysteresis controllers have fixed setpoints and dead bands state of charge-wise. However, the boilers have different settings for cold and hot water so in terms of water temperature, identical state of charges are going to be different. Simulation scenario: *Base Case ripple control GS off*.

The results for durations and number of charging and discharging phases of batteries should not be analyzed in too much detail. A small detail of the GridSense algorithm in the simulation platform could not be properly implemented in time. This means that the battery algorithm of GridSense does not have any information about the base load consumption of its household. In other words, the battery only reacts to the explicitly modelled devices like PV, heat pump, boiler, and electric vehicle. This missing feature does not have a big effect on the battery behavior in general and does certainly not significantly influence the results of standard scenarios where only three batteries were part of the system. However, it means that the detailed comparisons presented here should be taken with a grain of salt. We will thus restrict ourselves to the observation that the batteries under GridSense control exhibit a similar behavior like the conventionally controlled batteries in respect to duration and number of charging/discharging phases (see Figure 49 and Figure 50). The smaller discharging durations of the batteries with GridSense is most likely due to the missing information about the household base consumption which represents a load that could be served by battery discharge.

The SOC of batteries under GridSense control are more often at a value between 0 and 100 % as depicted in Figure 51. This observation implies that GridSense-controlled batteries preserve more flexibility so that they can react in special situations. Such a behavior typically improves grid-friendliness at the cost of a decrease in the rate of self-consumption.

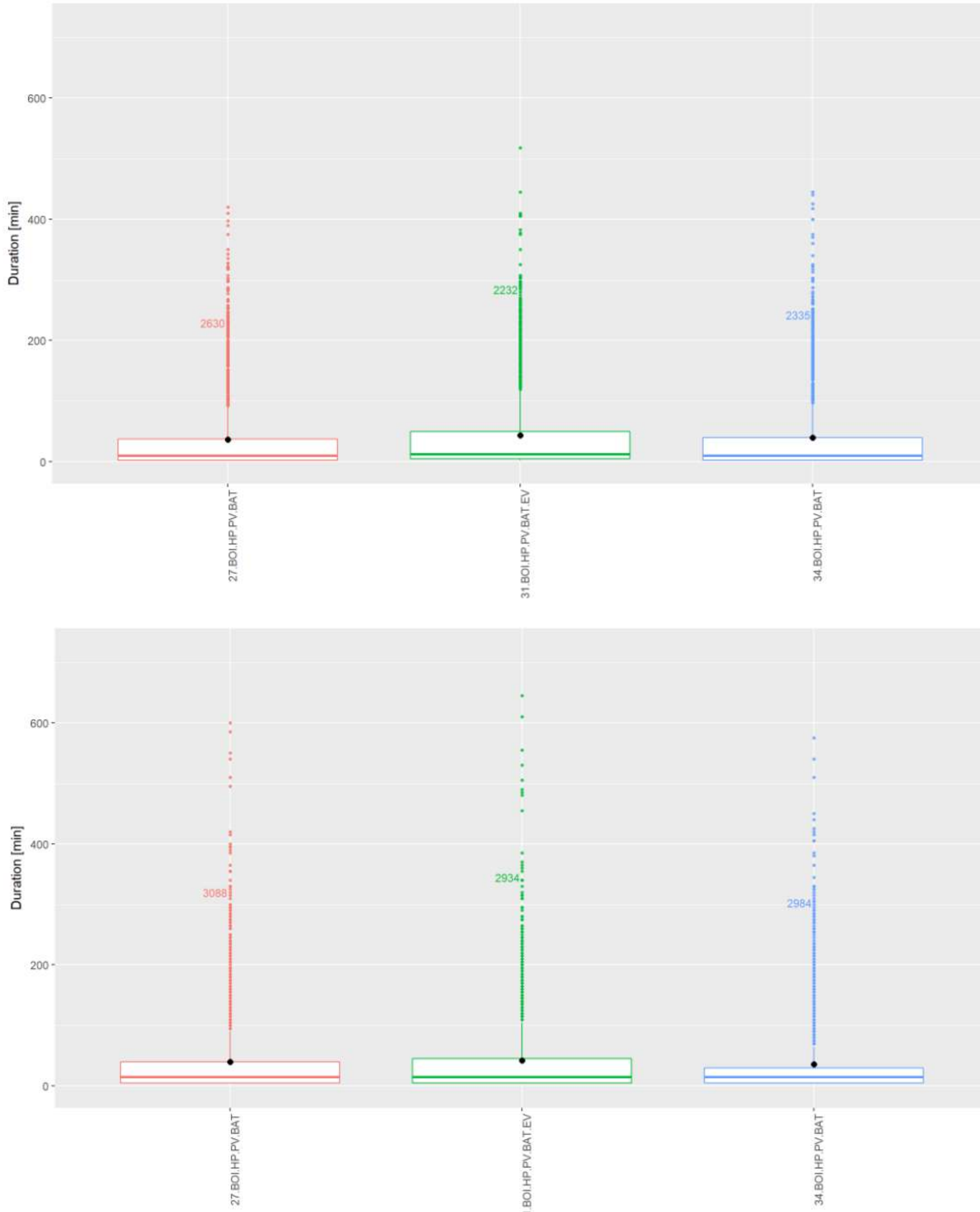


Figure 49 – Durations and number of charging-phases by individual batteries. The number of charging-phases are the figures given above every boxplot while the boxplot itself shows the duration of these phases. A charging-phase is defined as one activation of a battery from the start of power consumption until the consumption goes back to 0. Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*

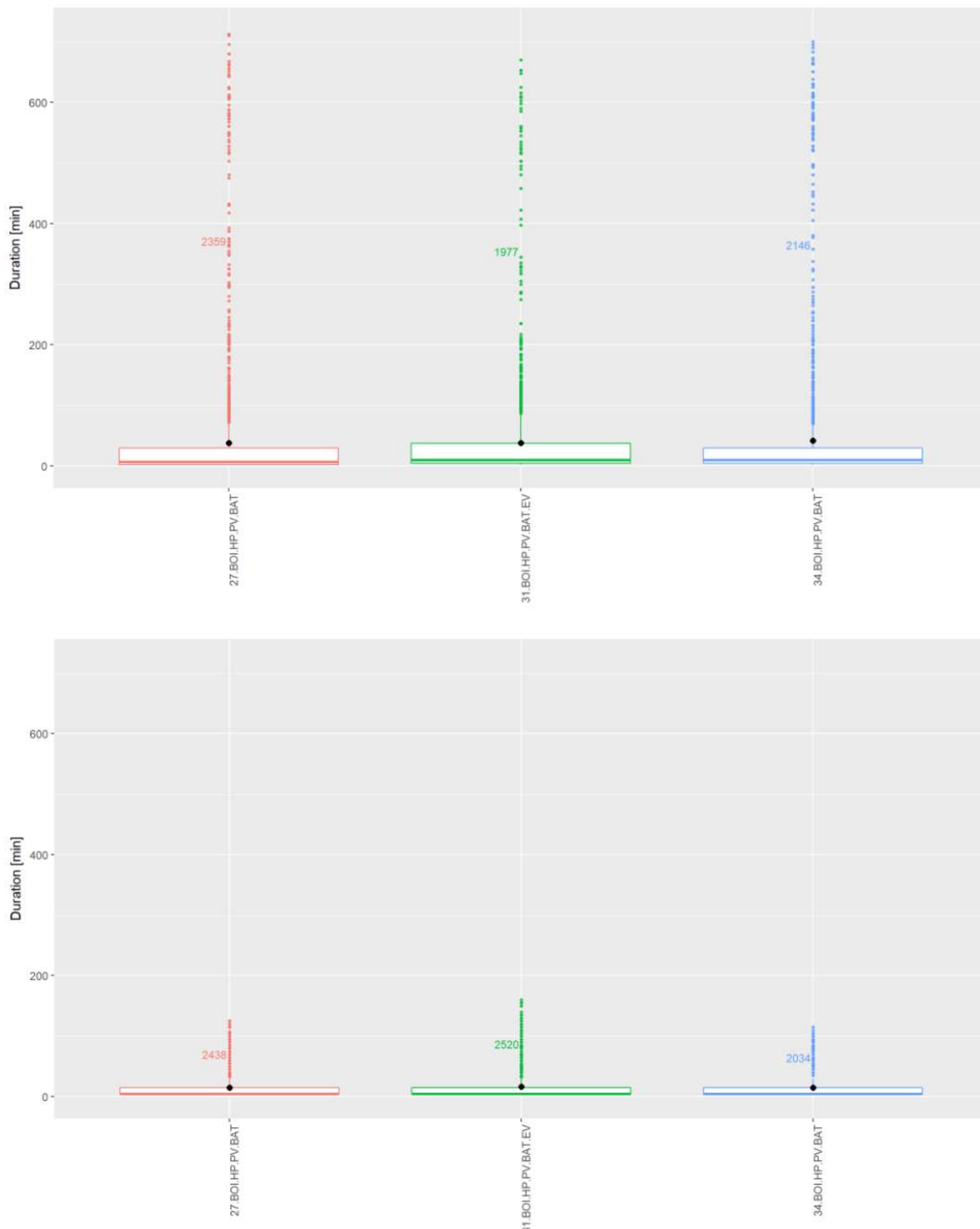


Figure 50 – Durations and number of discharging-phases by individual batteries. The number of discharging-phases are the figures given above every boxplot while the boxplot itself shows the duration of these phases. A discharging-phase is defined as one activation of a battery from the start of power discharge until it goes back to 0. Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*

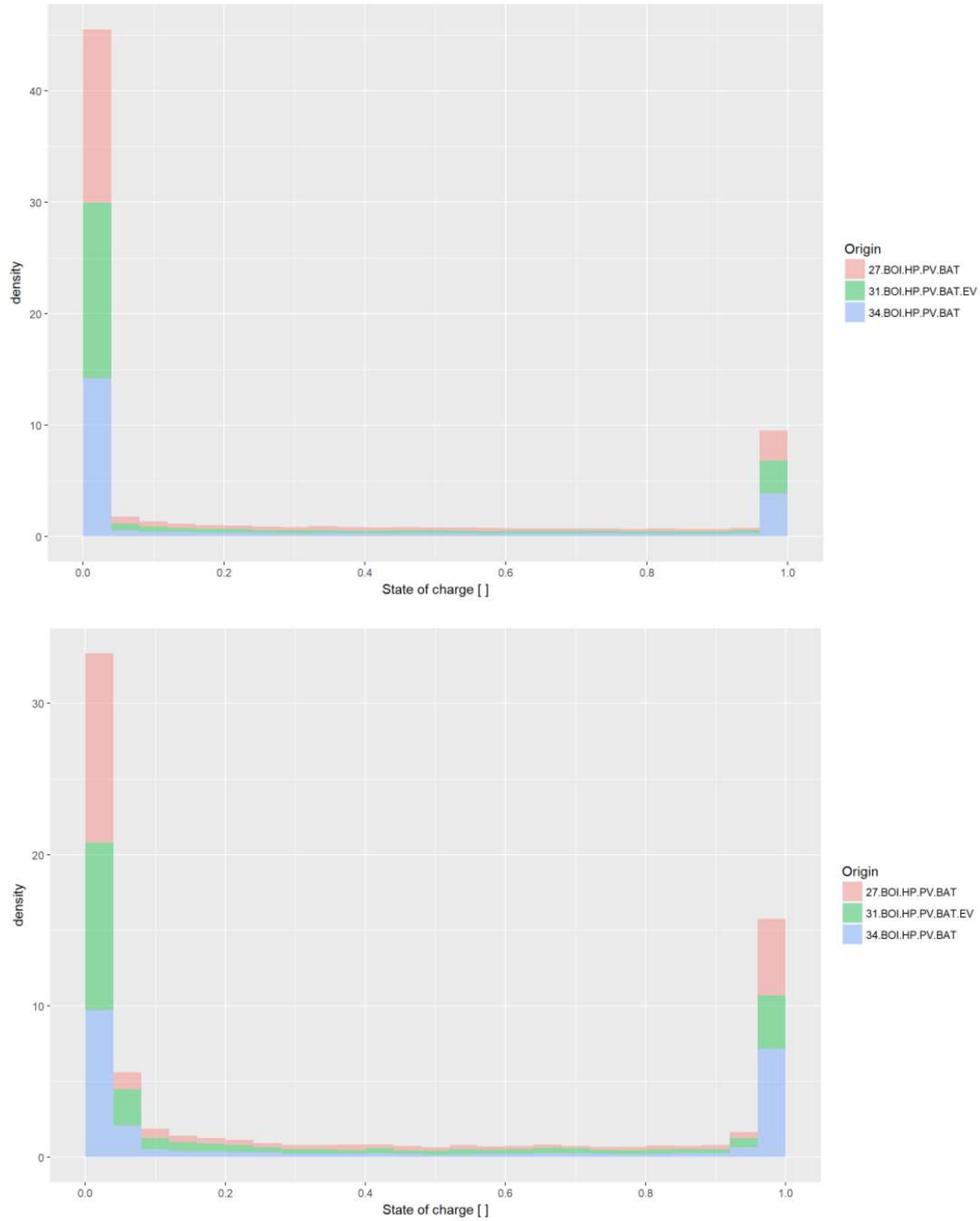


Figure 51 – Distribution of state of charges of batteries. Colors designate individual battery units. Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*

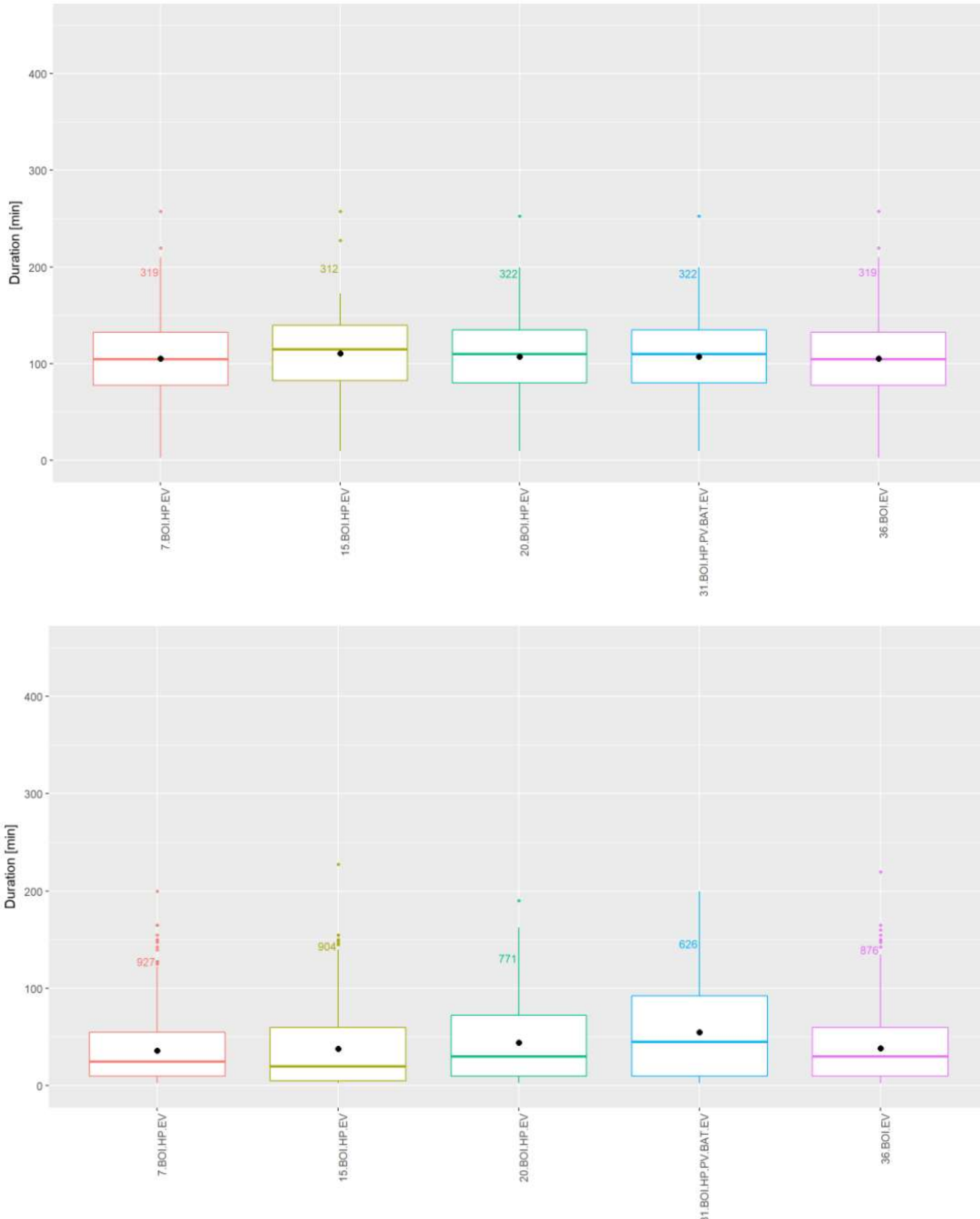


Figure 52 – Durations and number of charging-phases by individual electric vehicles. The number of charging-phases are the figures given above every boxplot while the boxplot itself shows the duration of these phases. A charging-phase is defined as one activation of an electric vehicle from the start of power consumption until the consumption goes back to 0. Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*

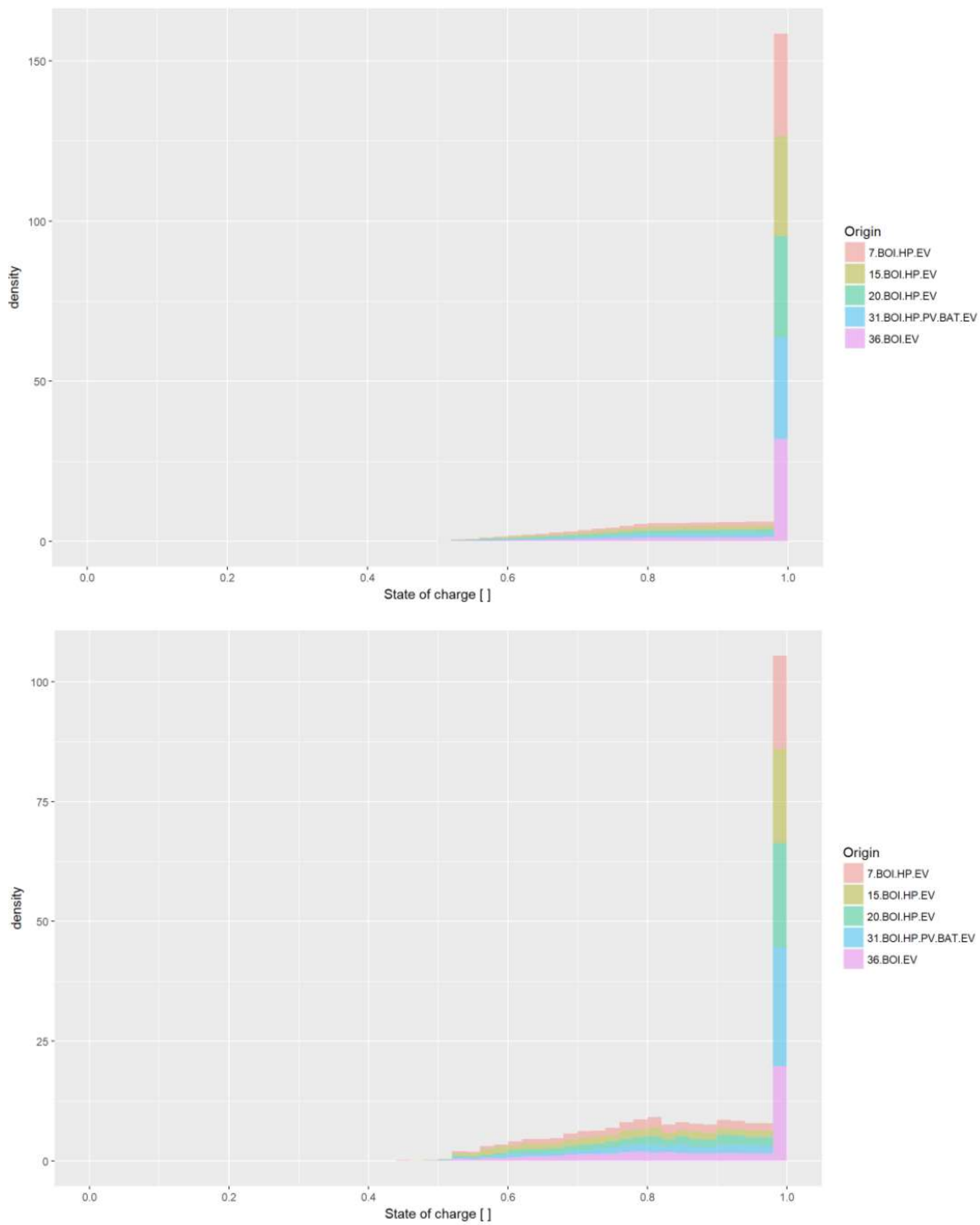


Figure 53 – Distribution of state of charges of electric vehicles only during plugged-in periods. Colors designate individual electric vehicles. Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*

The analysis of the electric vehicles' charging duration and number of activations shows a clearer difference than what was observed with batteries (see Figure 52). While the median charging duration without GridSense is around 100 min it is only around 40 min when the charging stations are controlled by GridSense. This comes in combination with two to three times more charger activations. Again, this comes as no surprise and is a reflection of the more flexible behavior of GridSense. In the conventional case, cars are directly fully charged whenever they are plugged-in. Their number of charging-phases therefore represents the lower limit of this measure. The results shown in Figure 53 are then a direct consequence of that behavior. Car batteries under the GridSense regime are more often at SOCs below 100 %. This ensures that there is more flexibility to charge the car battery when there is excess power in the local distribution grid or at least when the net consumption is low. With car batteries the consumer behavior comes into play as an additional complicating factor in comparison to home batteries. The owner wants the EV to be ideally charged and ready at all times. There is thus the trade-off between retaining some flexibility for grid support or maximization of self-consumption while still providing the availability of the car that the user expects. Importantly, the SOCs of the cars do not seem to remain for long times at relatively low levels. The consequences for user comfort are therefore hardly very detrimental. An in-depth analysis with several dedicated simulations would be needed for an improvedunderstanding of these dynamics.

Electricity bills base cases

Apart from the grid-mode, GridSense can also be run in hybrid- and self-consumption-mode. In hybrid-mode, the algorithm controls the flexible devices so that the electricity costs for households are reduced while the devices are still run in a grid-friendly way.

The effectiveness of this mode was examined by comparing the average electricity bills per household for a year-long simulation with the other base case simulations (*GS off, Grid-mode, and Ripple control | GS off*). The costs per household vary a lot because of the big differences in electric energy that is consumed (see Figure 67 for individual household energy consumption and Figure 69 for their respective electricity bills). The average costs are also rather high because even the base case features a high share of households with electric boilers, a substantial penetration with heat pumps and on top of that some electric vehicles (batteries are not charged with energy from the grid).

The results of the household bill comparison are shown in Figure 54. The most important feature of those results are the small differences across all results. Relatively, the difference between the two extremes is clearly below 10 %. Apart from the scenario *Base Case GS off* the results are totally in line with the general idea of a trade-off between grid-friendliness and cost optimization: with ripple control the household electricity bills are the smallest but the detrimental effects for the grid are clearly the worst (see Figure 38). The cost decrease that resulted from using the hybrid-mode of GridSense is small compared to the grid-mode but so are also the detrimental effects for the voltages in the grid.

Taking into account the effect of these different options on the grid voltages and on the electricity bills, it can be stated that both GridSense modes are clearly better compared to scenario *Base Case GS off* which performs worse in both comparisons. We would also argue that the GridSense modes are superior to the ripple control because the cost savings that it achieves are minimal while the number of voltage violations increases heavily. Between the two GridSense modes there is no clear winner. At this point the cost savings by the hybrid-mode seem to be too small to justify the decrease in grid support. However, this comparison is based on a current standard peak/off-peak tariff scheme how it widely occurs. If the tariff schemes become more dynamical the cost savings with the hybrid-mode compared to the grid-mode might increase. It is clear that a classical ripple control scheme is unimaginable in such a future scenario.

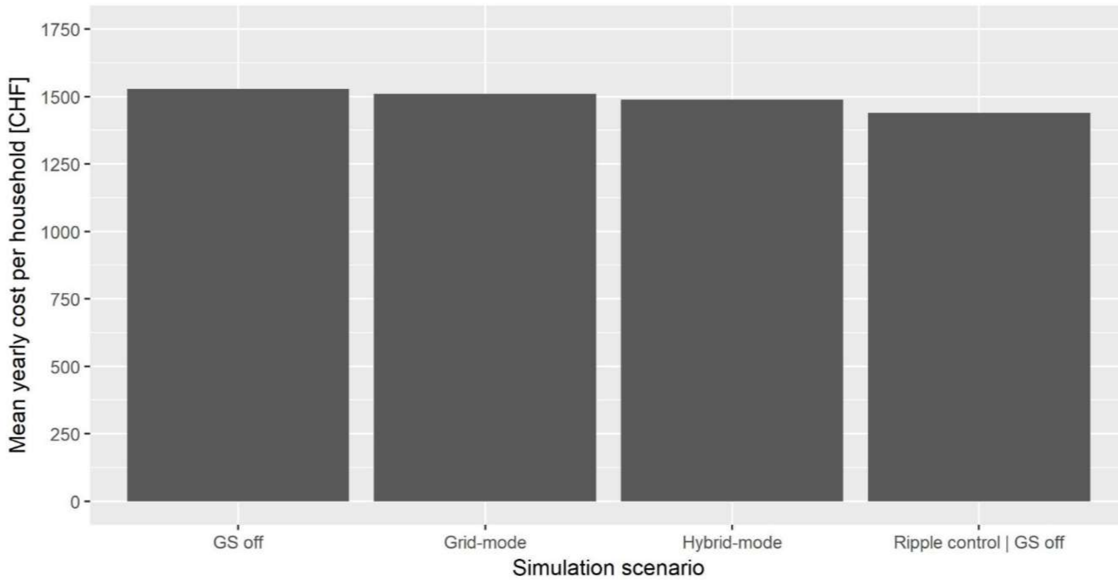


Figure 54 – Mean electricity costs per household over one year by simulation scenario. A standard peak/off-peak tariff was used for these simulations. Details are listed in the appendix. The GridSense hybrid-mode is an algorithm which optimizes the house-holds electricity costs and at the same time operates devices in a grid-friendly way. Ripple control here affects the boilers which are divided in three groups with two shifted 2-hour windows every night when they are clear to run. The boilers are therefore only activated during off-peak tariff hours.

Penetration with GSU

For the examination of the effects of different GSU penetration levels, the number of voltage violations depicted in Figure 38 is used. The scenario *Base Case GS off* serves as the reference for a scenario with a GSU penetration of 0 % while the scenario *Base Case grid-mode* equals a GSU penetration of 75 %.

All five scenarios are completely identical apart from the different levels of penetration with GSUs. The results can thus be very well compared. Most importantly, a continuous decrease of voltage violations with increasing GSU penetration all the way up to a level of 100 % is observed. However, a saturation effect is visible: the more devices equipped with GSUs the smaller the marginal effect of additional ones. This effect might also have something to do with the fact that households with several different flexible devices were equipped first because they were assumed to be preferable targets for GridSense installations. Such households are thus covered by GridSense even at low penetration levels. The results indicate that a cost and effort-wise efficient level of penetration lies somewhere around 75 % of GridSense-controllable devices. Another important implication is the evidence that even a small number of GSUs will have a positive effect for the grid; in these results we do not observe a minimal penetration level that needs to be reached in order to see any effect (if there is any it lies below 25 % GSU penetration).

Alternatives to GridSense (benchmark)

Here, simulation results of both categories “Alternatives” and “Combinations” of Figure 38 are presented and discussed. These simulations should provide a benchmark for GridSense in comparison with other ways to support the grid status. In our case these were an on-load tap changing transformer (OLCT), a classic grid reinforcement (replacement of long, main cable section), and PV curtailment for a scenario with an elevated PV penetration of 50 %.

It becomes evident that PV curtailment is more efficient at reducing over-voltages than GridSense with the system configuration in place (direct comparison of scenarios with identical systems: *Alternatives PV curtailment GS off* vs. *Unit variation PV 50% grid-mode*). However, there are two major downsides to this alternative. Firstly, PV curtailment means that some share of the potentially generated power is lost (here ca. 2 %). Secondly, PV curtailment obviously does not have any effect on voltage violations by under-voltages. The same scenario with activated GridSense is therefore in terms of total voltage violations still better than PV curtailment. Both, the OLTC and a classic grid reinforcement perform voltage violation-wise better than GridSense in the examined system configuration. The system under consideration is a very good application case for an OLTC because the grid problems are solely caused by voltage violations. Using an OLTC proofs to be very efficient under these circumstances. However, it should be noted that an OLTC which is used to decrease the voltage level increases the current flows in the lines. This becomes relevant in scenarios with high shares of PV. In Figure 55 the seasonal development of the main line loading in a high-PV, OLTC-scenario is presented (*Combinations PV 50% | tap-changing transformer GS off*). It can be seen that the line loadings approach 100 % during PV peak production in summer. This is not yet problematic, but it is an indication that the OLTC-solution also has its limits.

A thicker cable also leads to better results than GridSense voltage violation-wise in our model based simulaton scenarios. This is in contrast to the results of the measurement based simulations and will be addressed in the discussion of this report. However, it must be noted that GridSense is a holistic approach that supports the grid by tackling the core of the problem at hand: uneven usage patterns. An OLTC or a classic grid reinforcement might be more effective in the short-run but they both have their limits and downsides. It will, for example, reduce voltage problems when the main line is replaced but adjacent lines might still be overloaded at times of extreme demand. Furthermore, more potential is seen for GridSense in future scenarios: if there is increasing use of the electric power distribution grid, the potentially flexible devices which could be controlled by GridSense should increase in number. The combination of GridSense with a thicker cable is furthermore an interesting combination with a clear, positive effect by GridSense to reduce voltage violations even more (scenarios *Combinations HPs 66% | thicker cable grid-mode* and *Combinations PV 50% | thicker cable grid-mode*).

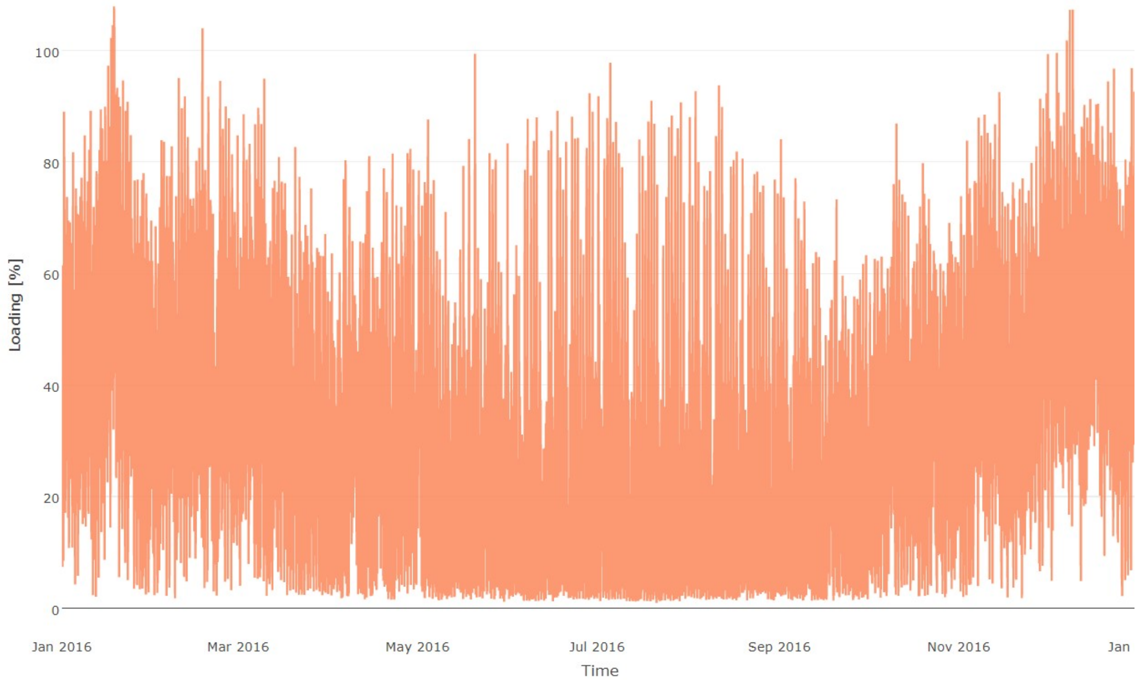


Figure 55 – Seasonal development of line loading of main connection line between transformer and the neighborhood with the distribution grid. Simulation scenario: *Combinations PV 50% | tap-changing transformer GS off.*

Different seasons

The analysis about different efficiencies of GridSense with varying seasons was conducted via a separate evaluation of the base cases broken down into seasons. Aggregated results are presented in Figure 56. One of the difficulties of this analysis is the point that meteorological seasons are used as proxies for weather conditions. Problematic about this approach is that the weather conditions are extremely diverse, especially during spring and autumn. But selecting different periods based on weather conditions would also not be trivial because there are multiple dimensions of the weather that have directly and indirectly an influence on the electric distribution system.

The analysis was therefore carried out for meteorological seasons anyway. As shown previously, there are no problems with overvoltage in the base case scenarios. It is thus not surprising that no voltage violations occur during summer because the power demand is reduced during that season. Heat pumps are only used for heating and are therefore not active in summer. The hot water consumption also decreases with warmer temperatures, a factor which leads to a decreased power demand by boilers. While the absolute reduction in voltage violations is largest during winter it is also important to have a look at the relative decrease. In this respect, GridSense is the most efficient in reducing voltage violations in spring. The relative reduction caused by GridSense in autumn is then closely followed by the one that occurs in winter. It cannot be definitely confirmed because no other scenarios were analyzed by seasons but it is likely that this is a valid pattern because the conditions in mid-seasons offer a certain flexibility for the system: there is potentially considerable PV generation, there is demand for heating but it is not overwhelming thus preserving some flexibility, and the hot water demand is typically bigger than in summer.

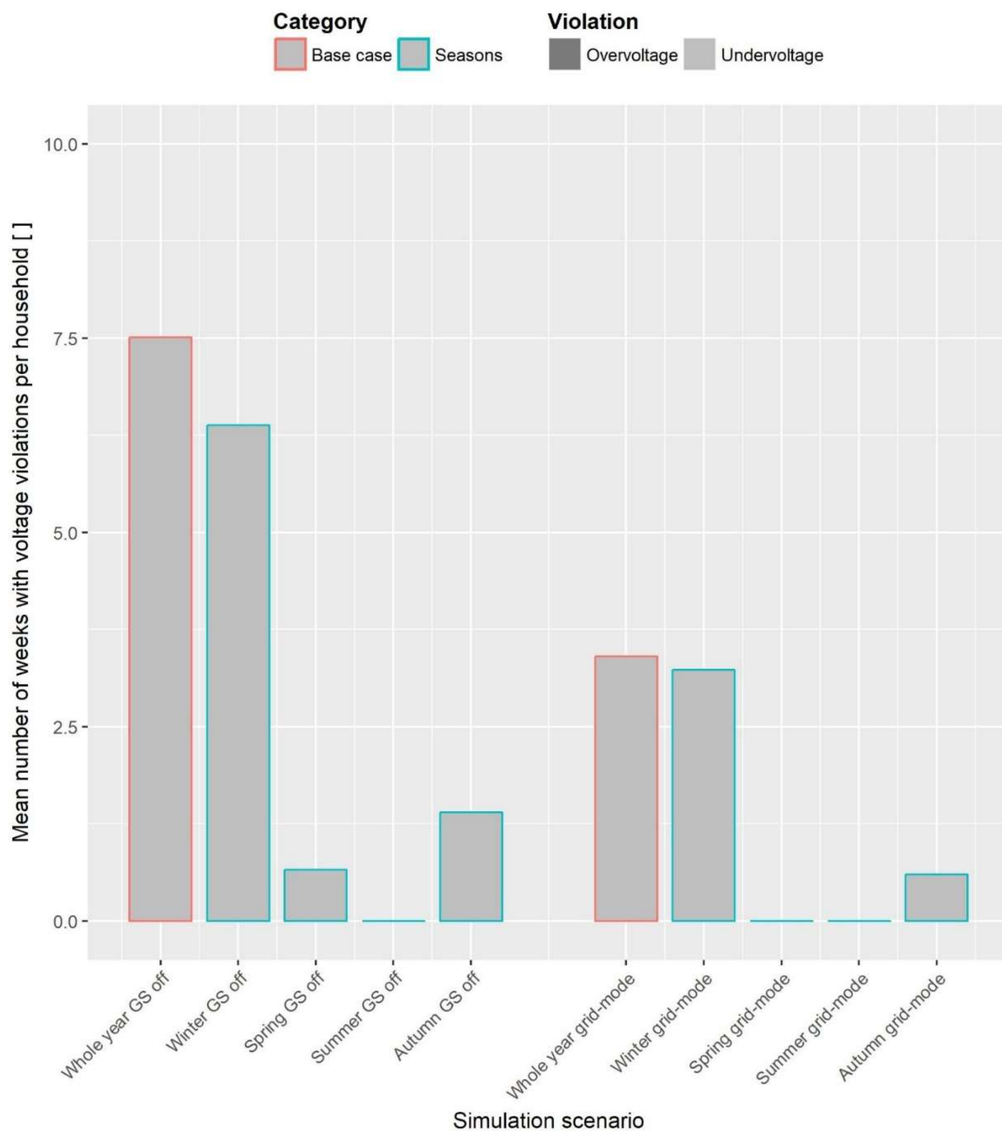


Figure 56 – Seasonal breakdown of base case mean number of weeks with a voltage violation (norm EN 50160) per household. Given in red are the results of the respective year-long simulations.
The aggregated seasonal values are a bit higher compared to their year-long counterpart because of some overlap in the considered weeks: weeks that were checked for voltage violations start on Mondays (ISO week date system) while the meteorological seasons start on the first day of a month. Some weeks are therefore shared by two seasons, hence the higher total.

Unit variation

The simulation package “unit variations” consists of many simulation scenarios. The scenarios were designed to test for GridSense performance trends with increasing shares of individual unit types. In addition, the results of these simulations should deliver indications with which device category GridSense works best. The results concerning voltage violations are presented in Figure 38.

The scenarios with increased shares of batteries were built upon the scenarios with 50 % penetration of PV units. The only difference is that there is a battery in every household with a PV unit. As mentioned and explained before, a feature of the GridSense battery algorithm is missing which leads to small deviations in the battery behavior so the results of a scenario with so many batteries should be taken with a grain of salt. It can still be stated though, that the way how GridSense controls the battery has a much better influence on the grid voltages than the conventional controller. With the conventional battery control mechanism, the batteries do not even cause the grid voltages to be substantially better than in the scenario without batteries (direct comparison *Battery 50% GS off* with *PV 50% GS off*). This is because the battery does not have enough capacity to deal with the day-long PV in-feed. In fact, the detailed results show that on days with a lot of PV power production the batteries are already fully charged before noon. This means that they cannot contribute to any substantial voltage reduction by taking up excess PV generation during peak generation times. The analogous effect applies for the discharging of batteries: they are usually fully discharged during times of highest demand. By only optimizing self-consumption, batteries might under unfortunate circumstances even have detrimental effects for the grid status. It is clear that a smart control algorithm can do a lot by activating the batteries not at the first opportunity but by saving some flexibility for times of extreme power consumption or extreme power generation. GridSense goes in that direction and clearly outperforms the conventional battery controller. However, it still does not manage to get rid of all voltage violations.

The results of scenarios with increased numbers of boilers and heat pumps are evaluated in combination because they offer an interesting opportunity for comparison: both boilers and heat pumps are flexible devices with an intrinsic thermal storage that allows for some flexibility. The most obvious observation is the fact that an increasing number of heat pumps brings the electric distribution system on the brink of collapse due to the extreme under-voltages and line loadings (see Figure 57 for e.g. line loadings). A penetration of 100 % heat pumps is definitely not supportable by the standard grid and even a relatively realistically achievable 66 % share of households with heat pumps causes massive problems. For the scenarios with a share of 66 % heat pumps the relative increase in the number of heat pumps compared to the base case scenario is equal to the relative increase in the number of boilers from base case to a share of 100 % households with electric boilers. Energy-wise the increase in the HP-scenario is larger which can be seen by the higher number of voltage violations. Interestingly, the reduction in voltage violations with GridSense is bigger in the boiler scenarios. This applies both to the absolute value and even more so to the relative one. This observation is a clear indication that, at least under the given circumstances, the boilers offer the bigger potential for grid support than HPs when they are controlled by GridSense. A reason for this might be their higher power to consumption ratio which theoretically makes them time-wise more flexible. An additional advantage of boilers is that they are in use all year round. If heat pumps were used for cooling in summer that would add another important source of flexibility to the system in summer.

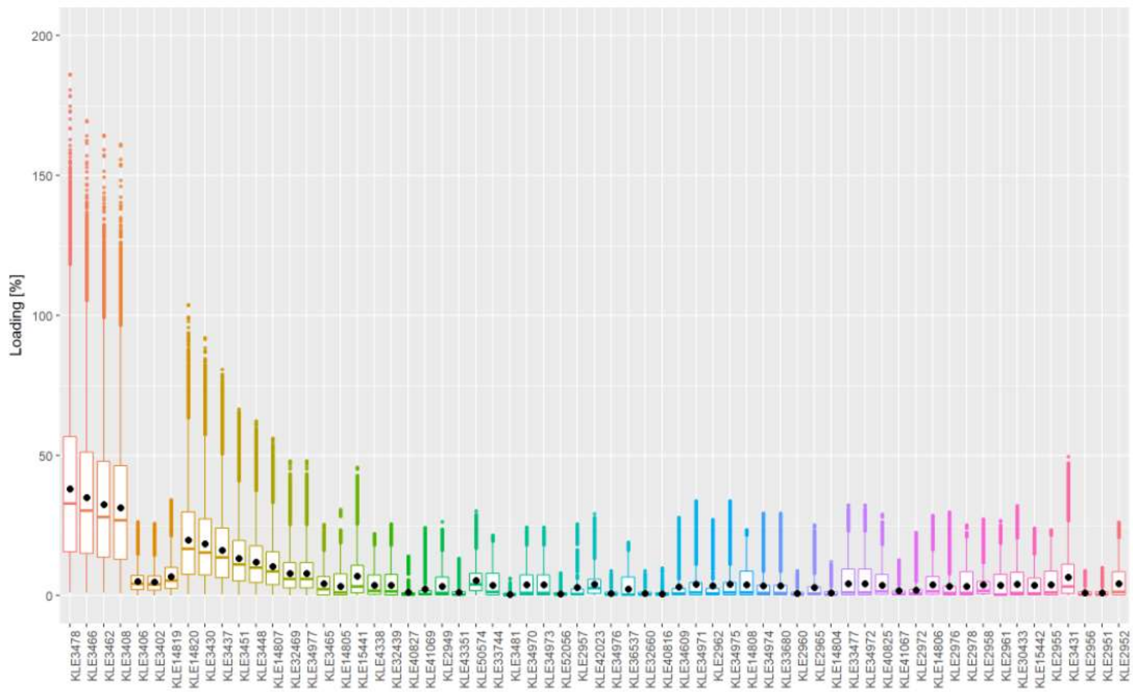


Figure 57 – Range of line loadings by individual line. Only line segments longer than 10 m were taken into consideration for this figure. The lines were roughly ordered from the transformer going downstream. Lines in between with very low loadings are branch lines from the main connection.
Simulation scenario: *Unit variation heat pumps 66% GS off*.

Electric vehicles might be a big source of flexibility under the right circumstances. To which extent this applies largely depends on the assumptions about usage profiles, both energy consumption- and time of the day-wise. The observed effect of GridSense in the scenarios with an EV penetration of 50 % is not substantially bigger than the effect that was observed in the base case. Very likely, this is caused by the conservative assumptions that were taken regarding the usage of EVs. With electric cars the usage patterns are absolutely crucial to evaluations of flexibility especially in combination with PV: if one assumes that the cars are not plugged-in at home during the day (due to work for example) there is no possibility to supply the electric vehicles' demand with power generated by PV. The usage patterns of electric vehicles were chosen conservatively in that most electric cars are never plugged-in from 9am to 3pm during weekdays so they are not available for the peak generation hours of PV. This measure was taken to avoid the generation of effects that are a result of overly positive assumptions concerning electric vehicle usage patterns. However, there is a good case to believe that real EV-usage patterns would be better suited for load shifting with GridSense since our assumptions are very conservative. An in-depth simulation study with benchmarks concerning the usage of EVs would be necessary for more profound findings concerning this topic.

To study the effect of GridSense with varying shares of PV, four different PV penetration levels were examined. It must be noted that the parameters of a few devices vary in the series of different PV penetration levels. This lies in the nature how the simulation tool is built and could hardly be evaded. The effect for the simulation results should not be very strong but it means that results which are on similar levels cannot be assumed to be significantly different from each other. It lies in the nature of the definition of voltage violations by the norm EN 50160 that the overvoltages with increasing PV penetration do not increase linearly. The results presented in Figure 38 indicate that a PV penetration of ca. 50 % is the limit for the current distribution grid. Starting from a share of 37.5 % the rate of voltage violations increases massively. GridSense is in the analyzed scenarios not able to substantially reduce overvoltages. This does not come as a huge surprise because of the missing flexibility during peak season for PV: heat pumps are completely turned off and the hot water demand that drives the boiler power demand is decreased. However, it can be seen that higher shares of PV in combination with GridSense slightly decrease undervoltages because GridSense can move the activation phases of flexible devices to times of PV power generation (this occurs during the cooler seasons). The results from 25 % to 50 % PV indicate that there is a saturation to this effect which comes into effect around or even before 25 % of PV (the minor differences between 25, 37.5, and 50 % are most likely not significant), though. This is probably due to the limits to flexibility which mainly apply to heat pumps and, depending on the usage patterns, to electric vehicles. During cold periods many heat pumps are effectively constantly active so there is no flexibility available.

Different grid topologies

Both different grid topologies that were represented in those scenarios are fictitious examples of distribution grids with shorter main lines from the transformer station to the beginning of the neighborhood. Such different configurations can serve as fictitious grid models representing distribution grid topologies that might occur elsewhere. Particularly, a shorter distance between transformer and surrounding households represents the usual situation in urban distribution grids.

The results of the analysis are depicted in Figure 38 under the category "grid topology". Please note that the scenarios *Grid topology line 100% GS off* and *Grid topology line 100% grid-mode* are identical to the base cases. The decreased length of the main line, generally leads to fewer voltage violations in the four scenarios than in the base case. The results also indicate that GridSense works as expected in case of such a different grid topology. Even though the absolute decrease of violations it causes in scenario *Grid topology line 50% grid-mode* compared to *Grid topology line 50% GS off* is of necessity limited, it is an important demonstration that GridSense manages to completely eliminate the few voltage violations that would have occurred. In conclusion, there is evidence that GridSense also has positive effects on stressed grids with other configurations like e.g. urban distribution grids where transformers are typically located closer to the households they supply.

7. Results IV: Grid Investment Analysis

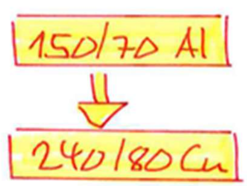
After the technical analysis and comparison of the operational performance between GridSense and other mitigation options, such as a conventional grid upgrade and voltage regulation technologies, an economic examination follows.

In the following, a grid investment analysis is performed for the three most plausible grid reinforcement options as examined previously in Chapter 6. For this purpose, AEK provided the concept for the conventional grid upgrade, as it could actually be implemented in the Riedholz pilot grid (Figure 58). The examined grid upgrade options are the following:

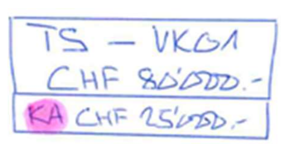
- Conventional grid upgrade, i.e. an effective doubling of the cross-section of the main supply cable in the Riedholz area,
- Active voltage regulation, i.e. the installation of an on-load tap changer (OLTC) or in the case of the Riedholz area preferably a line voltage regulator (LVR), and
- GridSense deployment, i.e. the deployment of 62 GridSense units for autonomous load management.

The technical performance showed that GridSense performs better than the conventional grid upgrade. The usage of active voltage regulation via an OLTC, or in Riedholz rather an LVR, is even more effective in reducing voltage peaks (the “symptom” of grid over-loading), however not peak grid loading (the actual “root-cause” of grid over-loading).

The conventional grid reinforcement consists of doubling the cross-section of the existing 350m-long main supply line in the Riedholz area. The actual implementation is here the replacement of the existing aluminium cable (150mm^2) by a thicker copper cable (240mm^2), as shown in the technical detail below (from Figure 58). Since copper has better electrical properties than aluminium, this leads to an effective halving of the line resistance, which corresponds to a doubling of the cross-section of the existing line.



Additional upgrade tasks, such as the reconnection of certain distribution cabinets (Verteilkabine), have to be performed (highlighted in purple in Figure 58). This occurs additional costs:



Total upgrade costs of at least CHF 105'000 are incurred. Including prior grid planning and documentation as well as other administrative tasks this leads to total costs of about CHF 120’000.

Please note that in the simulation analysis, only the first section of the main supply line from the transformer station to TK22 (green section in Figure 58), about 250m-long, were reinforced. The approximate costs for this limited upgrade is about CHF 75’000. With overhead costs this could go up to CHF 85’000.

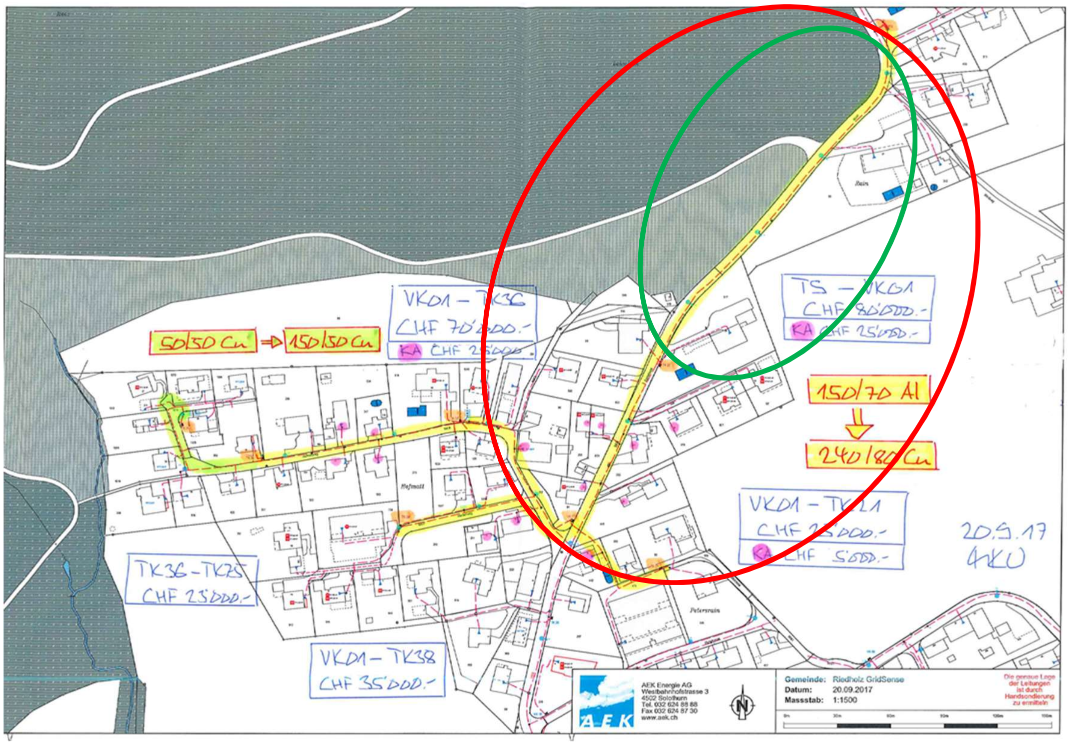


Figure 58 – Concept for conventional grid upgrade in Riedholz area.
Full grid upgrade (350m) shown in red versus limited grid upgrade (250m) in green.

The Riedholz pilot region contains about 62 'grid-active' GSU that directly improve the voltage quality. Altogether 103 GSU units were installed, of which 35 units are merely collecting SmartMeter measurements in each of the 35 households. Three units each are connected to PV and battery units and are also discarded.

Altogether, hardware and installation costs of about CHF 36'000 would result. In addition, yearly license fees for the GridSense technology would be incurred.

The third alternative, active voltage regulation by an LVR, would consist of an additional installation at the existing transformer site. An LVR with the necessary sizing to serve the Riedholz neighbourhood would cost about CHF 36'000. Due to the limited scope of the grid analysis, it cannot be assessed if a second LVR or OLTC in the neighbouring area south of the Riedholz pilot grid would be needed in order to provide N-1 security.

GridSense has additional benefits over a conventional grid upgrade or active voltage regulation:

- GridSense allows to closely monitor the low-voltage distribution grid down to the grid connection point ("Hausanschluss") and even into the household-level.
- GridSense allows to actively manage load demand inside the grid area and actively relieve grid stress instead of masking the mere "symptoms", i.e. over- and under-voltage events. It is effectively a better-performing alternative to conventional ripple control solutions.
    - Increasing the share of local consumption of distributed power generation will reduce transmission losses.

- Demand or production peaks in electric distribution systems are typically rather synchronous within homogeneous regions. These power transmission peaks are cumulated on higher grid levels. Less peak loadings in electric distribution systems reduce the stresses on higher grid levels. Thus, a wide application of GridSense might have the potential to reduce the need for grid reinforcements in higher grid levels.

- GridSense is potentially a more sustainable solution because it is expected to have an increasingly positive effect with the ongoing electrification of sectors like heating or transportation (i.e. more flexible electric units like heat pumps or electric cars). On the production side an increase in PV units should provide more potential for demand side management. Incrementally covering additional devices is easily possible with GridSense.
- Since GridSense is software based it can be updated and adapted to future developments. There is therefore the potential to adapt the strategies of demand side management in order to react to unexpected developments in the electric distribution systems.
- GridSense should increase the self-consumption rate of households with PV units and thus lead to economic benefits for such prosumers.

The expected life-time of GridSense units, as electronic components, is about 15 years. This is significantly shorter than the 40-years nominal lifetime for conventional, industry-grade grid elements such as copper lines and OLTCs.

An overview of the conducted techno-economical comparison is given below by Figure 59.

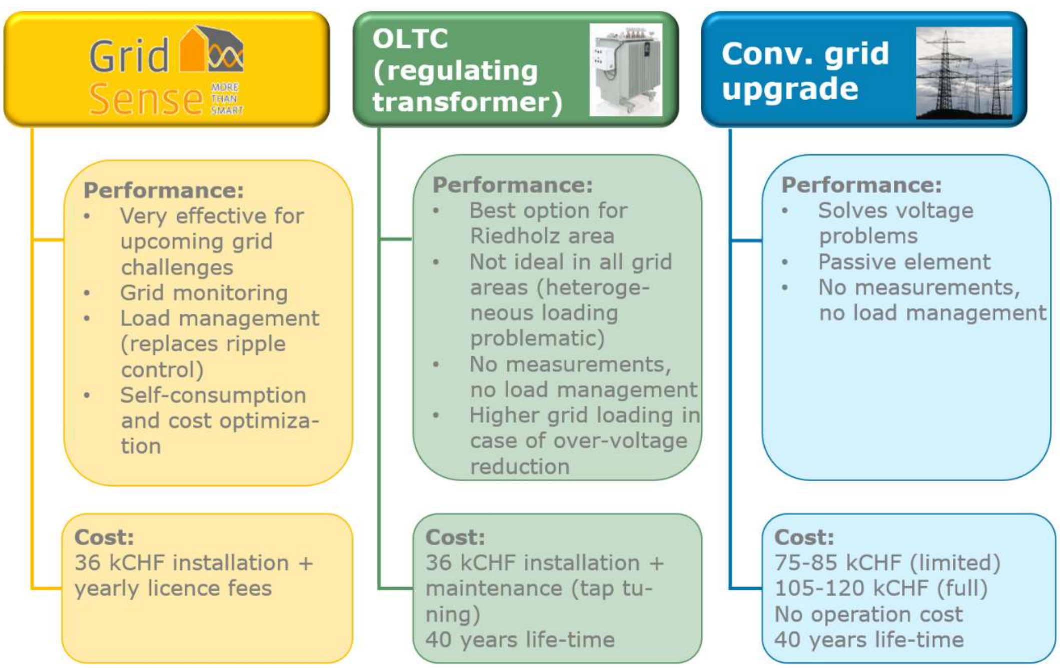


Figure 59 – Comparison of grid upgrade options – Technical performance and cost indications for Riedholz case.

Conclusion

GridSense is a retrofit for the existing grid infrastructure with the goal of reducing grid stress, i.e. line and transformer over-loading as well as voltage violations. Reducing the stress of grid components can increase the effective lifetime of the affected grid elements.

Due to the local load management, an increase of effective – not nominal – 'hosting capacity' of both distributed generation (PV), thermal loads (heat pumps, boilers) and otherwise shiftable loads (electric vehicles, batteries) can be achieved.

GridSense has several additional advantages (see Figure 59) over the two conventional options with unknown economic merits which are not quantified in this particular project. The individual valuation of these advantages is going to influence the final result of a fair economic comparison.

8. Results V: Communication

In this chapter the communication concept of the "lighthouse" project SoloGrid is explained. This also includes a presentation of the actual communication activities over the course of the project.

8.1. Communication goals

The goal of a pro-active communication was to reach a broad and varied audience. For this the show room in Luterbach was installed in order to have a forum for discussions about the energy transition – from expert groups to actual project participants.

8.2. Target groups

8.2.1. **Expert groups**

This includes industrial customers and companies in the areas of house and solar installations, electric utilities and distribution grid operators as well as the relevant professional and industry associations (VSE, …). Besides public on-site information events in Luterbach/Riedholz, dedicated meetings with C-level staff of specific DSOs were organized.

The SoloGrid project and its results were showcased at several technical conferences, for instance as keynote speeches at BDEW Treffpunkt Netze (Berlin) in March 2017 and the VSE Betriebsleitertagung (Brunnen) in September 2017.

8.2.2. **Project participants**

This includes first of all the owners and inhabitants of the participating households in the Riedholz neighbourhood as well as the Riedholz community but also interested neighbours. Good relationships and an on-going dialog with this group was essential and of high importance for the SoloGrid project.

Especially with the inhabitants of participating households a simple and effective communication regarding the project's timeline and results as well as an easily accessible contact point in case of potential technical problems and comfort issues during the project phase was essential.

During the course of the project it became apparent that only the involved project participants continued to be interested in information events. As the population of the Riedholz community was generally positively inclined towards the SoloGrid project, the remainder of the information events for the Riedholz community were then solely focused on project participants.

Information evening events were organized every four to five months for project participants, consisting of presentations of interim results and followed by open discussions. A community representative was present at the most important public events.

8.2.3. Canton and political stakeholders

Although members of this target group had not direct impact on the project's success, it was deemed important to include them in the information process. Political stakeholders decide and shape the future regulatory environment and needed to be informed about new technologies and technological potentials of the SoloGrid lighthouse project. SoloGrid was used as a showcase of such promising cleantech technologies by the cantonal pro-committee in this year's Swiss-wide voting on the national energy policy and energy transition.

8.2.4. Media

The SoloGrid project was covered by the local press, mostly as an outcome of the public information events. The project as well as the GridSense technology was already showcased twice in the technical journal VSE/SEV Bulletin. Another technical article is planned for after the official project closure.

8.2.5. General Public

The general public was informed about the SoloGrid project via press articles and the website content, which was continuously updated.

8.2.6. Competitors

Also, this group was informed passively via presentations at technical conferences and also via the website.

8.3. Communication Activities

The planned communication activitites were structured as the project proposal stage according to the logic given below.

Table 7 – Communication plan at project proposal stage.

	Expert groups	**Partici-pants**	**Canton / Political stake-holder**	**Media**	**Public**	**Compe-titors**
Internet	monthly updates					
Newsletter	every 4 months					
Information events	every 4 months	need-basis		every 4 mon-ths	every 4 mon-ths	
Speeches	min. 4		min. 2		min. 2	
Technical article	every 4 months			every 4 mon-ths		
Exhibitions	presentations at different technical conferences and exhibitions (at least 5)					
Info center	available with project start					
On-site visits	one		one	one		

The actual communication activities differed from the planned activities given above, which was influenced by the actual needs and stakeholder interest during the project course as well as the available result output in the different project phases. The (long) list of communication activities is presented further below.

8.3.1. **Homepage**

The website provided up-to-date information on the project concept and plan as well as the project status for all interested parties. This also included background information about the GridSense technology and SoloGrid project results.

The website was available at project start in German and was later-on also translated into English. In the end not as many newsletters as initially planned and hoped for were published. Also, due to project delays, many final project results only became available towards the project closure.

Figure 60 – SoloGrid homepage (www.sologrid.ch).

8.3.2. **Newsletter**

It was initially foreseen that a separate newsletter would be compiled and sent out every four months. However, only 26 persons registered on the website. Due to this unexpected low feedback/interest and the significant effort for a dedicated newsletter, project news were communicated during the later project phases via the already existing company newsletters (AEK, Alpiq, Adaptricity).

8.3.3. On-site visits and Show Room

The SoloGrid project information center was installed in AEK's training and meeting center at the nearby Luterbach sub-station. The equipment included professional presentation equipment as well as a SoloGrid information wall. The room was used for most of the official SoloGrid information events.

Figure 61 – Utensils for the on-site show room in Luterbach.

Information events for the project participants took place every 4-5 months. This information space and format was highly successful – both for the divers target group events (see list below) as well as for dedicated presentation events for C-level staff of Swiss DSOs.

At the beginning a dedicated GridSense test installation (including live measurements) in Luterbach was planned in order to limit on-site visits in the private houses of Riedholz participants. However, due one highly dedicated and motivated project participant, numerous on-site visits in Riedholz were in fact possible. Thus, the test installation in the Luterbach info center never needed to be realized.

End-customer information events:

17.03.2016	End-customer information event in Luterbach (status report)
11.08.2016	End-customer information event in Luterbach (status report)
25.11.2016	End-customer information event in Riedholz including social event
06.04.2017	End-customer information event in Luterbach (status report)
24.08.2017	End-customer information event in Luterbach (status report)

Utility and DSO event:

17.05.2016	Utility companies event including on-site visit
06.07.2016	Utility companies event including on-site visit
02.09.2016	IBAarau management event including on-site visit
20.10.2016	Groupe-e management and technical event including on-site visit
10.11.2016	tbgn (Technische Betriebe Glarus Nord) technical event
06.10.2016	VKW (Vorarlberger Kraftwerke) E-mobility project in Luterbach

Political events:

09.04.2017	Co-Präsidium Canton Solothurn – “Ja-Kommitee” in Luterbach

Universities:

10.10.2016	FHNW

Public event:

24.11.2016	Public event at Luterbach info center

Figure 62 – Utility event in Luterbach information center.

8.3.4. Exhibitions and speeches

The target audience at exhibitions and conferences are technical experts from industry and academia.

This format proved to be highly successful, as many invitations for speeches were received and numerous presentations at high-level conferences in several European countries were given (see event/speech list below).

Speeches:

26. - 27.02.2016	OTTI – Netzkonferenz 2016 (Berlin)
09. – 13.04.2016	Smart Grids Week (Linz)
14. - 15.06.2016	CIRED Workshop (Helsinki) – Poster Presentation of SoloGrid pilot project
31.1.-1.2.2017	UK SmartMetering (London)
07. - 08.03.2017	Treffpunkt Netze (Berlin)
30. – 31.03.2017	Innovationsforum Energie (Zürich)
15. - 19.05.2017	Smart Systems Week (Graz)
18.05.2017	swissgrid Netzforum 2017 (Luzern)
14.09.2017	Betriebsleitertagung (Brunnen)
10.11.2017	SAEE Jahrestagung 2017 (Zürich)
16.11.2017	Zero Carbon Emission (Fribourg)
16.11.2017	Swiss Solar Event (Yverdon-les Bain)
05.12.2017	ENCO BFE; Smart City Event (Bern)

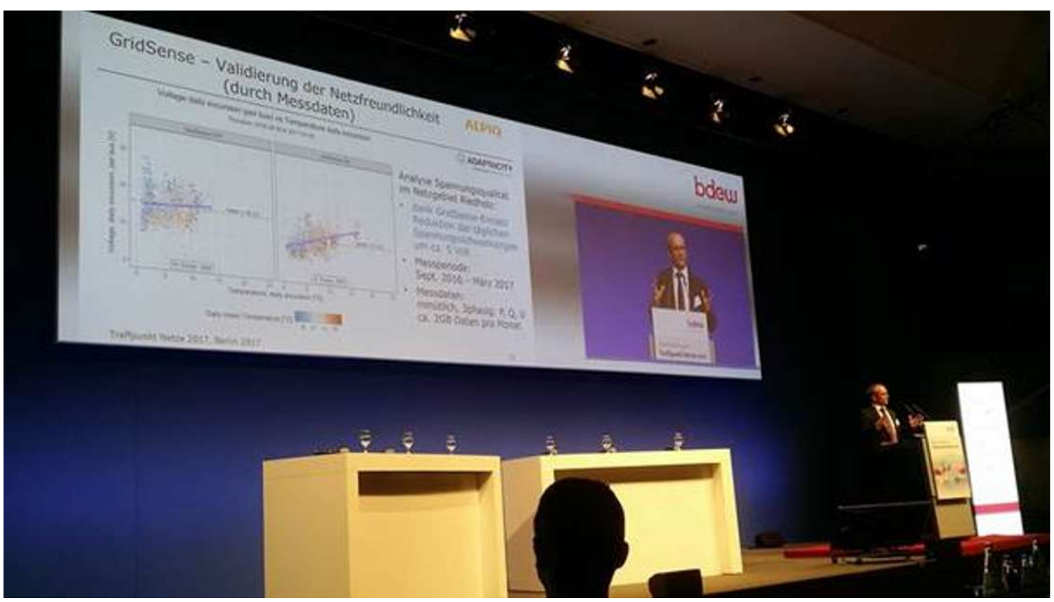


Figure 63 – Presentation of GridSense and SoloGrid by Marcel Morf
at BDEW event ‘Treffpunkt Netze’ in Berlin on 08.3.2017.

Besides speeches and technical talks, the SoloGrid project was presented at the key European technical conferences and exhibitions as shown by the following list.

Exhibition:

16. - 18.02.2016	E-world (Essen)
09. – 13.04.2016	Smart Grids Week (Linz)
01. - 02.03.2016	Treffpunkt Netze (Berlin)
08. - 09.06.2016	BDEW Kongress (Berlin)
22. - 24.06.2016	Intersolar Europe (Munich)
15. - 17.11.2016	European utility week (Barcelona)
31.1. - 1.2.2017	UK SmartMetering (London)
07. - 08.03.2017	Treffpunkt Netze (Berlin)
15. - 19.05.2017	Smart Energy Systems Weeks (Graz)

Figure 64 – GridSense/SoloGrid exhibition stand.

8.3.5. Press releases and specialist articles

Regular press newsletters, about every four months, informed the general public about the progress of the SoloGrid project. Press highlights surely included an interview by SRF. Also here, the project delays that were incurred also meant that for a long time easy and consolidated project results were missing. Due to this, there will be a final project closure event where all key results will be presented to the press and the general public.

Table 8 – Publications during the project

Date:	Where:	Title:	Autor:
Mi. 24.02.2016	Solothurner Zeitung	Hier steuert künstliche Intelligenz	Urs Mathys (Zeitung)
September 2016	Bulleting VSE/SEV	GridSense die intelligente Lösung im Praxischeck	Marcel Morf (Alpiq)
October 2016	Bulletin VSE/SEV	Stromflüssen auf der Spur	Andreas Ulbig (Adaptricity)
Sa. 26.11.2016	Solothurner Zeitung	Leiuchtturmprojekt läuft in Riedholz	
Sa. 26.11.2016	az Medien	In Riedholz wird die Energiezukunft getestet	Hanspeter Schläfli (Zeitung)
Fr. 25.11.2016	SRF Regionaljournal Aargau Solothurn	Interview mit Daniel Cajoos	

8.3.6. Reports

Besides press-related information, continous reporting regarding project status, project progress and results towards the SFOE was ensured.

BFE reports/presentations

05.01.2016 First interim report

21.06.2016 First yearly report & presentation

15.11.2016 Second interim report & presentation

23.08.2017 Second yearly presentation

06.11.2017 Final project report & presentation

9. Discussion

9.1. Outcome

The SoloGrid lighthouse project showcases the effectiveness of the GridSense load management technology for a residential neighbourhood under real-life operation conditions.

The effectiveness of the GridSense technology was validated by

- Pure measurement data based analysis,
- time-series simulation based analysis using actual grid operation data as well as (measurement based simulations)
- time-series simulation based analysis for hypothetical future scenarios (more PV, more heat-pumps, …) using synthetic grid operation data (model based simulations).

The simulation based analysis allowed to correctly compare the current setup and operation status of the Riedholz pilot grid with plausible future grid usage scenarios, i.e. higher PV and heat pump shares, as well as with different grid upgrade options, i.e. conventional line upgrade and on-load tap changer usage, while ensuring that exactly the same boundary conditions (ambient temperature, solar insolation, load consumption) apply to the various test setups. Altogether more than 40 different full-year grid scenarios have been modelled, simulated and analysed.

The key outcome of the combined measurement data and simulation analysis is that the GridSense technology is an effective solution for

- Shifting loads effectively to optimal grid situation time frames, reducing local peak demand as well as local production peaks and thereby
- Stabilized the distribution grid by significantly improving voltage quality

in distribution grids with decentral power generation and flexible loads.

The main difference between the three types of analyses is whether grid measurement data were used or not. Using measurements reduces result uncertainty but also means limited numbers of observations and non-identical boundary conditions. The way how the analyses are structured and how data is visually presented needed to be tailored to the data origin and so the different analysis types featured slightly varying results. The result accuracy is generally higher, the more measurement data is used. In that light, the precision of results is highest in the measurement analysis, followed by the measurement based simulations, and lastly the model based simulations.

The measurement data analysis showed that, opposed to times when it was inactive, no voltages below the lower limit of 0.85 p.u. occurred when GridSense was active. The simulations generally yielded lower voltage values than what was measured most likely due to a combination of effects including assumptions that had to be taken to replace unmeasured data. So although GridSense has relatively seen a comparable, positive effect, the absolute voltage levels in the simulations are infrequently below 0.85 p.u. even with GridSense.

The focus of the simulations was benchmarking GridSense with other technologies and assessing its performance with various different scenarios. The main finding of the measurement based simulations is that the positive effect of GridSense on daily voltage ranges is similar if not better than a conventional grid reinforcement while the model based simulations indicate that a conventional grid reinforcement would actually be a bit more effective in reducing voltage violations than deployment of GridSense. As stated before, the measurement based simulations are in this case closer to reality than the model based ones where additional assumptions had to be taken. It can thus be said that in the case of the Riedholz neighbourhood, GSU usage in (only) about 60% of households had a similar or even slightly better grid-stabilizing effect than a plausible conventional grid upgrade, i.e. an identical second main distribution cable over a length of up to 250 m or a thicker replacement cable with twice the original cross-section.

Furthermore, the GridSense solution performs significantly better than today's still dominating demand response technology – ripple control. In fact, it was found that in the particular setup of the Riedholz pilot grid, ripple control activation was responsible for the largest observed load peaks and, in turn, for the significant voltage violations.

It would indeed be conceivable that the GridSense solution could in the future become a better performing substitute for traditional ripple control technology.

10. Conclusions

The SoloGrid project turned out to be essential for several crucial aspects:

- The product development, including product verification, consolidation and findings.
- The system understanding, especially the behavior of the combined components, the effect of the influencing parameters, the interaction of controllable and uncontrollable parameters and a set of distinct and quantifiable results.
- The external communication as substantial part of a lighthouse project and as well as an ideal platform for partnerships and involvement of end user.

The following conclusions can be drawn:

Product effectiveness

- The functionality of the GridSense technology has been confirmed in a real and representative field environment.
- GridSense is effective and competitive in all evaluated operational modes.

Applications

- The respective effectiveness of GridSense depends on the chosen GSU mode as well as the given boundary conditions (grid, devices, user behavior, weather etc.).
- GridSense can be applied as a sole solution or in combination with other measures.

Benchmark

- The decision for a cost-optimized improvement measure for the grid depends on the individual case and the considered optimization parameter, e.g. voltage violations, cable load or operating costs.
- GridSense addresses the causes, while alternative measures only tackle symptoms.

11. Outlook

General

The experiences and results from the SoloGrid project were important contributors for the commercialization of GridSense. In combination with the simulation environment from Adaptricity it will in the future be possible to analyze scenarios upfront or run simulations to complement running projects.

Market

There was already a high interest by DSOs especially from Germany, Austria and Switzerland while the project was ongoing. Until the end of the SoloGrid project contracts with two Austrian and one German DSO have been signed. Therefore, the DACH-Region will be in the focus of the market strategy.

Product

The field test helped to discover weaknesses of the installation process and in the parameter settings. Solutions developed in this context will be part of the upcoming product release in order to make GridSense even customer friendlier as well as easier to install and to parametrize.

Further field tests

Grid integration of electric mobility is currently one of the most discussed topics by DSOs. InnoSense will put a stronger focus on this topic and will become an expert in this area with further tests, simulations, and projects. Currently, two projects with this focus are in the realisation.

12. References

[1] BFE, Botschaft zur Strategie Stromnetze, April 2016, Bern.

[2] Andreas Ulbig, Toni Rullan, Stephan Koch, Francesco Ferrucci, Assessment of Aggregated Impacts of Prosumer Behaviour, CIRED Workshop 2016, 14-15 June 2016, Helsinki, Finland.

[3] Stephan Koch, Andreas Ulbig, Francesco Ferrucci, An innovative software platform for simulation and optimization of active distribution grids for DSOs and smartgrid researchers. Proceedings of CIRED Workshop, June 2014, Rome, Italy.

[4] Norm EN 50160 – Wikipedia
[URL] https://de.wikipedia.org/wiki/EN_50160, available on 10.10.2017.

[5] Christof Bucher, Göran Andersson, Generation of domestic load profiles - an adaptive top-down approach, Proceedings of PMAPS, June 2012, Istanbul, Turkey.

[6] Stromverbrauch vergleichen – EKZ
[URL] http://www.ekz.ch/de/private/kontaktieren/stromverbrauch.html, available on 31.10.2017.

[7] N. Pflugradt, B. Platzer. Behavior based load profile generator for domestic hot water and electricity use, Innostock 12th International Conference on Energy Storage, 2012, Lleida, Spain.

13. Appendix

13.1. Simulation details

13.1.1. **Additional plots voltage validation**

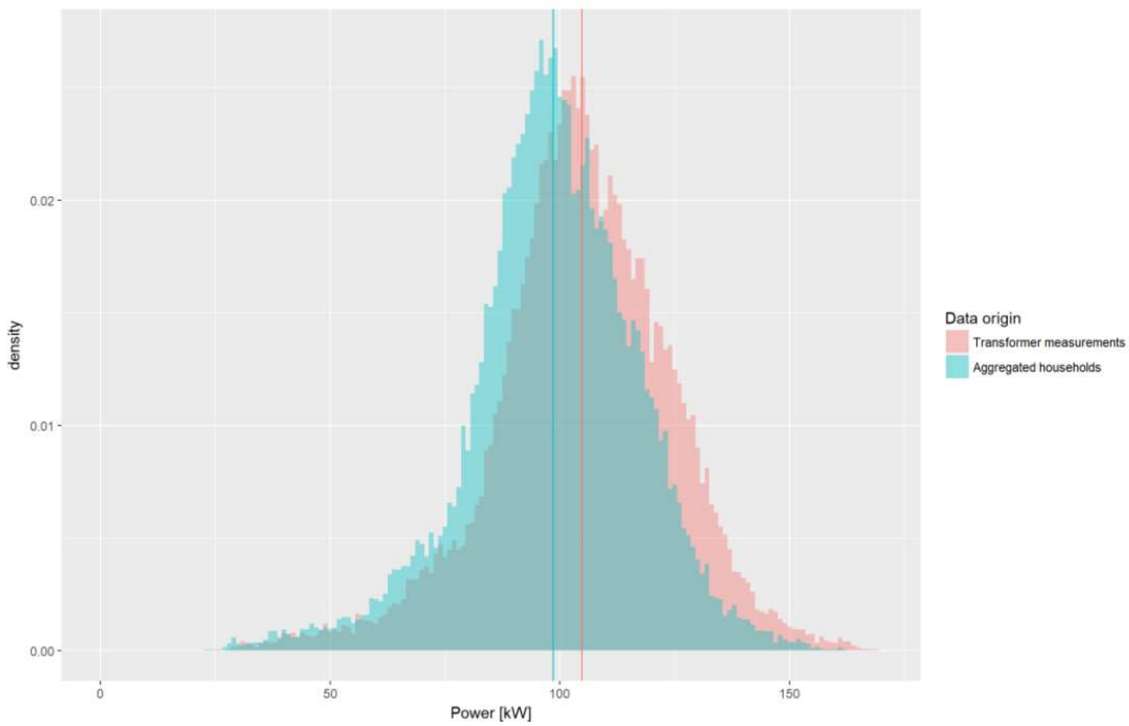


Figure 65 – Comparison of distributions of active power measurements at the transformer and aggregated power values of measured and synthesized households time series. Means are indicated by vertical, colored lines.

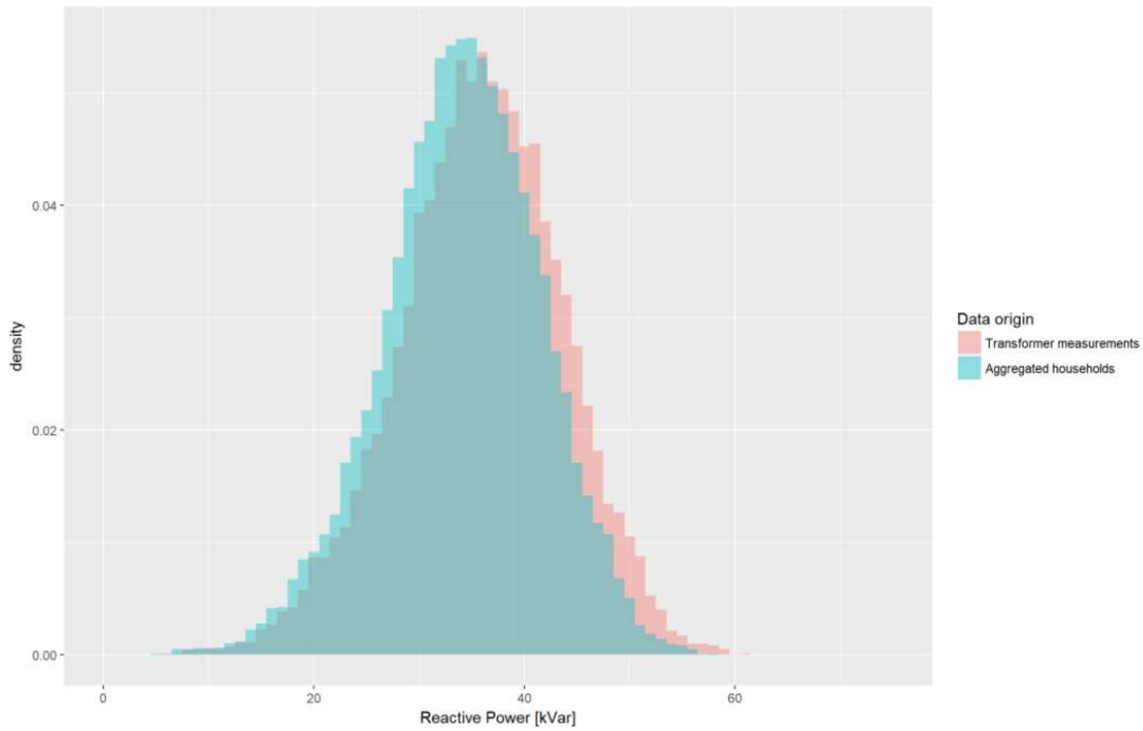


Figure 66 – Comparisons of distributions of reactive power measurements at the transformer and aggregated power values of measured and synthesized households time series.

13.1.2. **General simulation details**

General simulation settings
Aggressiveness is a GridSense parameter which controls the trade-off between shifting as much power as possible and comfort reductions. Different aggressiveness-settings were used depending on the unit category. The settings were chosen depending on the learnings from the field trials. They were not varied in the simulation campaign. Boilers were at an aggressiveness of 110, while heat pumps, electric vehicles, and batteries were run with a value of 100. Independent of the GridSense mode used for all other devices, batteries were always run in self-consumption mode.

In the field, transformer voltages are often set to be a bit above 1.00 p.u. in order to compensate for the voltage drop between transformer and households. This is also how it is done at the transformer that supplies the Riedholz test area. To cover this in the simulations, the transformer voltage in all simulations was at a fixed value of 1.02 p.u. The value was fixed over time so no result interferences from the middle voltage grid were part of the simulations.

All simulations were run with a fixed master seed in order to keep parameters of all units identical. When the number of units was varied there were in certain cases changes in the parameters in the limited set of households which had a varied unit configuration compared to the base case. These differing parameters were still within the limited boundaries of the parameter distributions listed in the following. Also, it is very important to state that the counterpart scenarios GridSense ON/OFF for direct comparison of the effects of GridSense were always identical and the direct comparison therefore absolutely fair.

Weather data was needed as inputs for unit models. The solar irradiance and the ambient temperature, measured 2 m above ground, of Riedholz from 2016 were used as inputs for the heat pump and the PV models.

Parameters of device models
Model parameters were chosen so that the units' yearly electric energy consumptions or productions were realistic and in line with reference values. Realistic yearly reference energy consumptions/productions for Switzerland are 2000 – 4000 kWh for electric boilers, 4000 – 12000 kWh for heat pumps, 4000 – 13000 kWh for PV (given unit sizes of 5 – 10 kWp with 800 – 1300 kWh per kWp and year), and 1850 – 7350 kWh for the base load consumption of a household [6].

Effectively used for simulations were energy consumption/production ranges of 2000 – 4000 kWh for boilers, 4500 – 10000 kWh for heat pumps, 5000 – 9000 for PV units, and 1850 – 7350 kWh for the base load consumption (see Figure 67 and Figure 68 for details). As evident from these specifications, the range of possible parameter values was narrowed down for the heat pump and PV models. This was done in order to prevent distorting effects from randomization processes to set unit parameters. For the scenarios with increased numbers of PV units, the yearly output was fixed and equal at all devices (production of ca. 8000 kWh per device and year).

The energy consumption of electric vehicles is fully dependent on the usage pattern. More information on our assumptions can be found together with the EV-parameters.
Also, the amount of energy cycling of batteries depends on assumptions about the battery controller. For this project, batteries are assumed to be only charged with power from PV units in the same household. Charging batteries with energy from the grid is inhibited.
Important parameters of the used unit models are subsequently given. Three conventions apply for the list of unit parameters:

- If four values are given the parameters are truncated normally distributed with these parameters: expected value, standard deviation, lower boundary, upper boundary.
- If two values are given the parameters are uniformly distributed with these parameters: lower boundary, upper boundary.
- If a single value is given then it is a deterministic parameter.

Boilers
Volume [m^3]: 0.35, 0.05, 0.3, 0.5
Electric heating efficiency: 0.9
Rated power [kW]: 4.5, 1, 3, 6
Average hourly hot water demand [l/h]: 6, 1, 5, 7.5
Higher water temperature [°C]: 55, 62
Lower water temperature [°C]: 10
Three varying hot water demand profiles (early, standard, late), randomly assigned to individual boilers

Heat pumps (air source)
Rated power [kW]: 4, 1, 3, 6
Temperature set points[°C]: 20, 22

PV
Rated power for all scenarios with base level of PV penetration [kW]: 8, 2, 5, 11
Rated power for all scenarios with elevated levels of PV penetration [kW]: 7.0
Solar irradiance time series of Riedholz from 2016 as input

Batteries
Energy capacity [kWh]: 7.2
Charging/discharging efficiency: 0.9
Charging/discharging power [kW]: 4.8

Electric vehicles
Energy capacity [kWh]: 18
Charging efficiency: 0.9
Charging power [kW]: 3.7
Three varying electric car usage profiles (early, standard, late), randomly assigned to individual EVs:
Weekdays departure between 05:00 – 07:00, 06:00 – 08:00, 07:00 – 09:00 (early, standard, late); arrival between 15:00 – 19:00, 16:00 – 20:00, 17:00 – 21:00 (early, standard, late); SOC when returning between 0.5 - 0.8.
Weekends departure between 06:00 – 23:00; trip length 1-20 h, maximal to the end of the day; SOC when returning between 0.2 – 1.
Times stated in this description are given in local time. It was assumed that the electric vehicles were not too intensely used. With assumptions of energy usage of 0.2 kWh/km and an utilization of 10000 km per year the yearly consumption totals to a moderate value of 2000 kWh per electric vehicle. Depending on the stochastic usage profiles this number varies slightly. For the scenarios with high EV penetration, usage time series with less EV usage were added. These are realistic if the EV is not regularly used e.g. if it is a second car. An important reason to keep the yearly energy consumption of EVs at a moderate level is the potentially considerable influence of the assumptions about the usage profile on the simulation. These assumptions are for this project also conservatively chosen in that the EVs are normally not plugged-in during the day. This would be an important time to provide additional flexibility, especially during summer in combination with high levels of PV.

Base load consumption households
This is an aggregation of all household consumption not explicitly modelled via other unit models.
Rated power [kW]: 6, 8
Annual energy consumption [kWh]: 4000, 1000, 1850, 7350

A load profile generator [7] provided realistic household electric consumption profiles as models. These were randomized within the simulation engine Adaptricity.Sim so that every household featured a unique profile.

Base case simulation settings

Table 9 – Details of system configuration of base case scenario. For each household it is listed if its devices are GridSense-controlled in the base case scenario, the name of the grid node to which they are attached is given, and it is indicated what flexible electrical components are part of the household. This information can also be deduced from the household name, which contains an abbreviation of each unit present.

Household Number	Household Name	Grid Node	GS control	Boiler	HP	PV	Battery	EV
1	1.BOI.PV	HAS732	yes	x		x		
2	2.BOI.HP	HAS11829	no	x	x			
3	3.BOI	HAS758	yes	x				
4	4.BOI.HP	HAS11715	yes	x	x			
5	5.BOI	HAS747	yes	x				
6	6.BOI.HP	HAS754	no	x	x			
7	7.BOI.HP.EV	HAS10306	yes	x	x			x
8	8.BOI.HP	HAS1100	yes	x	x			
9	9.BOI.HP	HAS731	yes	x	x			
10	10.BOI.HP	HAS757	yes	x	x			
11	11.BOI	HAS757	yes	x				
12	12.BOI.HP	HAS10400	yes	x	x			
13	13.BOI.HP	HAS9913	no	x	x			
14	14.BOI.HP.PV	HAS11665	yes	x	x	x		
15	15.BOI.HP.EV	HAS9663	yes	x	x			x
16	16.BOI	HAS739	yes	x				
17	17.BOI.HP.PV	HAS10334	yes	x	x	x		
18	18.BOI.HP	HAS1084	no	x	x			
19	19.BOI.HP	HAS10327	yes	x	x			
20	20.BOI.HP.EV	HAS10142	yes	x	x			x
21	21.BOI.PV	HAS753	yes	x		x		
22	22.BOI	HAS10325	yes	x				
23	23	HAS730	no					
24	24.BOI	HAS4897	yes	x				
25	25.BOI.HP	HAS755	no	x	x			
26	26.BOI.HP	HAS740	yes	x	x			
27	27.BOI.HP.PV.BAT	HAS11768	yes	x	x	x	x	
28	28	HAS740	no					
29	29.BOI.HP	HAS10465	yes	x	x			
30	30.BOI	HAS10544	yes	x				
31	31.BOI.HP.PV.BAT.EV	HAS743	yes	x	x	x	x	x
32	32.BOI	HAS744	yes	x				

33	33.BOI	HAS760	yes	x				
34	34.BOI.HP.PV.BAT	HAS1080	yes	x	x	x	x	
35	35.BOI.HP	HAS10360	yes	x	x			
36	36.BOI.EV	HAS735	yes	x				x
37	37	HAS741	no					
38	38.BOI.HP	HAS741	no	x	x			
39	39	HAS742	no					
40	40	HAS1053	no					
41	41	HAS12567	no					
42	42.BOI.HP	HAS12567	no	x	x			
43	43	HAS12567	no					
44	44	HAS12567	no					
45	45	HAS12567	no					
46	46	HAS11706	no					
47	47	HAS12818	no					
48	48	HAS10180	no					
49	49.BOI.HP	HAS734	no	x	x			
50	50	HAS733	no					
51	51	HAS738	no					
52	52.BOI	HAS737	no	x				
53	53	HAS736	no					
54	54	HAS10189	no					
55	55.BOI	HAS11768	no	x				
56	56	HAS11768	no					

Specifications of electricity tariffs (important for assessment of household electricity bills)
The applied tariff consists of two values, a higher one for peak hours and a lower one for off-peak hours. The following time designations are given in UTC. Peak hours are on weekdays from 7:00 to 21:00 and on Saturday from 7:00 to 12:00. The off-peak tariff applies during the remaining time. The absolute tariff levels are 0.2061 CHF/kWh during peak times and 0.1255 CHF/kWh during off-peak times.

Ripple control specifications
Ripple control is applied to the electric boilers. They are randomly assigned to three groups of equal size. Each group features different clearance time windows at night and on weekends (see Table 10 for clearance time windows).

Table 10 – Overview details for boiler ripple control. The clearance times of all three boiler groups are listed. Outside of the listed time periods boilers could not be active. Time designations are in UTC.

	Weekdays	Weekends
Group A	23:00 – 01:00 and 02:00 – 04:00	Sat. 02:00 – 04:00 Sat. 14:00 – Sun. 24:00
Group B	00:00 – 02:00 and 03:00 – 05:00	Sat. 00:00 – 02:00, 03:00 – 05:00 Sat. 15:00 – Sun. 24:00
Group C	01:00 – 03:00 and 04:00 – 06:00	Sat. 00:01 – 03:00, 04:00 – 06:00 Sat. 16:00 – Sun. 24:00

13.1.3. **Additional plots simulation results**

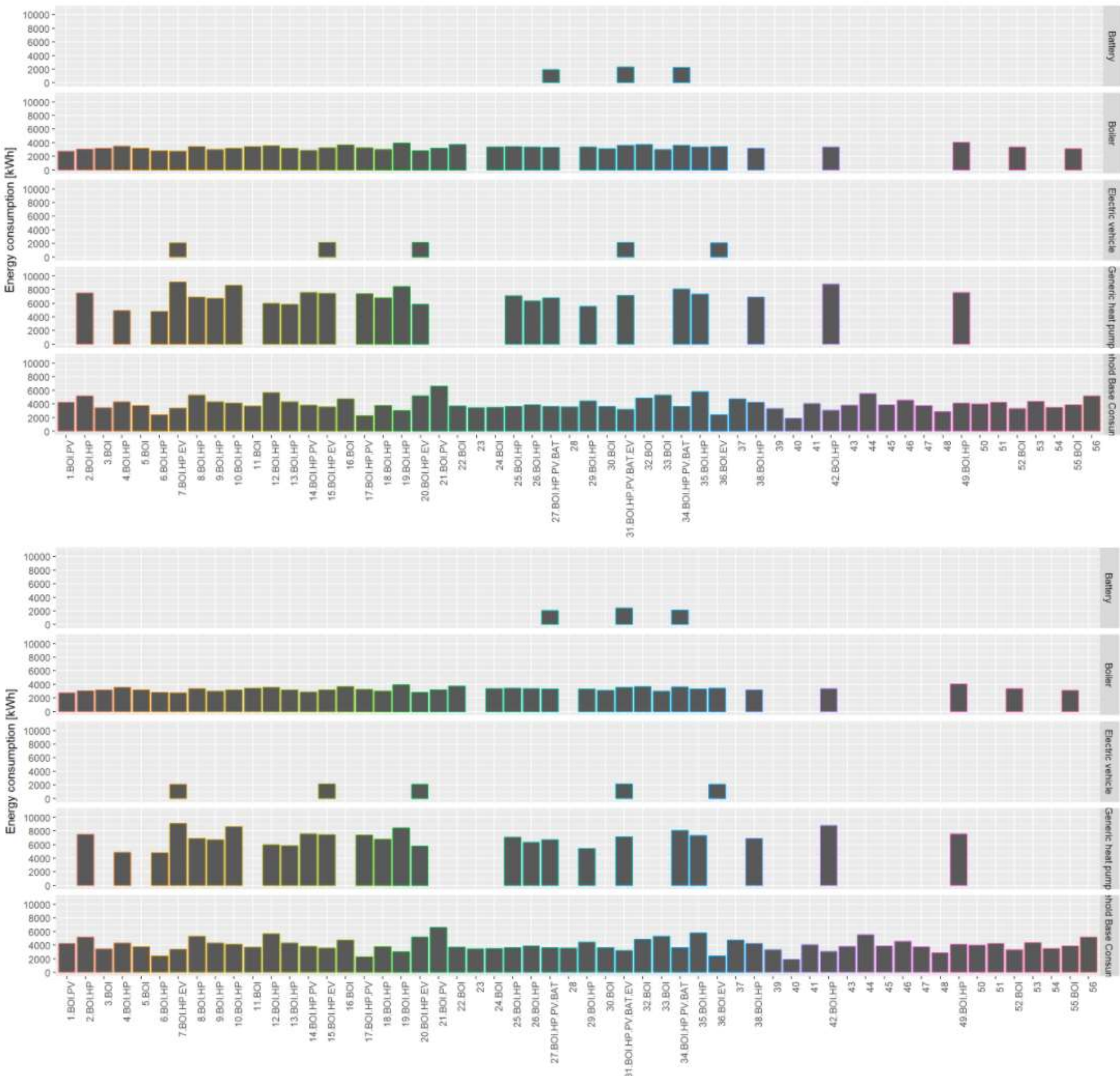


Figure 67 – Energy consumption of individual devices over year-long simulation. The five device types that consume electric energy in the simulations are batteries, boilers, electric vehicles, heat pumps, and, a device type called household base consumption which serves as an aggregation for any household consumption that is not covered with the other four device types. Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*

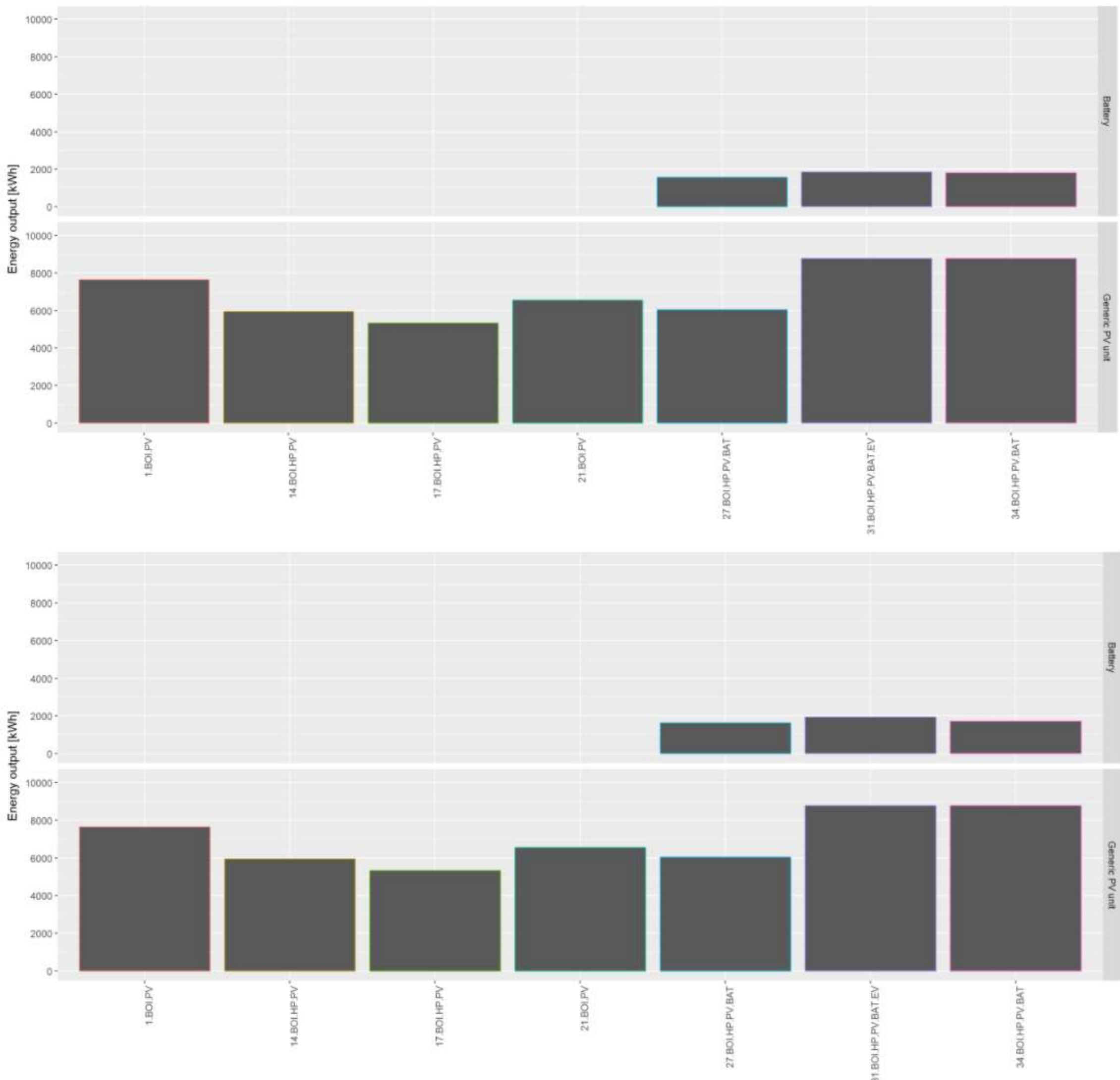


Figure 68 – Energy output of individual devices over year-long simulation. Batteries and PV units are the only device types that can deliver electric energy in the households. Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*

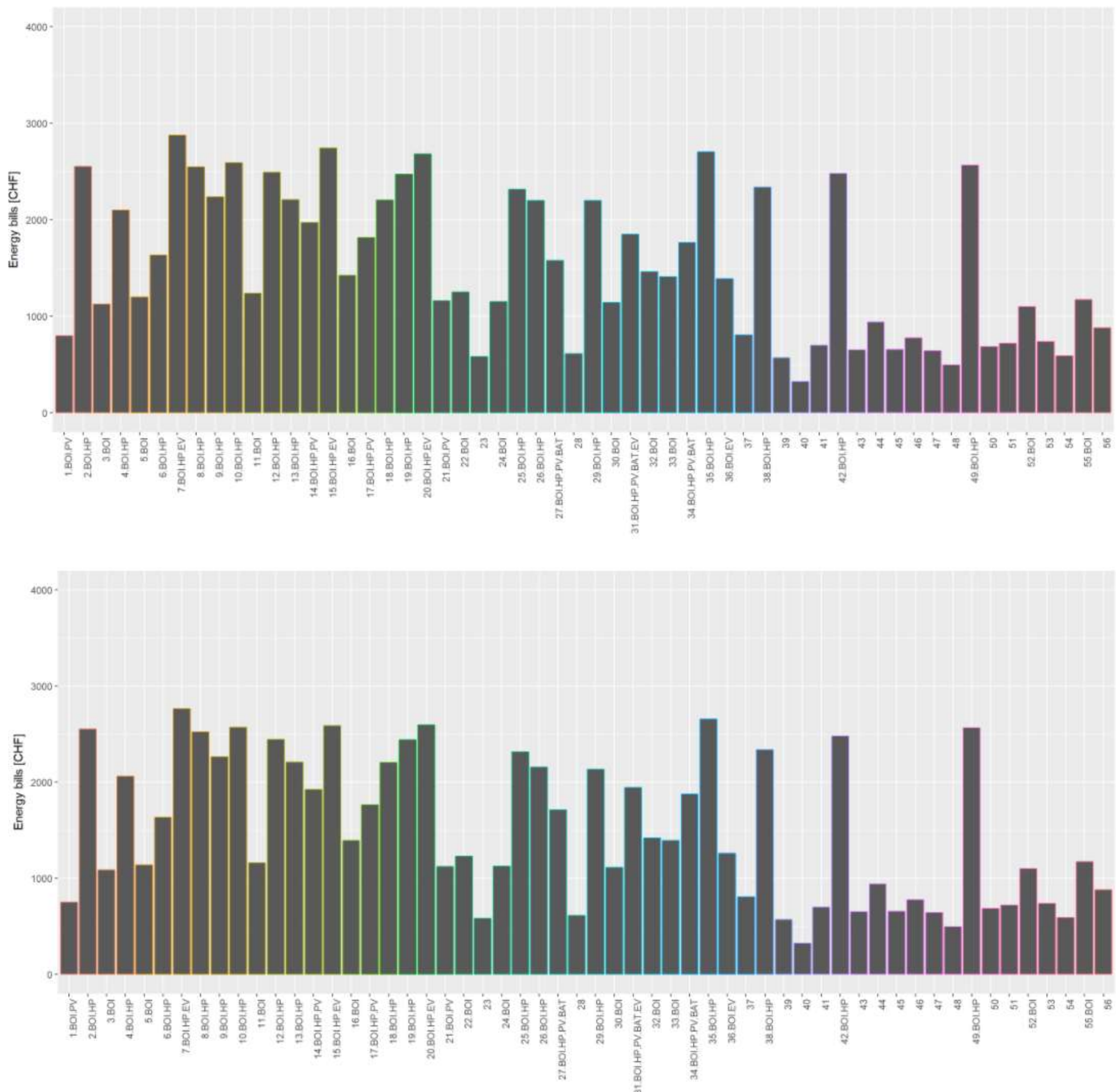


Figure 69 – Energy bills per household over year-long simulation. The net power consumption per household was used for billing. No reimbursement of power from PV units was considered. Upper part of figure: *Base Case GS off*; lower part of figure: *Base Case grid-mode.*