Energieforschungsprogramm

Publizierbarer Endbericht

Programmsteuerung:
Klima- und Energiefonds

Programmabwicklung:
Österreichische Forschungsförderungsgesellschaft mbH (FFG)

Endbericht
erstellt am
27/05/2018

Projekttitel: iniGrid

Projektnummer: 845018

Ausschreibung	04. Ausschreibung e!Mission.at
Projektstart	01/09/2014
Projektende	28/02/2018
Gesamtprojektdauer (in Monaten)	42 Monate
ProjektnehmerIn (Institution)	AIT Austrian Institute of Technology GmbH
AnsprechpartnerIn	DI Dr. Mark Stefan
Postadresse	Giefinggasse 2, 1210 Wien
Telefon	+43 664 88964900
Fax	+43 50550+6640
E-mail	Mark.Stefan@ait.ac.at
Website	www.ait.ac.at

iniGrid

Integration of Innovative Distributed Sensors and Actuators in Smart Grids

Authors:

Dr. Mark Stefan, Dr. Friederich Kupzog, Dr. Oliver Jung *(AIT Austrian Institute of Technology GmbH)*

Dr. Michael Bartonek, Dr. Wolfgang Hauer, Kenan Askan *(Eaton Industries (Austria) GmbH)*

Dr. Natalie Prüggler, Dr. Wolfgang Prüggler *(MOOSMOAR Energies OG)*

Stefan Kollmann, Stefan Wilker, Marcus Meisel, Dr. Alexander Wendt, Lampros Fotiadis, Georg Kienesberger *(Technische Universität Wien, Institut für Computertechnik)*

Dr. Johannes Böhm *(ZELISKO GmbH)*

FH-Prof. Dr. Peter Zeller, Andres Moreno, Khalil Hamad *(Fachhochschule Oberösterreich – F&E GesmbH)*

Dr. Stephan Hutterer *(Sprecher Automation GmbH)*

1 Table of contents

2 Introduction

2.1 Project description

The aim of the iniGrid project was to develop and validate innovative sensor and actuator components for smart distribution grids. Because of massive integration of renewables, active capacity management in distribution grids is getting more and more important to avoid high investments in grid reinforcement. Management of line use in congestion situations, as well as fault detection and fast service restoration, are only possible with appropriate sensors and actuators in place. Appropriate cost-effective components that provide advanced functionality such as integrated communication capabilities which can be retrofitted with reasonable effort are missing today at the distribution level. The market is beginning to request such devices on low and medium voltage level. iniGrid targeted this window of opportunity, so that this key technology for smart grids is made in Austria.
Two radically new sensor and actuator developments, along with the necessary information/automation technology were in the scope of the project. These items fill the gaps in the required observability of distribution grids for future grid operation:

a) The first key innovative approach of iniGrid was the integration of the power management and grid protection functions within one device – the so-called Smart Breaker. The challenge was to integrate necessary components in a compact device with reasonable costs. These innovative switching devices are located in the energy customer domain (low voltage, commercial/industrial/residential customers) to provide protection functions, power management, measurement services, and communication for individual load or generation branches.
b) The second innovation is an air-insulated medium voltage sensor, integrated into post insulators or other insulating structures for retrofit of the significant number of existing air-insulated medium voltage installations. The challenge here was to provide precise data since these isolators have no earthed cover and therefore, suffer from parasitic capacitances to geometrically and electrically undefined external structures.

The project dealt with the individual technology development and the integration of these novel components (as well as existing ones such as smart metering and other sensors) with future-proof and secure automation architecture and protocols. The challenge addressed in the liberalized market environment is how to technically and conceptually network sensors and actuators in the smart grid for applications ranging from local energy management to virtual power plants, grid voltage control, fault detection and others. An increasing number of such networked smart grid application are emerging. Together with the push for PV and other distributed volatile generators into low voltage networks, a strong pressure for innovative and cost-effective sensor and actuator technologies is developing. iniGrid innovates the way electric energy is brought to end-use equipment by providing cost-effective technologies for actively managed distribution grids. System interaction of novel and existing hardware and software technology was evaluated in comprehensive laboratory tests, followed by different field tests, starting from a local household and ending up in controlling the loads of an exhibition in Lower Austria.

2.2 Project goals

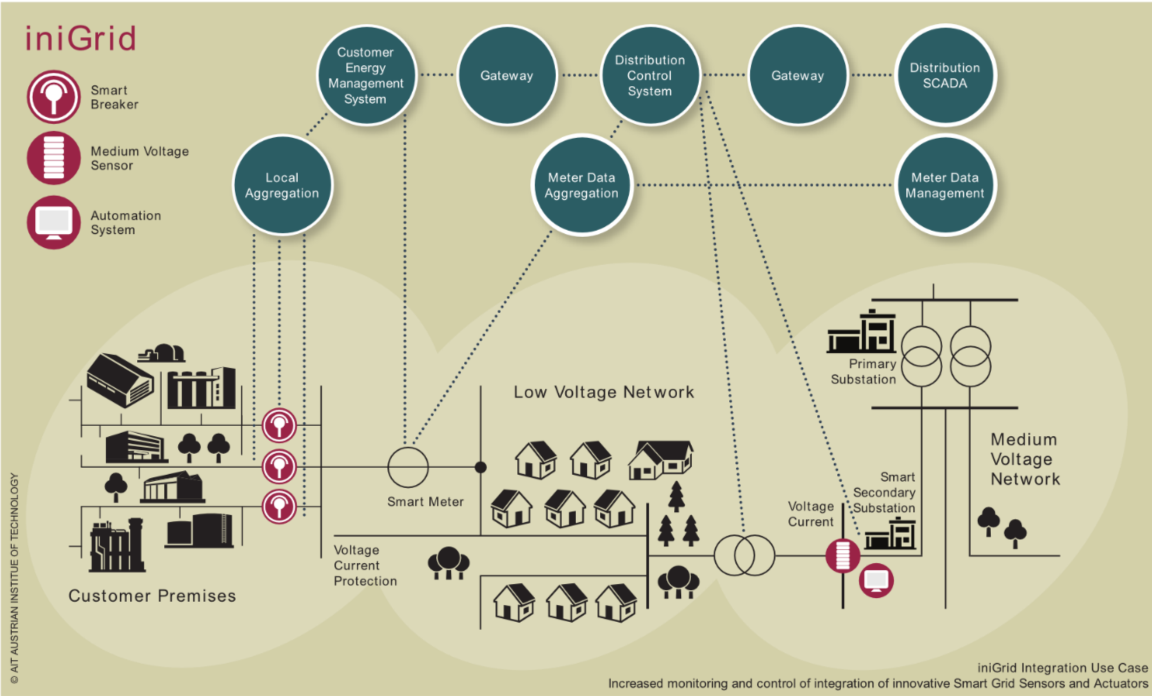


Figure 1: Overview of the iniGrid scope

Figure 1 shows a symbolic distribution grid with an indication of the iniGrid scope. The vast majority of European distribution grids today are passively operated, i.e., without several of the blue components. The iniGrid project aims to integrate new sensor and actuator components into the system, together with the communication junction from the customer domain to the distribution control center. In particular, iniGrid aimed to:

1. Develop innovative sensors and actuators for the customer domain and distribution grid domain. Two particular integrated sensor and actuator devices were in scope, where current demand for innovative solutions is high and cost pressure is an obstacle for smart grid realizations. The key innovative approach of iniGrid was the integration of power management functions and grid protection functions within one device, called the Smart Breaker. The consolidation of these two function-layer is reasonable both from a technical and a cost perspective. These innovative switching devices are located at the energy customer domain to provide protection functions for downstream system components (e.g., power consumers, installation facilities, etc.) or humans in the case of a fault, comparable to known devices like circuit breakers. Additionally, the devices should provide power management by intentionally switching on and off related power branches and data on system state by additional sensor-based data to proactively indicate possible future faults on the grid, this increasing the overall power availability and reliability.
   In a significant number of medium voltage switchgear and structures, voltage sensors for air-insulated equipment are needed. Here accurate and stable voltage sensors have to be integrated into post insulator or other insulating structures. iniGrid aimed to reach the required accuracy of at least class 0.5 according to IEC 61869 although these isolators have no earthed cover and therefore suffer from parasitic capacitances to geometrically and electrically switching state undefined external structures.

2. Integrate these systems with future-proof automation architecture and protocols. To setup a local power management system and support active grid operation based on Smart Breakers, these devices need to be network-enabled so they can send data to a remote node and to receive and process incoming data from a remote node. Depending on the system status a specified device can be switched off and on to follow a dedicated power policy (e.g., load shedding or load shifting).
3. Perform cost/benefit analysis for selected grid integration approaches with and without iniGrid technology. While it has become eminent that conventional grid reinforcement is often a costly approach, smart grid solutions enabling active management of renewable generators can be seen as the solution of choice for certain grid areas. However, currently state of the art smart grid technologies comprising of industrial controllers, automation equipment, and specialized hardware comes with a price. This reduces the application spectrum of smart grid technology and is a barrier for economic scale affects. Here it was analysed how technology developed in iniGrid can change the picture by implementing cost estimation as well as real cost data during the validation phase of the project.
4. Ensure flagship character by interlinked field trials in customer and grid operation domain. The developed smart LV breaker and MV sensor components will be tested in realistic environment, where also the proof of the automation architecture and procedures for large scale distributed installations is performed. With several test sites, different target groups can be reached.

2.3 Methodology

In general, the project could be divided into two parts:

1. The main focus of the first part of the project was the development of the new components (hardware and software) based on the use cases and the requirements. Additionally, the automation architecture as well as a generic rollout-concept were defined.
2. The second part dealt with the validation of the components. Therefore, a three-step approach, covering simulation, laboratory tests, and field tests of the developed technologies was taken. Figure 2 shows the focus on analysis in simulation, laboratory, and field. System simulations were conducted on the basis of hardware and software. Lab tests were conducted in-house at the industry partners, but also in the AIT SmartEST lab. Field tests were performed separately for low voltage domain (Fachhochschule Oberösterreich, Sonnenwelt Großschönau) and medium voltage domain (Replica of switch gear used in Linz).

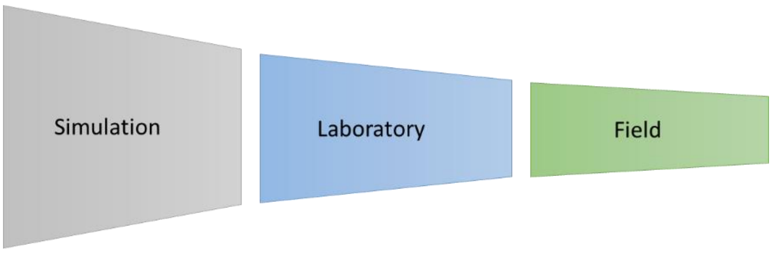


Figure 2: iniGrid-Methodology focused on simulation, laboratory, and field.

Beside these two main parts of the project, a cost benefit analysis was performed, considering the new technologies in hardware and software as well as results of simulations and field validation (see Section 3, Figure 3).

3 Content Presentation

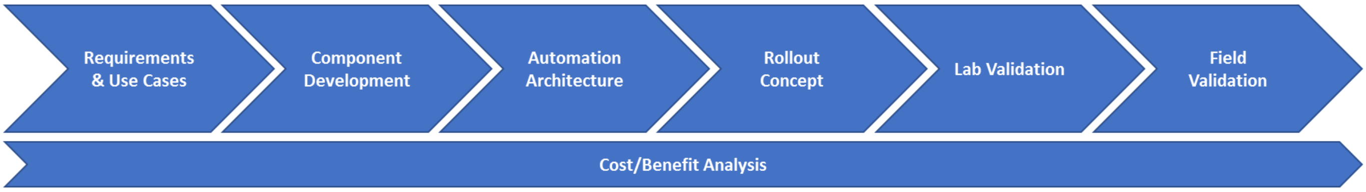


Figure 3: Overview about iniGrid work packages

Figure 3 gives an overview about the activities in the project and how the results of a particular activity are used as input for the subsequent tasks in the project. The main activities of the projects can be divided into the following tasks:

- Requirements analysis and Use Case Definition (Section 3.1): As a first step in the iniGrid project, the requirements were defined and based on that, a number of use cases were derived. These use cases were the base for the subsequent activities, e.g. as base for the cost/benefit analysis, the definition of the automation architecture, simulation, test cases to name but a few.
- Component Development (Smart Breaker and Medium Voltage Sensor, Section 3.3): After identifying the requirements and use cases, the component development started. After the first prototypes and the corresponding lab validation, another iteration for improving the hardware components was performed.
- Definition of the future-proof automation architecture (Section 3.4): Based on the use cases and the innovate hardware components, a future-proof automation architecture was defined, including the customer premises, the low and medium voltage grid themselves including the new components, and the grid operator. Additionally, a comprehensive risk assessment was performed, to identify new risks and their avoidance due to the new components.
- Definition of the rollout concept (Section 0): Afterwards, rollout concepts for the new and innovative components were defined. In particular, scalable solutions in planning, rollout, and operation with the constraint of having a minimum of individual effort were developed.
- Lab Validation of the components and the system (Section 3.7): After the development of the components, several lab tests were performed, to identify missing functions, faulty implementations, etc. Therefore, it was necessary to develop a proprietary Customer Energy Management System, providing the connection to the hardware on one hand, and the connection to the grid operator on the other hand. Additionally, several smart grid functions were implemented.
- Comprehensive Field Validation (Section 0): To test the devices and the interaction of the developed and existing systems within a real environment, a number of field tests were performed over a period of several month. The validation was done one several locations and environments.
- Cost/Benefit Analysis which was done in parallel to the other activities (Section 3.9): To estimate the monetary impact of the new components, a comprehensive cost/benefit analysis for selected use cases as well as for the field validation was done within the project.

In the following sections, the activities and its results are presented in detail.

3.1 Requirement Analysis and Use Case Definition

For the definition of requirements of the technology development and the design of simulation, lab and field experiments, a use case-driven methodology has been chosen. For iniGrid, a use case is defined as the description of a control loop including one or more of the sensor, actuator and automation technologies developed by the project. An overview can be found in Table 1. In the following subsections, the use cases are described roughly, further information is provided in the project Deliverable D1.1.

Table 1: Overview of iniGrid use cases

ID	Use Case Name	Sensors	Actuators	Controller	Controlled process
A	Energy Management on Prosumer Level / Electric Mobility	Smart Meter, **Smart Breaker**	Manually controlled switches, set-points, **Smart Breaker**	Customer Energy Management System (CEMS)	Energy consumption of processes on prosumer site
B	Low Voltage Network Optimisation	Smart Meter, dedicated grid sensors, **Smart Breaker**	On-load-tap-changer, feeder configuration (switches), active and reactive power setpoints of distributed generators, storage systems, potentially **Smart Breaker** for load management	Secondary Substation Controller	Voltage level at nodes in low voltage power grid (limitation to allowed voltage band). Potentially limit line load
C	Medium Voltage Network Optimisation on Substation Level	**Medium voltage sensor,** measurements from low-voltage side	On-load-tap-changer, feeder configuration (switches), active and reactive power setpoints of distributed generators, secondary substation controllers	Primary Substation Controller	Voltage level at nodes in medium voltage power grid (limitation to allowed voltage band). Potentially limit line load
D	Medium Voltage Network Optimisation on Management System Level	**Medium voltage sensor,** measurements from low-voltage side	On-load-tap-changer, feeder configuration (switches), active and reactive power setpoints of distributed generators, secondary substation controllers	Network operator SCADA system (Distribution management system)	Voltage level at nodes in medium voltage power grid (limitation to allowed voltage band). Potentially limit line load
E	Distribution Optimisation across Voltage Levels	Smart Meter, dedicated grid sensors, **Smart Breaker, Medium voltage sensor,** measurements from low-voltage side	Those from B + C	Substation controllers, Network operator SCADA system (Distribution management system)	Maintain system stability, avoid contradictory control actions, reactive power balancing

3.1.1 Use Case A: Energy Management on Prosumer Level / Electric Mobility

This Use Case (Figure 4) has a focus on the prosumer domain and deals with applications of the Smart Breaker in the context of customer energy management with a potential interface to power grid operation and other use cases in that domain. Application scenarios can range from residential to Industry or SME sites equipped with smart breakers in main circuits for monitoring and/or energy management. Also, electric mobility charging infrastructure could be equipped with smart breaker as sub-component (see e.g. [1] for a discussion of application and modelling scenarios).

The benefit of such systems can be:

- Benefit for Customer: Increase of energy self-coverage
- Benefit for Customer: Increase in monitoring and controllability of the consumption processes
- Benefit for Customer: Increase in Energy Efficiency due to the possibility to remotely switch off unused circuits

Benefit for Customer:

- Additional income from demand side management schemes

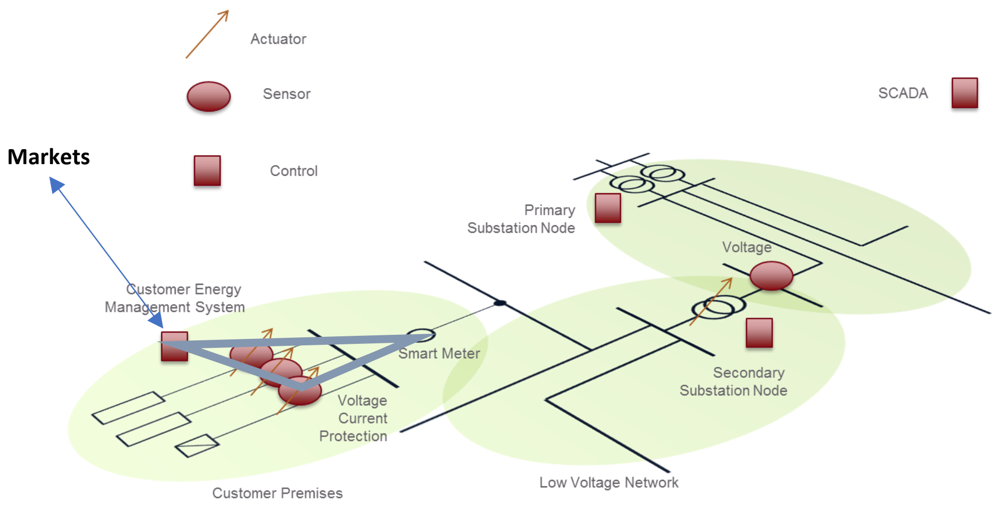


Figure 4: Use Case A: Energy Management on Prosumer Level / Electric Mobility

This use case focusses on the Smart Breaker and customer site infrastructure including the customer energy management system. This system has (or will have in future) two logical external interfaces towards

1. energy markets (e.g. aggregators such as virtual power plants, or time varying energy prices)
2. power grid (communication for grid-supporting customer behaviour).

Use case A has a focus on the energy market interface. Use Case B below will focus on functionality of the power grid interface.

3.1.2 Use Case B: Low Voltage Network Optimisation

New sensor and actuator technology allows advanced methods for optimised operation (and also planning) of low voltage networks (Figure 5). In order to increase the hosting capacity for distributed generation, voltage control can be performed to actively keep voltages in the allowed voltage band and avoid or delay demand for grid reinforcement by a substation-level controller [2]. In urban networks, also current monitoring and active limitations can be an application. The focus here is on the interface between grid automation and the customer energy management.

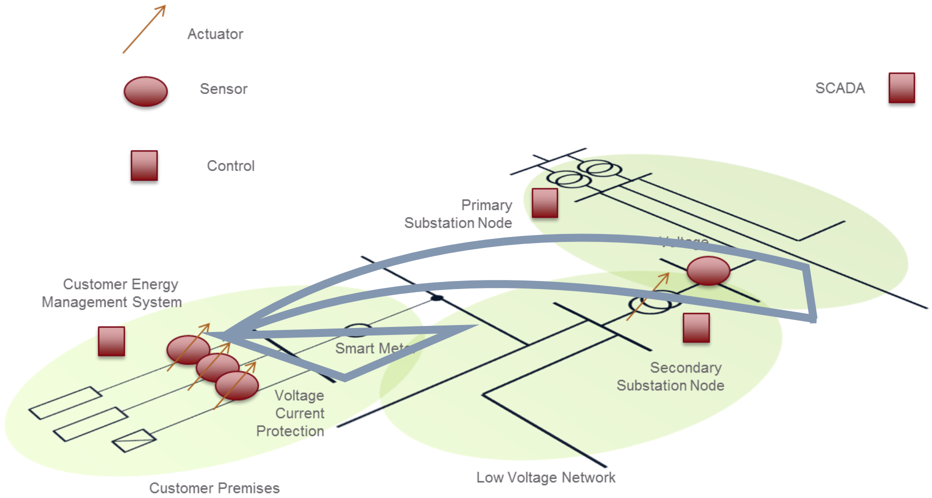


Figure 5: Use Case B: Low Voltage Network Optimisation

3.1.3 Use Case C: Medium Voltage Network Optimisation on Substation Level

New sensor and actuator technology allows advanced methods for optimised operation (and also planning) of medium voltage networks. In order to increase the hosting capacity for distributed generation, voltage control can be performed to actively keep voltages in the allowed voltage band and avoid or delay demand for grid reinforcement by a substation-level controller [3]. In urban networks, also current monitoring and active limitations can be an application (Figure 6).

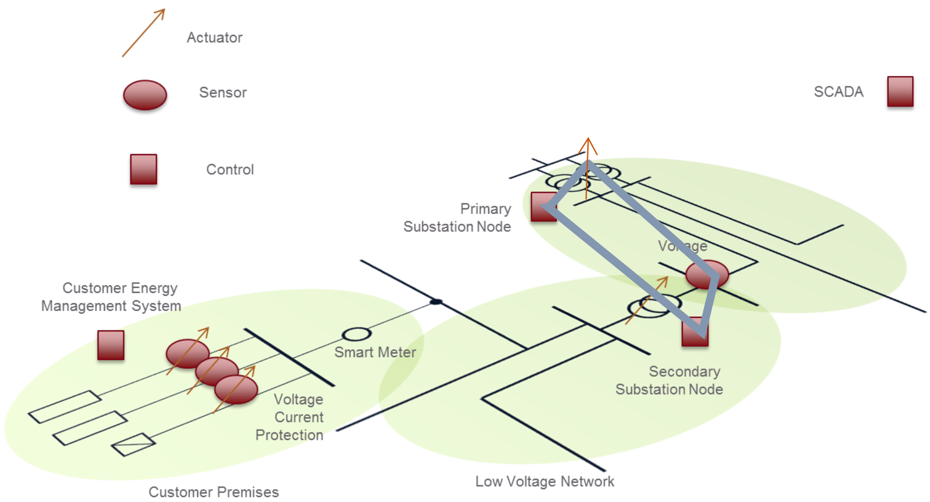


Figure 6: Use Case C: Medium Voltage Network Optimisation on Substation Level

3.1.4 Use Case D: Medium Voltage Network Optimisation on Management System Level

Similar to the substation-level controller, an alternative control architecture is to integrate additional sensors and actuators in existing distribution management systems (Figure 7) and process the voltage control functionality together with optimal power flow calculations [4].

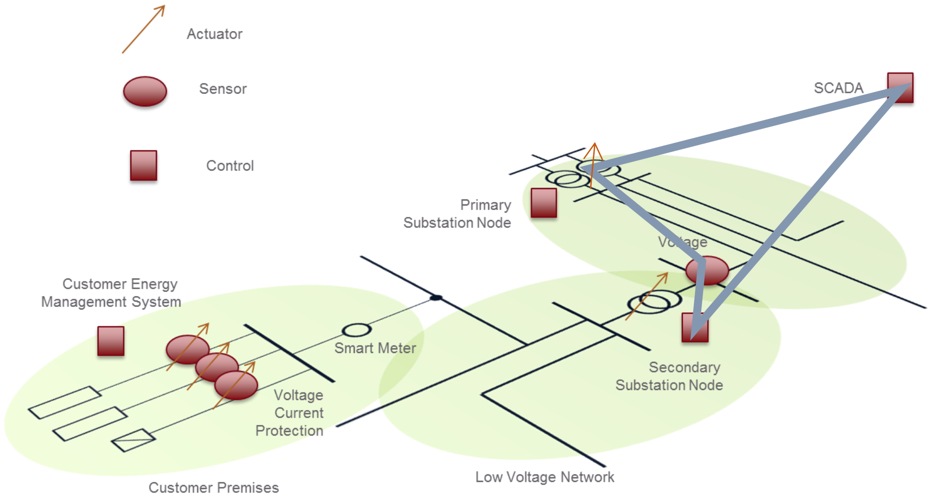


Figure 7: Use Case D: Medium Voltage Network Optimisation on Management System Level

3.1.5 Use Case E: Distribution Optimisation across Voltage Levels

Emerging control approaches focusing on low or medium voltage level only might negatively interfere with each other without proper design and/or central coordination (Figure 8). The aim of this use case is to maintain system stability, avoid contradictory control actions, as well as to perform reactive power balancing on the basis of sensor data from the field.

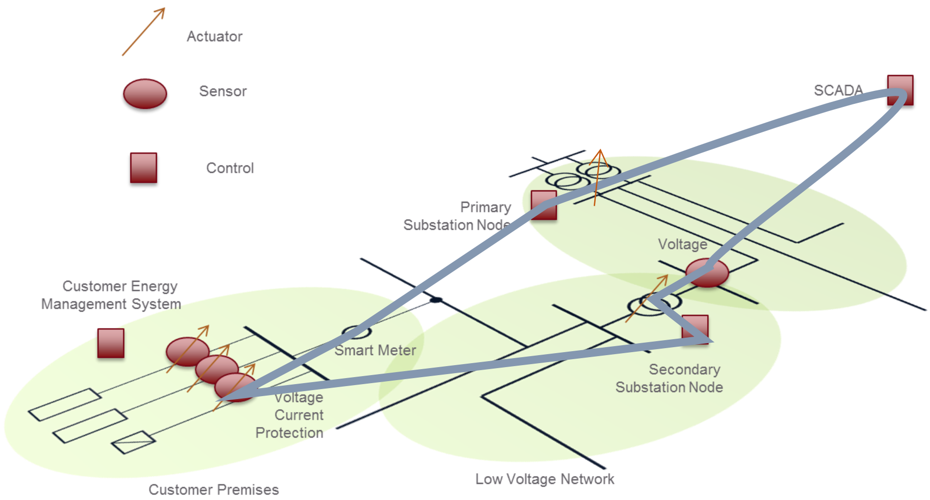


Figure 8: Use Case E: Distribution Optimisation across Voltage Levels

3.2 General requirements

General requirements (non-functional requirements) are as follows:

1. The overall system has a state-of-the-art cyber security
2. The overall system exhibits safe operation also in exceptional states
3. The overall system should use synergy effects to make operation more efficient. Newly developed components should act as a missing peace in this context
4. Economy of scale should allow economic viability of the proposed use cases
5. The overall system should be interoperable (see interfaces in Figure 9)

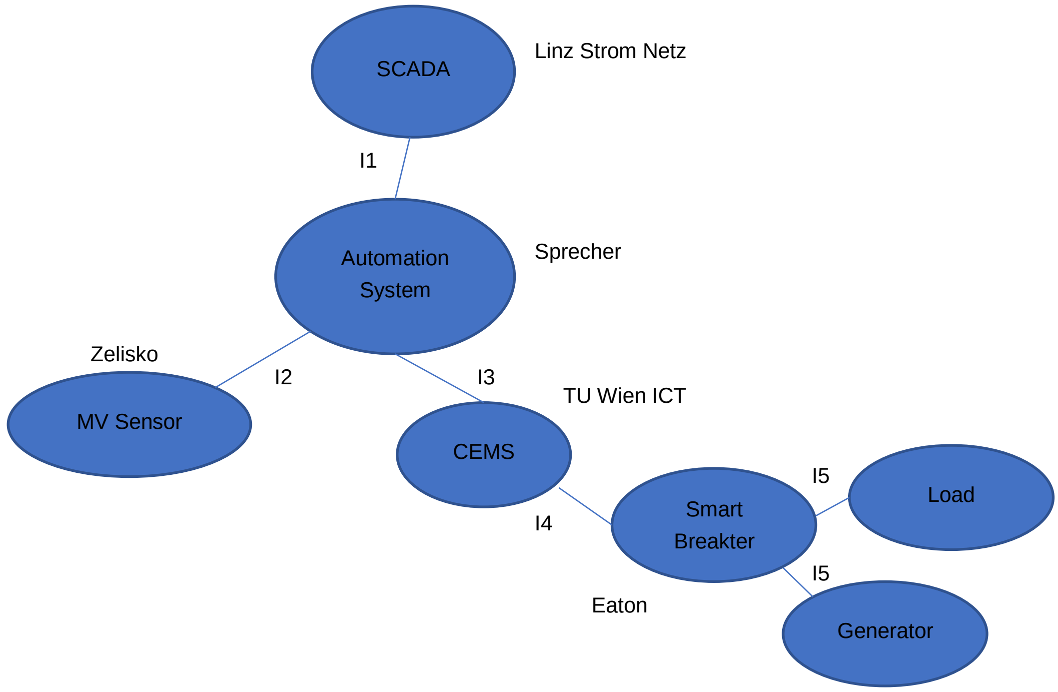


Figure 9: iniGrid focus components, associated partners and interfaces

3.3 Component Development and Improvement

Within the iniGrid project, two innovative devices were developed:

1. Evolve the Smart Breaker from concept to first experimental hardware as a first step, followed by further improvements for the validation in the laboratory and eventually in the field validation site.
2. Develop retrofit Medium Voltage sensor concept, development and adaption including laboratory validation.

3.3.1 Smart Breaker

The basic concept of a hybrid circuit breaker is built around a central “hybrid switching function”, integrating a low-impedance superfast electromechanical by-pass relay with a semiconducting switching component. The synergies of employing both technologies enable the design of a switching function which benefits from both solutions:

- low power dissipation current conduction during normal energy distribution when the by-pass relay is in its ON-state (contacts closed) and
- an arc-free current switching technology when driving the electrical conduction state of a semiconductor (power electronic switch) into a blocking state within a minimum of time.

Due to the parallel topology of these two solutions it is possible to establish the current path through the hybrid structure in two ways, either via the by-pass relay or via the power electronic switch (Figure 11). Both elements are addressable by electric signals, thus it is possible to provide an integrated solution which can be controlled by an embedded approach (µP controlling the system based in incoming and outgoing electronic signals). There is no need for further actuators or motors to drive the switching function, as it is the case in state-of-the art electromechanical circuit breaker designs.

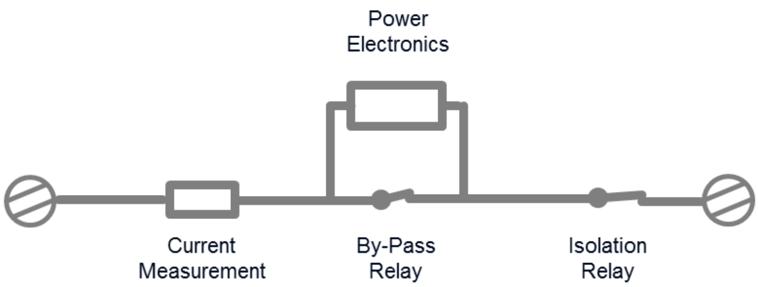
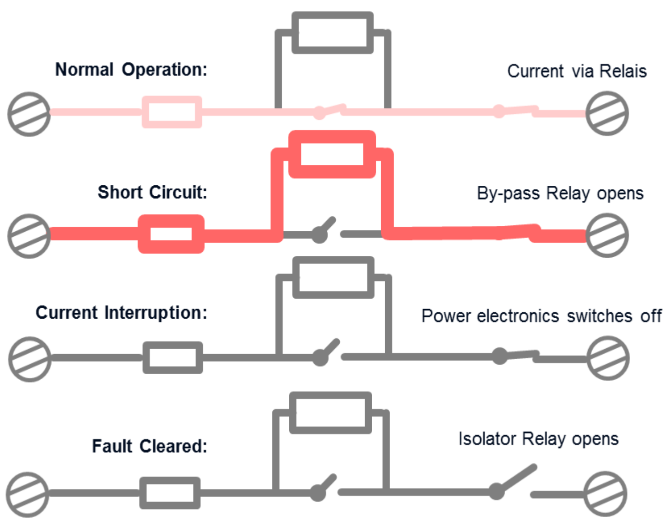


Figure 10: Basic topology of a hybrid switch

In Figure 10 the parallel structure is shown, together with a current measurement unit and a serial insulation relay. In normal operation, when the current level is within the nominal load current specifications of the breaker, the by-pass relay is closed and the power electronics section is not powered (and thus not dissipating energy due to losses). A fault detection unit (not shown in Figure 10) identifies a faulty situation (overload or short circuit), activates the power electronics and opens the by-pass relay. The current will thus commutate to the parallel (power electronic) path but the established voltage drop across the by-pass relay will be too small to create a sustainable electric arc (15-20 V needed) at the contacts of the relay.



Normal power distribution, by-pass relay closed, power electronics dissipates no energy

Current measurement unit and fault identification algorithm identifies faulty situation (e.g. short circuit event). Power electronics gets conductive and the by-pass relay opens.

Power electronic device switches off the fault current without arcing

Isolation relay opens the connection between load and the grid to provide a galvanic separation.

Figure 11: Elementary operation sequence in case of a fault current

Hybrid switching *per se* is not new, but was not yet applied to low voltage switching applications including high short circuit interruption. To identify the current state-of-the art a thoroughly patent and literature search was performed in this field.

Based on these results and first concept findings an architecture was designed around the central hybrid switching approach. Specific sub-tasks have been identified which are key in order to provide a robust solution:

- Reliable and capable power module (main switching functions based on power electronic elements)
- Superfast by-pass relay (electromechanical solution with enhanced response time requirements which is not available on the market)
- Fault detection algorithm to identify a fault condition (e.g. a short circuit) and discriminate against other transient current surges which should not lead to a trip of the circuit breaker.

The designed Smart Breaker solution was intended to be integrated into a dedicated field tests setup to demonstrate its capabilities to support a customer management system (CEMS) in order to optimize the electric power consumption within a commercial application. The main purpose was also to demonstrate the feasibility to incorporate the above-mentioned functions within a state-of-the art mechanical footprint. Although the final demonstrator is not a “product” it should be not too far off from current solutions on the market, as far as the general appearance/design is concerned. It is key to prove the feasibility of the concept based on these requirements, as the future acceptance is strongly related to a design, current stakeholders are used to. Size and shape are therefore important parameters. This design will further on be named as “Demonstrator-1”.

The general topology of the solution can be seen in Figure 12 and was realized by a modular approach, consisting of the following main sections:

- Analog Detection PCB
- Central Processing Unit:
- Connector PCB:
- Earthfault Detection PCB
- Output Voltage Measurement PCB:
- Power Section PCB
- Power Supply PCB:
- Relay Driver PCB:

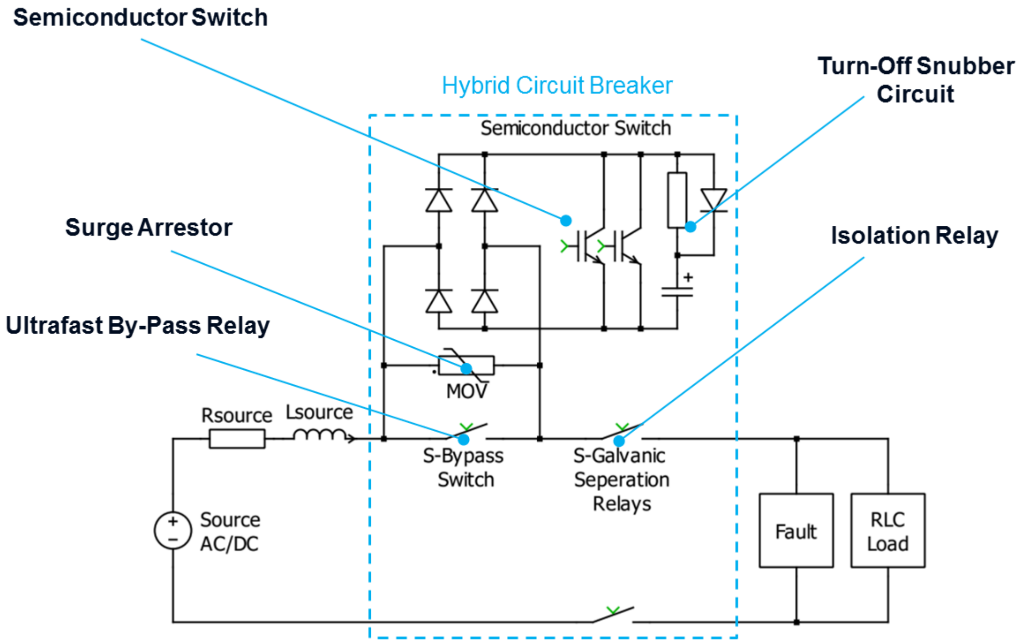


Figure 12: Basic architecture of "Demonstrator-1" Smart Breaker

These basic blocks have been assembled into a mechanical design which was very much aligned to existing electromechanical circuit breaker products in order to prove the feasibility to realize a similar footprint size needed to prepare a future industrialized solution which is compatible with market requirements. A main challenge was the miniaturization of the power section, which includes the power electronic solutions (diodes and IGBTs) and which has to be sized down from existing power electronic modules solutions to dimensions fitting within the proposed Smart Breaker housing. This was accomplished by a fully dimensioned bare-die based solution on a dedicated ceramic substrate, chip bonding and encapsulation. This approach was verified through detailed component and sub-component testing and a final integration test on system level.

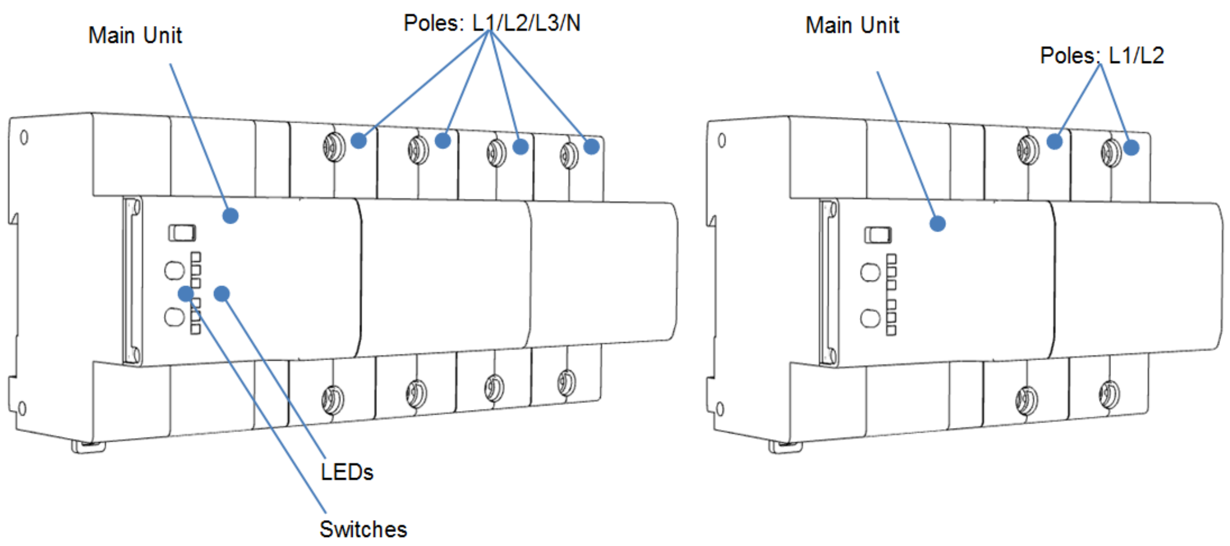


Figure 13: Overall view of 4p/3pN- and 2p-Smart Breaker (Demonstrator-1)

The final solution of the Demonstrator-1 is shown in Figure 13 as a schematic of the housing for the 2 and 4 pole versions, resp. A view on the internal assembly of a single pole is given by Figure 14. With this modular design is was possible to reduce the system complexity when realizing 2- and 4-pole versions of the demonstrator.

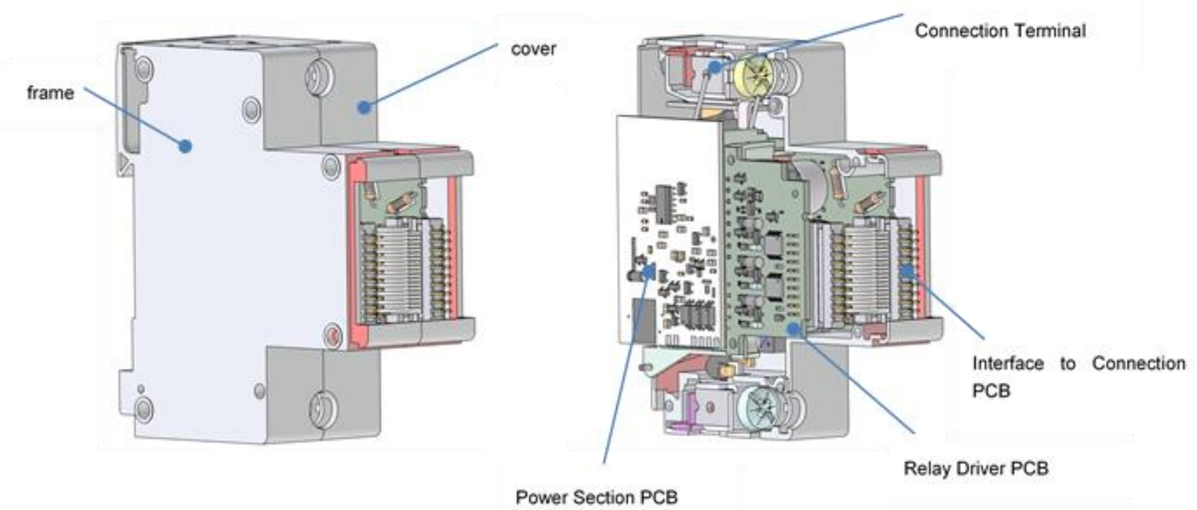


Figure 14: Single pole 3D-CAD design of Demonstrator-1

The main signal processing, communication and power supply was embedded into the Main Unit (Figure 15) which is attached to the poles.

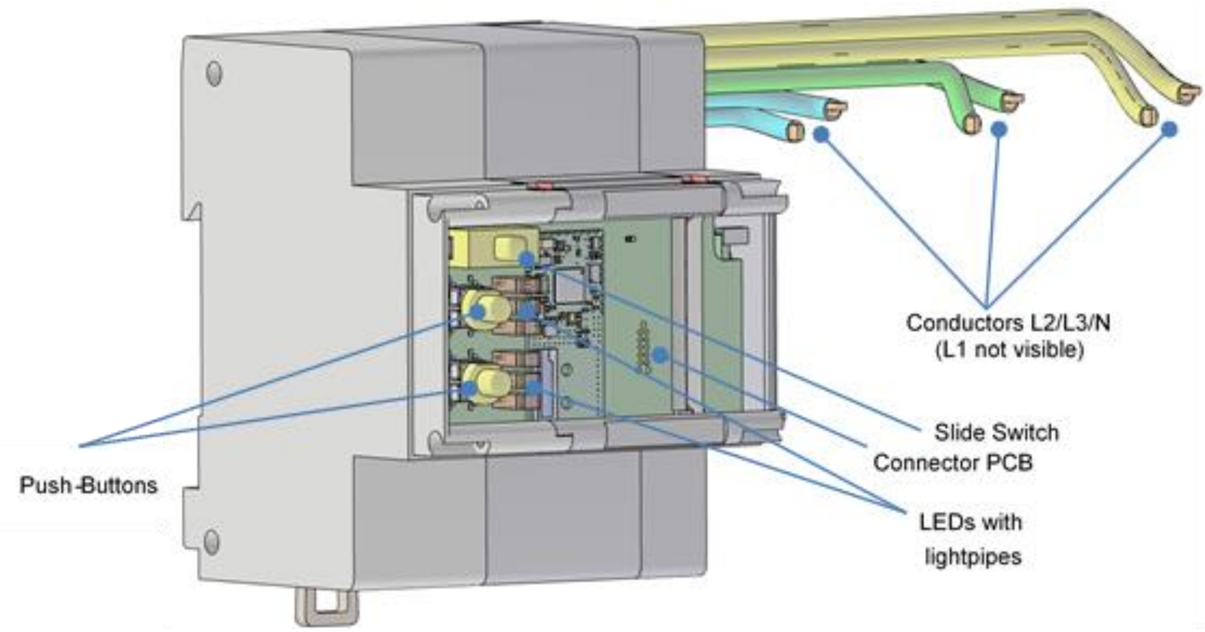


Figure 15: 3D-CAD breakdown of the Main Unit, showing the conductors of the Phases and the Neutral and the main local control elements (switches and LEDs). Representative for 2-pole and 4-pole units

Based on this design concept the first components (Figure 16) have been manufactured and tested on a single component level, followed by integration tests up to final complete system behaviour evaluation

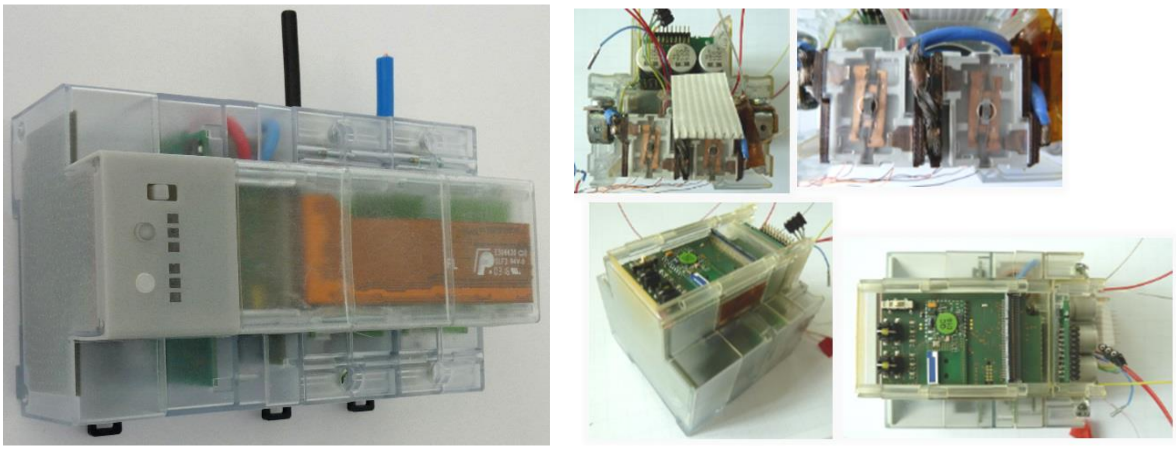


Figure 16: First samples of a 2-pole "Demonstrator-1" with transparent housing for initial function evaluation.

Finally, a new, non-transparent, more durable material was chosen to assemble the Demonstrator-1 samples as 2-pole and 4-pole versions (Figure 17). They can be mounted on a standard DIN-rail available within typical power distribution boxes/enclosures.

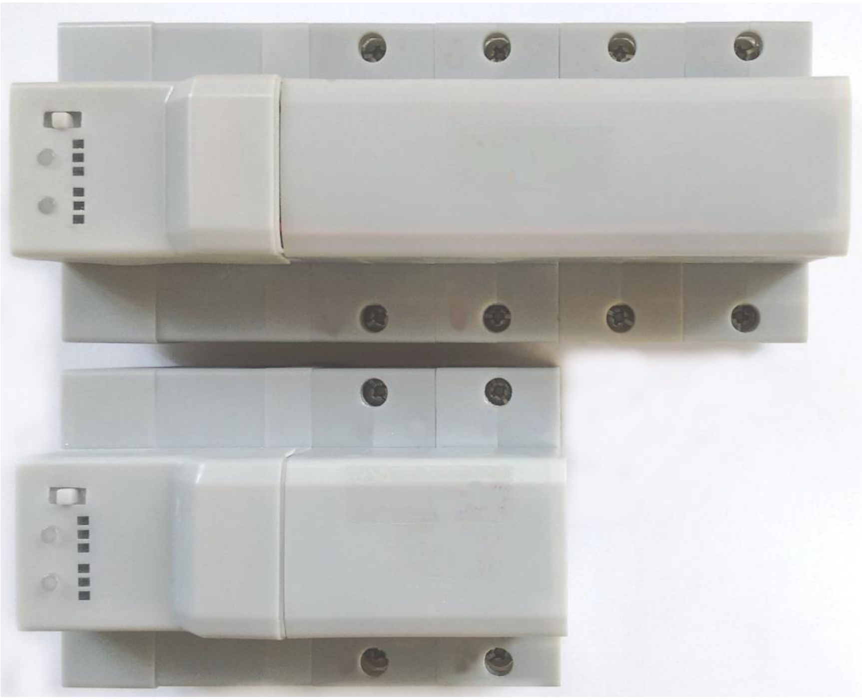


Figure 17: Final design of the "Demonstrator-1" samples with housing provided by rapid prototyping

The main reason for choosing a hybrid switching architecture is to avoid the power loss of semiconducting switches when permanently driven in the conducting (ON) state by deploying an electromechanical by-pass relay which is placed in parallel to the transistor. It conducts the current during normal operation, opens the contacts in case the hybrid switch is commanded to disconnect the load circuit, drives the current into the parallel power electronics path which will then switch off the current, as soon the by-pass contacts have opened to a sufficient high contact gap distance to prevent a re-ignition. In this project the hybrid switch has to switch off high short circuit currents up to 10/20 kA, therefore special care had to be taken to design the system accordingly.

In order to provide a Smart Breaker solution which does not rely on bulky power electronic modules, the maximum current in through module has to be as low as possible, leading to the requirement of switching off at a very early stage of the short circuit rise. Beside a very fast detection of the short circuit situation a “super-fast” by-pass relay design is a key requirement to make the concept feasible. As such relays are not available on the market, the design of an appropriate solution was one of the mission critical work packages of the whole Smart Breaker study.

Two concepts have been selected for further design work, one for 45 A and one for 125 A nominal current I_n (Figure 18). The main challenge in this respect is to find a suitable solution which is on the one hand capable to provide enough load currying capacity (A) and on the other hand fulfil the required operation speed to satisfy the requirements for high-current hybrid breaking. These specifications are opposite to each other, as a high current capacity needs a larger cross section of the conducting parts to avoid a high resistivity and therefore heat dissipation but on the other hand increases the detrimental effect of inertia which reduces the dynamical response behaviour.

The final two concepts which have been selected for further h/w prototyping have been mainly designed based on simulation tools (force calculations and subsequent multi-body evaluation). With this approach the efforts for setting up samples could be reduced.

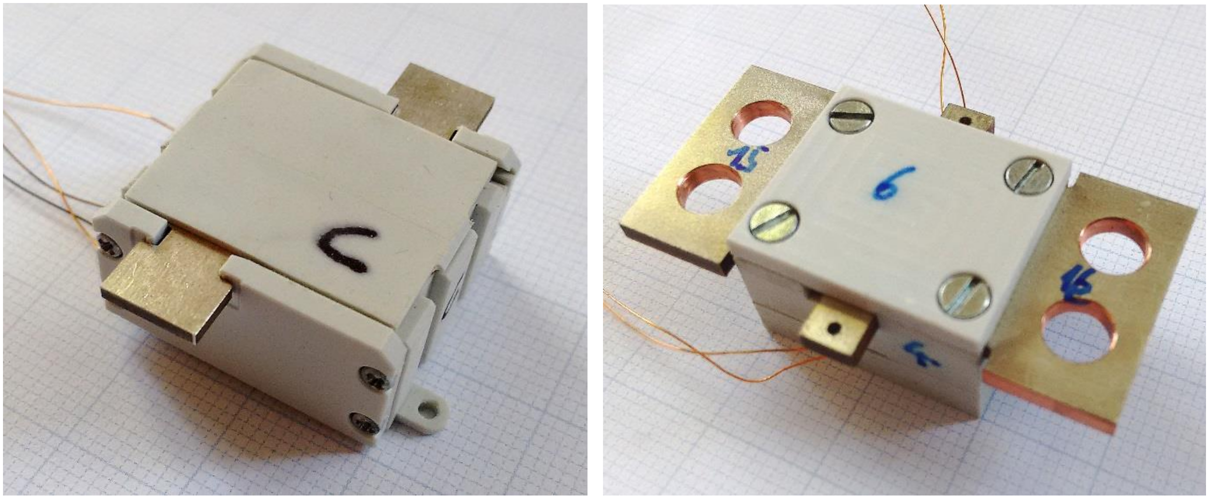


Figure 18: Samples of By-Pass Relay I (left) and II (right).

Final Demonstrator-1 samples have been installed at the field test site in Großschönau (see Section 0 for details) within a suitable switchboard together with a dedicated back-up installation to secure the electrical installation against any possible failures due to the experimental nature of the setup (Figure 19).

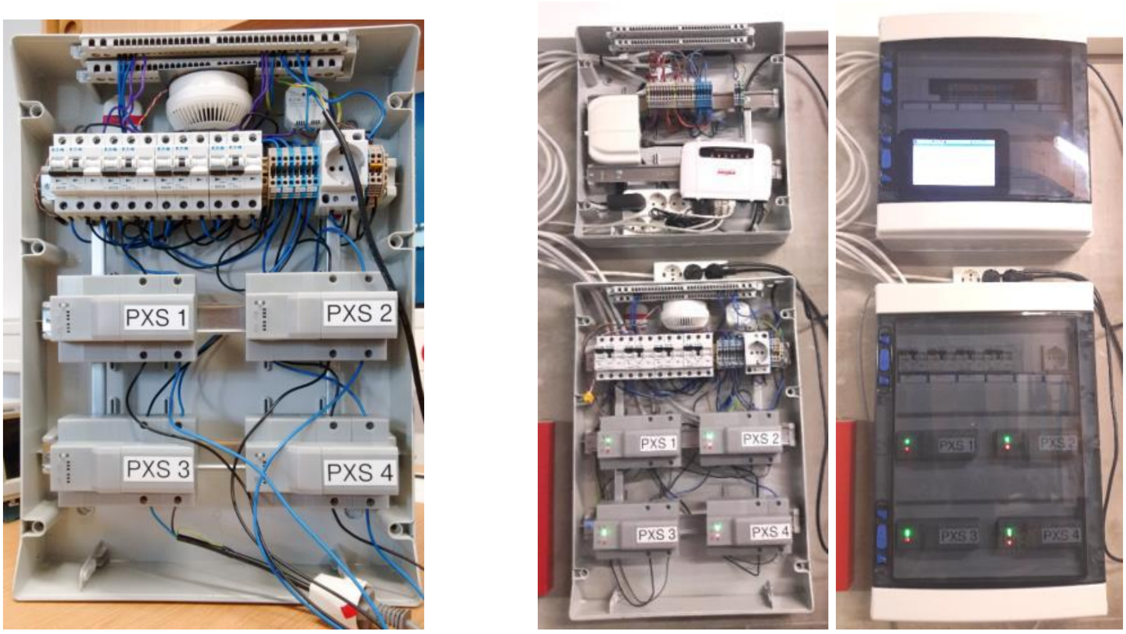


Figure 19: Field test setup at Großschönau: detailed view of the Smart Breakers (left) and view of the complete setup with communication interface and CEMS (right).

Beside the hybrid approach for power electronic switching a concept for implementing a pure power electronics based switching element (solid state circuit breaker) was proposed and evaluated. It was based on a parallelized structure with state of the art and newly developed dedicated MOSFET-technology (also improved packaging technology) to offer an optional architecture which provides an even faster current interruption in a short circuit event (Figure 20).

Figure 20: Comparison between Solid-State Circuit Breaker topology realized with state of the art switching elements and dedicated MOSFET technology.

3.3.2 Medium Voltage Sensor

In a significant number of important applications, sensors for air insulated equipment are needed. In these configurations, the parasitic capacitances are not well-defined. Here accurate and stable voltage sensors have to be integrated into post insulators or other insulating structures.

The prototype of the medium voltage sensor for air insulated switchgears, as developed during this iniGrid project, have be designed for 12 kV as well as for 24 kV highest voltage for equipment U_m (r.m.s.).

Firstly, for both voltages U_m the prototypes fulfill the requirements of the instrument transformer standard IEC 61869. This means, the prototypes passed successfully the type test and the routine test according to IEC 61869. More precisely, the sensor was designed in order to transform medium voltage in the accuracy class 0,5 P, i.e. admissible ratio error ± 5 % and phase deviation ± 20'.

Furthermore, a sophisticated design of the internal components of the sensor yields a minimization of the impact of uncontrollable parasitic external capacitances.

Additionally, the maximum bending strength has been determined for both types.

It is planed that the sensor will be implemented in an operating air insulated substation. Consequently, the dimensions of this medium voltage sensor are similar to corresponding indoor-post insulators. Additionally, the design of the sensor is near to the well-known design of conventional post insulators. More precisely, the height was adjusted depending on the insulation level in order to satisfy the requirements given by the setup of the air insulated substation.
Mainly NCIT (nonconventional instrument transformer) with appropriate accuracy are based on the divider principle. The function principle of the voltage sensor for iniGrid is based on a resistive divider, see Figure 21.

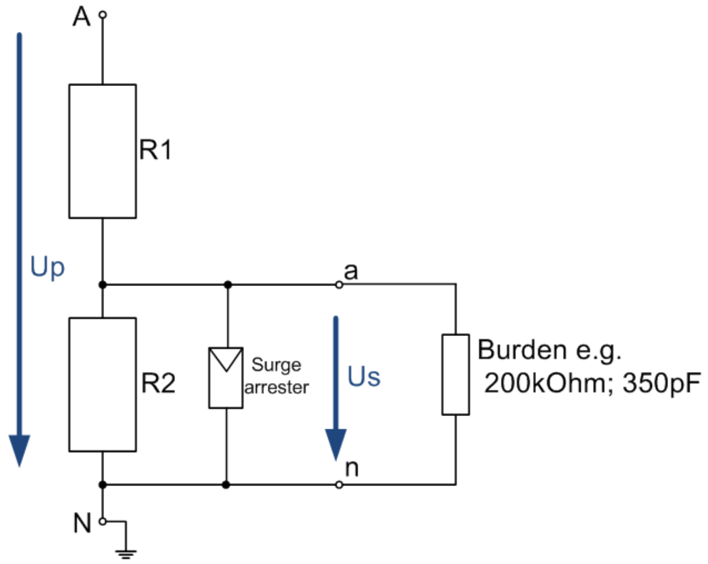


Figure 21: Functional principle of the medium voltage sensor.

It consists of two resistive elements, which divide the input signal in order to receive a normalized output value. Additionally, the sensor is equipped with a surge protector, which pro-vides protection of the se-quentially connected measuring devices. The voltage sensors can be equipped with shielded 2-pole con-nection cable with an industrial socket. The connection to the electronic device of the substation will be realized with an additional extension cable with open ends or will answer customer requests. Firstly, the rated secondary voltage is 3,25/√3 V. In Addition, the sensors have been designed in order to fulfil the requirements of class 0,5P, according to IEC 61869.

Medium voltage sensors for air insulated switch gears have to take into account undefined parasitic ca-pacitances. Therefore, the design of the medium voltage sensor has been optimized in order to minimize the impact on external earth potentials, cf. Figure 22

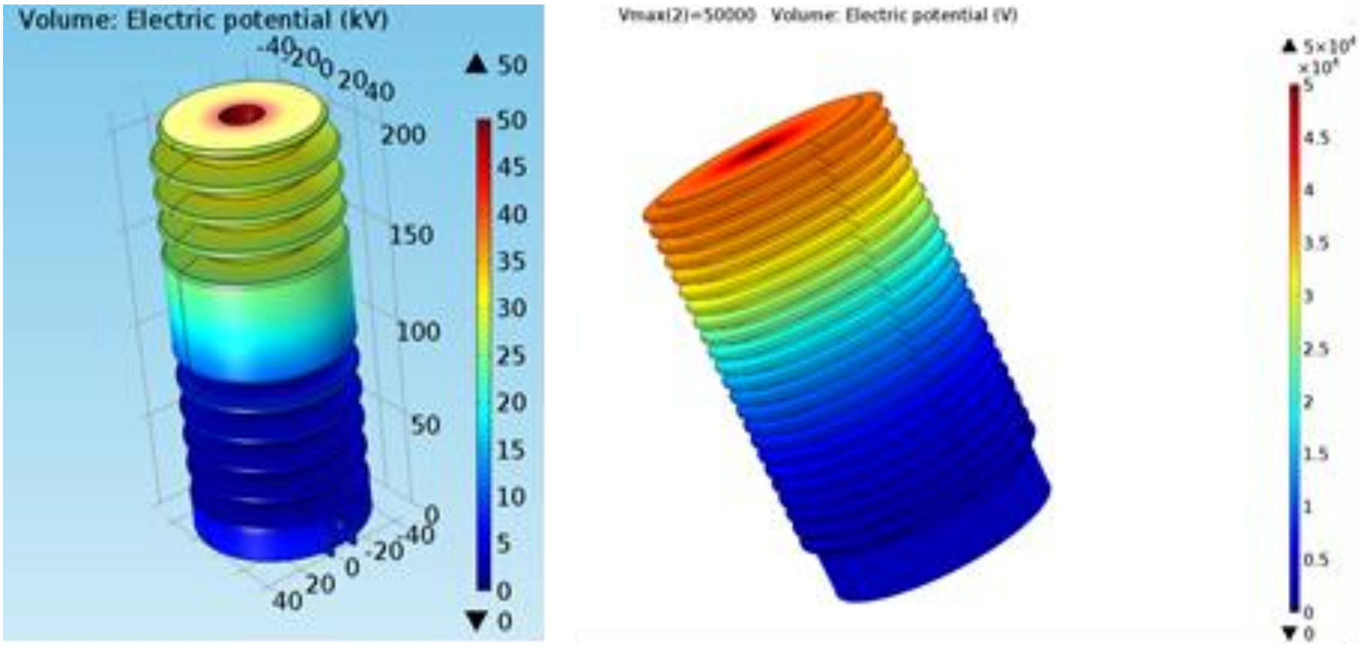


Figure 22: FEM simulation of electric potential in first prototype de-sign (left) and optimized design (right).

As mentioned, medium voltage sensors for air insulated switch gears have to take into ac-count undefined parasitic capacitances. More precisely the position of external potentials has an impact on the accuracy, cf. Figure 23, i.e. ratio error and phase deviation, of the medium voltage sensor.

LP(X)	P[%]	W[']
100%	0,00	0,0
100%	0,00	4,8
100%	0,05	20,5
100%	0,02	-46,8
100%	0,04	-43,3
100%	0,08	-33,8
100%	0,09	-27,7
100%	0,09	-27,7
100%	-0,03	-36,1
100%	0,02	-14,4
100%	0,02	-44,9
100%	0,05	-31,2
100%	0,06	-32,0

Figure 23: Different arrangements of electrodes at high voltage and earth potential (left side) and impact of parasitic capacitances on ratio error and phase deviation for different arrangements of external potential (right side).

Furthermore, it was planned to apply the medium voltage sensor for retrofit purposes and to replace post insulators. Thus, based on some FEM simulations, as shown in Figure 24, the maximum bending force of different configurations has to be taken into account.

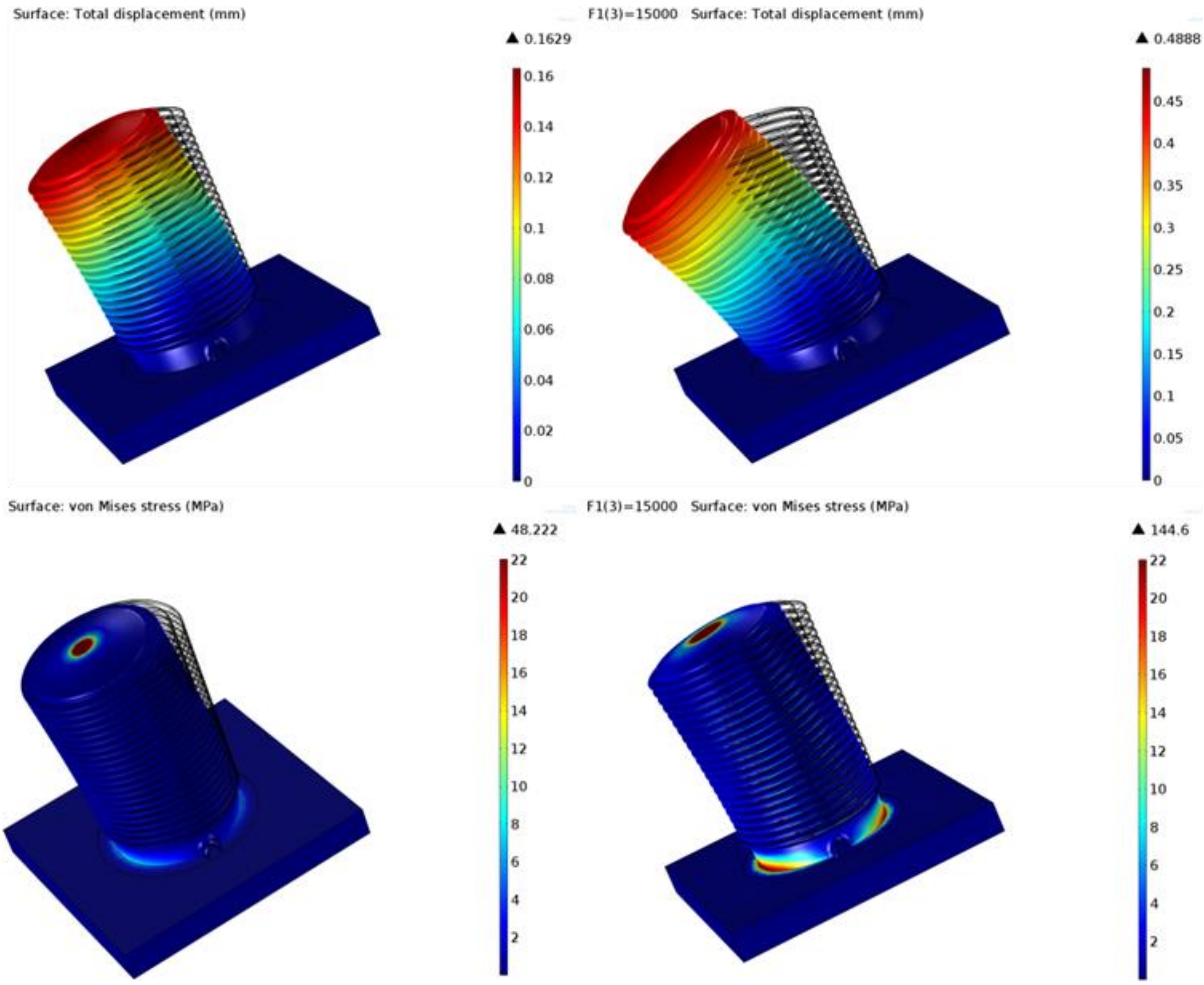


Figure 24: FEM simulation of the deformation (first row) and von Mises stress (second row) of the medium voltage sensor for 5kN (left) and 15kN (right).

To determine the bending strength tests have been done with a 12kV and a 24kV version. The different between these two versions is mainly the height of the sensor. The 24kV-version is much higher due to the need of a longer creeping distance.

Figure 25: Break of the 12kV-version at approx. 24kN (left) and of the 20kV-version at approx. 12kN (right).

As it can be seen in Figure 25, the FEM simulation is validated by the experiment. Shape and position of the crack corresponds to the maximum of the calculated von Mises Stress, as shown in Figure 24, (second row, left side).

Furthermore, in preparation for the field validation impulse test have been performed at AIT (Figure 26 left) according to IEC 61869.

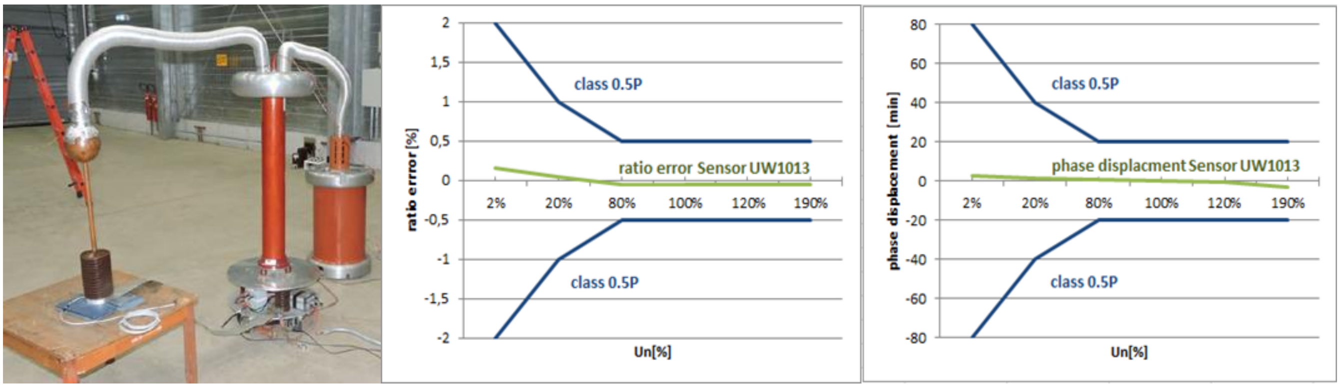


Figure 26: Test setup for impulse test at AIT (left), Ration error (middle) and phase deviation (right) of a sensor for the field validation.

In Addition, the sensors have been routine tested according to IEC 61869. The sensors have been designed in order to fulfil the requirements of class 0,5P, see Figure 26 (middle, right). In the iniGrid project it was planned to simulate and test the capabilities of the new medium voltage sensor for air-insulated switch gears. Therefore, a reconstruction of an existing air-insulated switch gear has been equipped with the new medium voltage sensors as well as with already existing current sensors of ZELISKO GmbH, see Figure 27 (right).

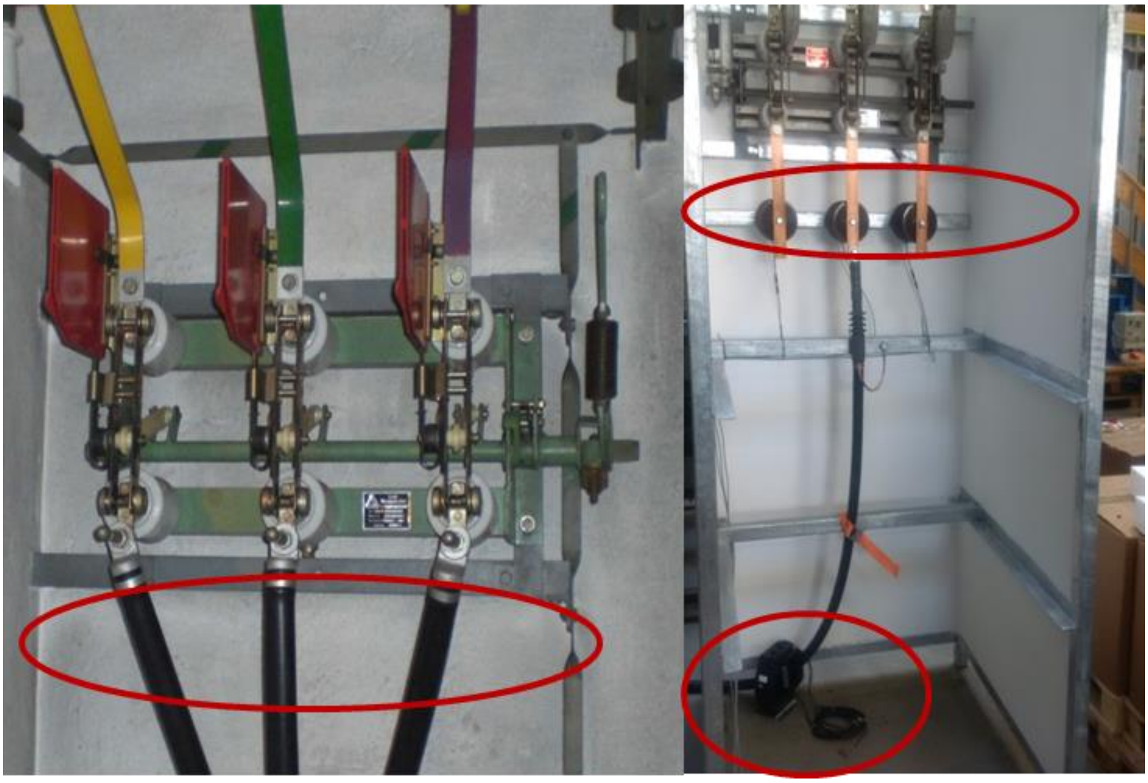


Figure 27: Field-test – real switch (left) and replica equipped with voltage and current sensors (right).

More precisely, a medium voltage sensor for each of the three phases was mounted in addition to existing post insulators, not directly at the switching mechanic. The voltage sensors were contacted to the switches by means of separate, additional busbars. In addition, a current sensor for earth fault detection was mounted on the middle phase of the replica of the switch gear.

In combination with the automation infrastructure of Sprecher Automation, the voltage has been measured during an artificial earth fault – further details are presented in Section 3.8.3 (Air-insulated switch gear test (Medium Voltage Sensor)).

3.4 Definition of automation architecture and risk analysis

The objective of this activity was to develop of a secure iniGrid architecture taking into account the integration of new products such as novel medium-voltage sensors (Zelisko), smart breakers (Eaton) and Home Automation and Substation Control System (Sprecher). To derive a set of security controls and measures, we have defined the process as outlined in Figure 28. Firstly, the textual descriptions of the use cases defined in iniGrid was mapped into the SGAM Framework [5]. The initial architectural decisions were based on the security requirements provided in the project deliverable D1.1 (System Requirements). In the next step, we used the guidelines provided in NIST IR 7628 [6] and by mapping the iniGrid architecture model onto the NIST logical reference model we derive a set of high level security recommendations per each use case and interface.

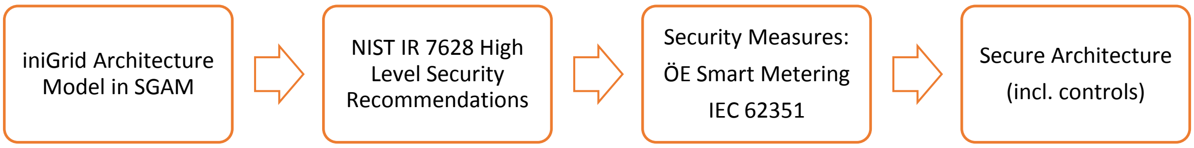


Figure 28: Process of deriving the secure iniGrid Architecture.

Since security requirements provided by NIST guidelines are rather generic, we have combined other resources to get more specific suggestions for technical security measures, such as Österrreichs Energie guidelines on security for smart metering systems [7] and IEC 62351 standard [8]. In the following, the methodology used in each of the steps is described in more detail.

3.4.1 Integration and Security Requirements

An initial set of security requirements was provided earlier in the project and can be summarized in following points:

1. Software hardening is required for all introduced components,
2. DSO (network) and customer level network should be separated. There should be no direct communication between the Home Automation and medium voltage sensors.
3. Communication with consumer should be done through Data Concentrator to Smart Meter/SM Server up to Customer Energy Management System (CEMS)
4. Communication path (between DSO and customer) should be cryptographically secure in terms of integrity and confidentiality (end-to-end security)

5. Unidirectional connection between Smart Meter and CEMS is required, i.e. load profiles should be available to the CEMS via the smart meters however no feedback on the actual Smart Breakers state should be sent from CEMS to the smart meter.

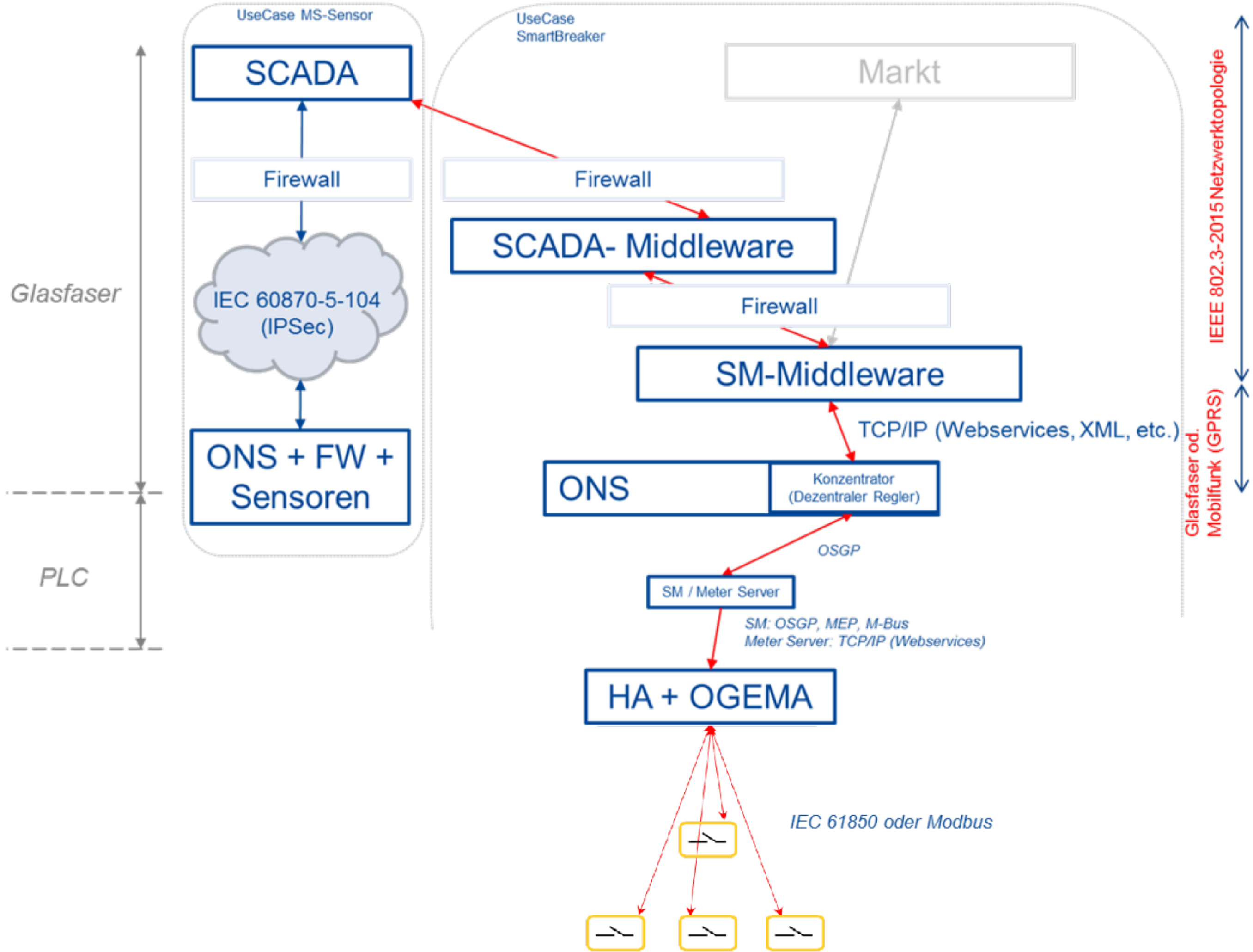


Figure 29: The outline of the main components in iniGrid architecture and suggestions for their communication technologies and protocols.

Additionally, as illustrated in Figure 29, the requirements are incorporated in the initial draft of the architecture, outlining the main components as well as their communication technologies and protocols. This has served as a basis for the iniGrid architecture model (SGAM).

3.4.2 Smart Grid Architecture Model Framework

The Smart Grid Architecture (SGAM) framework has been proposed by Smart Grid Coordination Group (CEN-CENELEC-ETSI) [5] to standardize the way of describing smart grid systems. SGAM framework allows to represent interoperability viewpoints in a technology neutral manner. The key advantage of the SGAM approach is the layered structure of the model which enables interoperability by combining organizational, informational and technical aspects of the system. In this way, the common understanding among different stakeholders can be achieved. As depicted in Figure 30, SGAM describes the smart grid system in three dimensions: interoperability, domains and zones. There are five interoperability layers in the model: Business, Function, Information, Communication and Component layer. The SGAM Business layer focuses on the business context of the system, outlining the market models, goals and business processes, then the Function Layer describes functions and services in form of hierarchy of use cases. The three bottom layers, i.e. component, communication and information layers, are used to describe the realization of the use case, specifically the components, their communication protocols used between them, and information that is exchanged (data model standard).

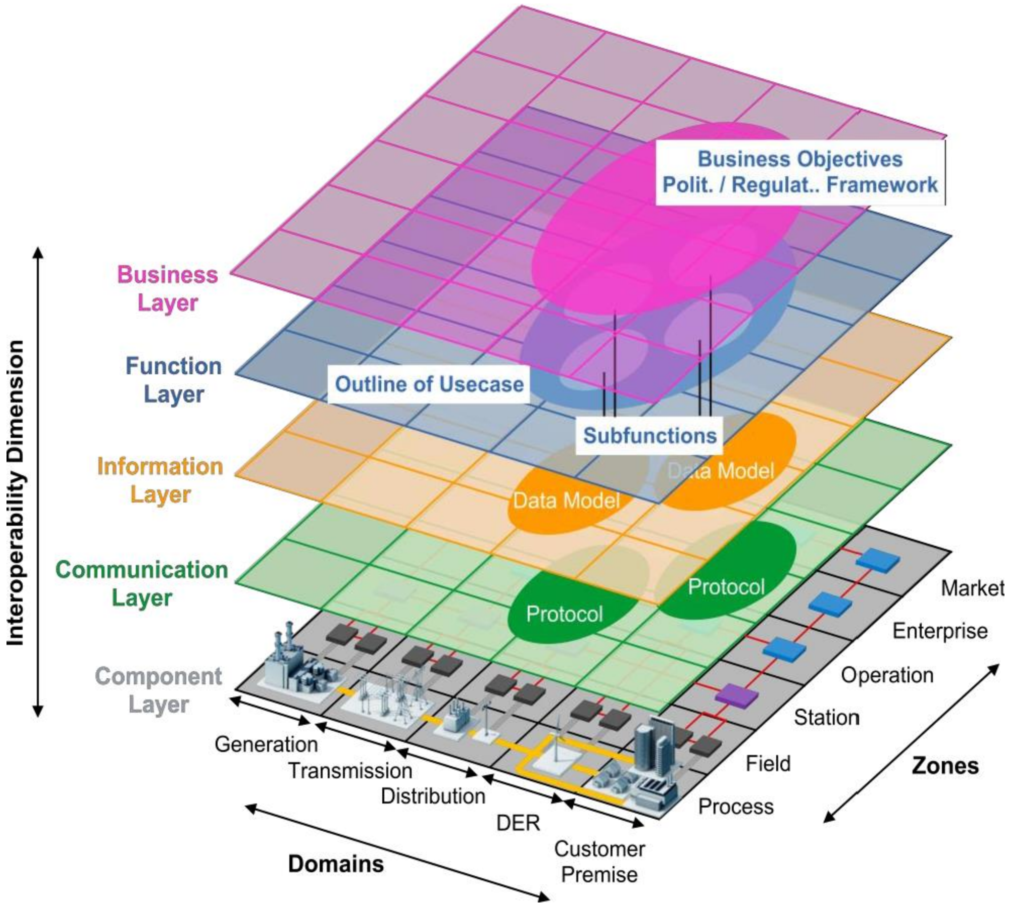


Figure 30: Overview of the Smart Grid Architecture Model (SGAM)

Furthermore, each SGAM layer, also called a smart grid plane, is further divided into a two-dimensional grid of domains and zones. Domains reflect the physical viewpoint of the electrical delivery process, whereas zones correspond to the hierarchy of the management of this process. SGAM defines five domains (Generation, Transmission, Distribution, DER and Customer Premise) and six zones (Process, Field, Station, Operation, Enterprise and Market).

The process of creating an SGAM-based representation of the smart grid system description is supported by SGAM Toolbox [6], an extension for the SPARX Enterprise Architect UML (Unified Modelling Language) software. The toolbox defines two stages for model development, namely (1) System Analysis Phase, focused on the two top layers, specifying the requirements and functionality of the system, and (2) System Architecture Phase, focused on modelling the three bottom layers of the system, i.e. the components, their communication and information exchanged.

3.4.3 NIST IR 7628

The report by NIST 7628 [6] propose an overall risk assessment process tailored for smart grid systems. The process results in guidelines on ensuring security of the system and high-level security recommendations adjusted to the part of the system under consideration. NIST defines a conceptual smart grid model, organize the actors/components in seven domains: service providers, customer, transmission, distribution, bulk generation, markets and operations. There are 49 actors in overall and their communication is defined by uniquely coded logical interfaces. The NIST logical reference model is illustrated in [6], where actors are coloured by the domain. Furthermore, the logical interfaces are grouped into logical interface categories (LICs) by their similarity with respect to the security related characteristics. NIST distinguishes 22 categories dedicated to different parts of smart grid system. Each category is associated with a set of high-level technical security requirements.

In order to use the NIST guidelines for iniGrid project, we adapted the NIST model to the architecture developed in SGAM. We follow the procedure defined in [9]:

1. Identifying and specifying the use case (A-E)
2. Identification and mapping of logical interfaces, interface categories
3. Integration of the logical interface (LI) onto the SGAM Function Layer
4. Assign the requirements
5. Mapping to additional SGAM Layers

3.4.4 Technical measures and controls

Although the NIST recommendations give a good overview on what should be taken under consideration in security for particular use cases, the requirements are still quite generic and suggestions about their implementation would be of benefit. In this section we shortly describe two documents used for more detailed controls and security measures analysis. First one proposed by Österreichs Energie [7] and its main focus is on smart metering part, therefore is mostly used in use case A (home automation). The second is the IEC 62351 [10] standard to cover both, smart metering and also substation automation – tackled in the use cases A to E (grid control).

3.4.5 iniGrid Secure Architecture

The architecture presented in this chapter has been built on the assumptions, requirements and description of the system functionality defined in chapter 3.1.

As outlined earlier, the main objective of the project was to develop and validate innovative sensor, actuator and automation technologies. The proposed use cases describe control loops of different scope, starting with the home area automation, through low and medium voltage grid control at substation and finally control at management level. The architecture in SGAM addresses the requirements (from Section 3.4.1) and as well provides a seamless integration of all novel components within the use cases in low and medium voltage grid.

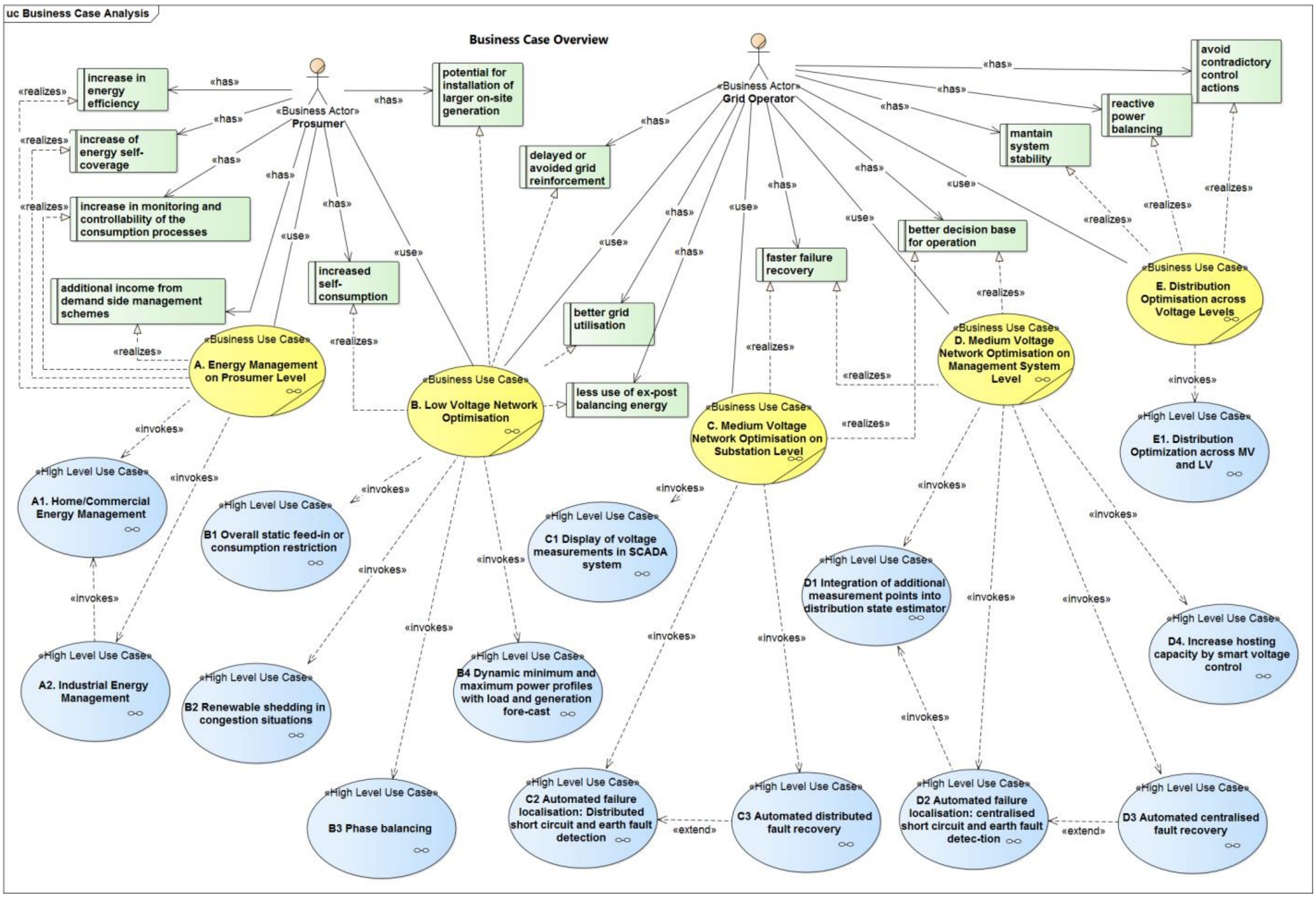


Figure 31: SGAM Business Layer overview.

Figure 31 shows the overview of the SGAM business layer for the iniGrid architecture. We have defined two major stakeholders, in SGAM called the business actors, namely: the grid operator (DSO) and a Prosumer. Each of the business actors have a set of business goals (depicted in green), that are realized by one or more business cases (in yellow), e.g. the prosumer's goal of increasing the energy efficiency is realized by use case A. Energy Management on Prosumer Level. There are five business cases corresponding to the ones described in 3.1. Each of the use case is implemented in more detailed by high-level use cases (shown in blue).

3.4.6 Use Case B: Low Voltage Network Control

In the following use case B is presented as an example. It focuses on the prosumers' domain and deals with integration of Smart breakers into customer energy management. It applies to both, residential and industrial prosumers.

3.4.6.1 Use Case B Model

Components involved in use case B are depicted in Figure 32 at the SGAM domain/zone grid. The connections and communication protocols between the components are shown in blue and green, respectively. The components at the customer premises are the same as in previous use case (A). At the secondary substation we have Smart MV-LV transformer with on-load tap changer (OLTC) and substation controller (Sprecon). Controller communicates directly with OLTC, distributed Zelisko sensors, and PV inverters. All the appliances, energy generators (PVs) and storage (batteries) are connected to the low voltage grid. Since in iniGrid there is no direct connection between substation controller and CEMS at the customer premises, Substation communicates directly with DER gateways (analogous to smart breaker gateway), such as in case of PVs and batteries, over Ethernet, IEC 61850 protocol. It is also considered that the power measurements from the customer premises can potentially made available through the Meter Data Management System (MDMS). There is analogue connection between substation and sensors, and serial connection with the transformers' OLTC, over Modbus.

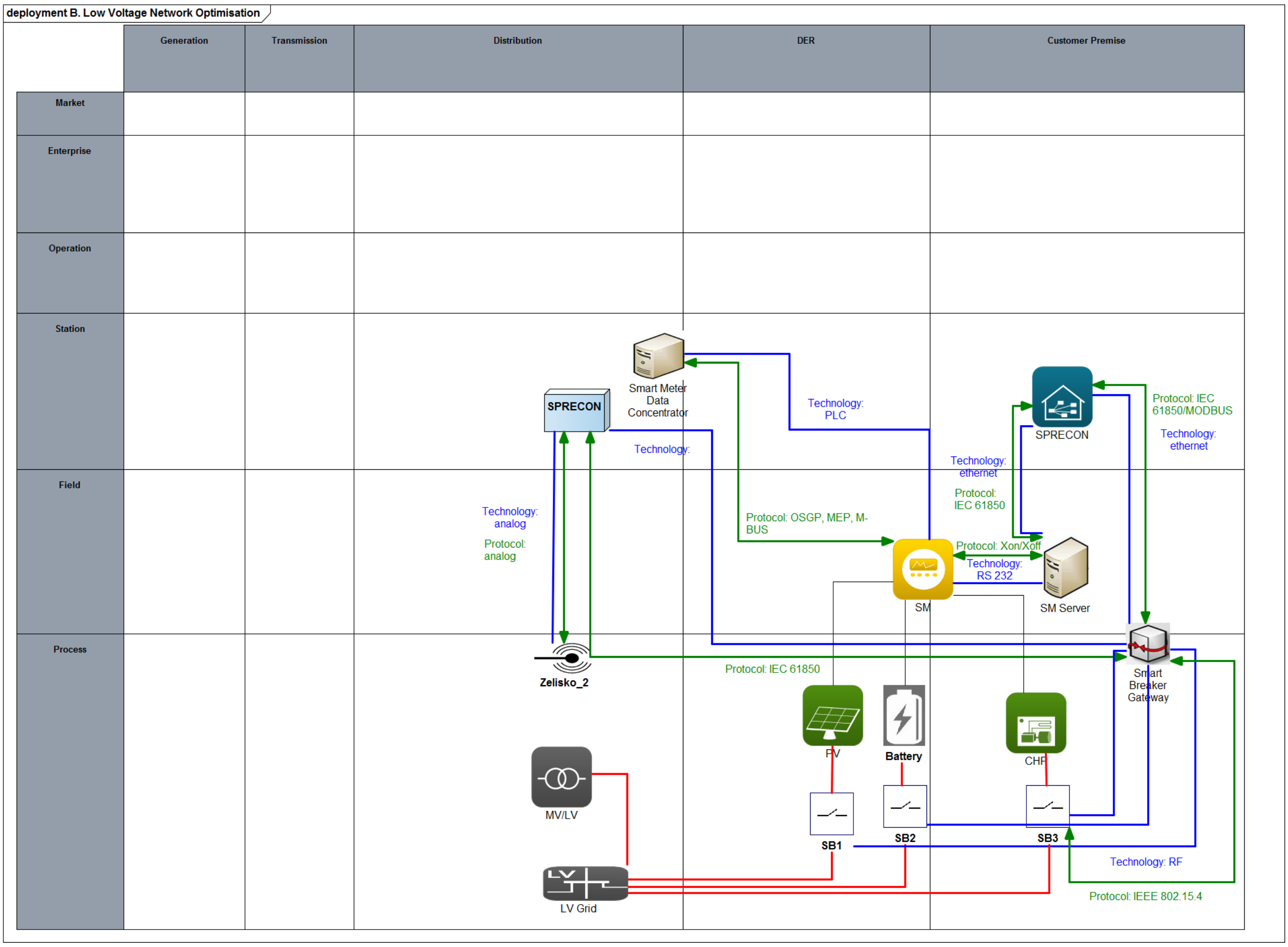


Figure 32: SGAM Component and communication layer diagram for use case B

3.4.6.2 NIST requirements

The SGAM actors involved in use case B are mapped to the iniGrid components and then to the corresponding NIST actors. Figure 33 below depicts the NIST components involved in the use case and the mapping to the SGAM plane with corresponding communication paths. Each of the communication paths are labelled with the unique interface number.

The identified interfaces are included in several categories. Categories 1-5 represent Interface between control systems and equipment (SCADA, substation controllers and field devices). LIC 11 is the interface between sensor and sensor networks, whereas LIC 12 denotes connections between sensors and substations. Category 14 represents the AMI network and here are relevant for transmitting measurements from smart meters up to the MDMS. Category 15 tackles interface between systems at customer sites and category 18 - metering and sub-metering interfaces.

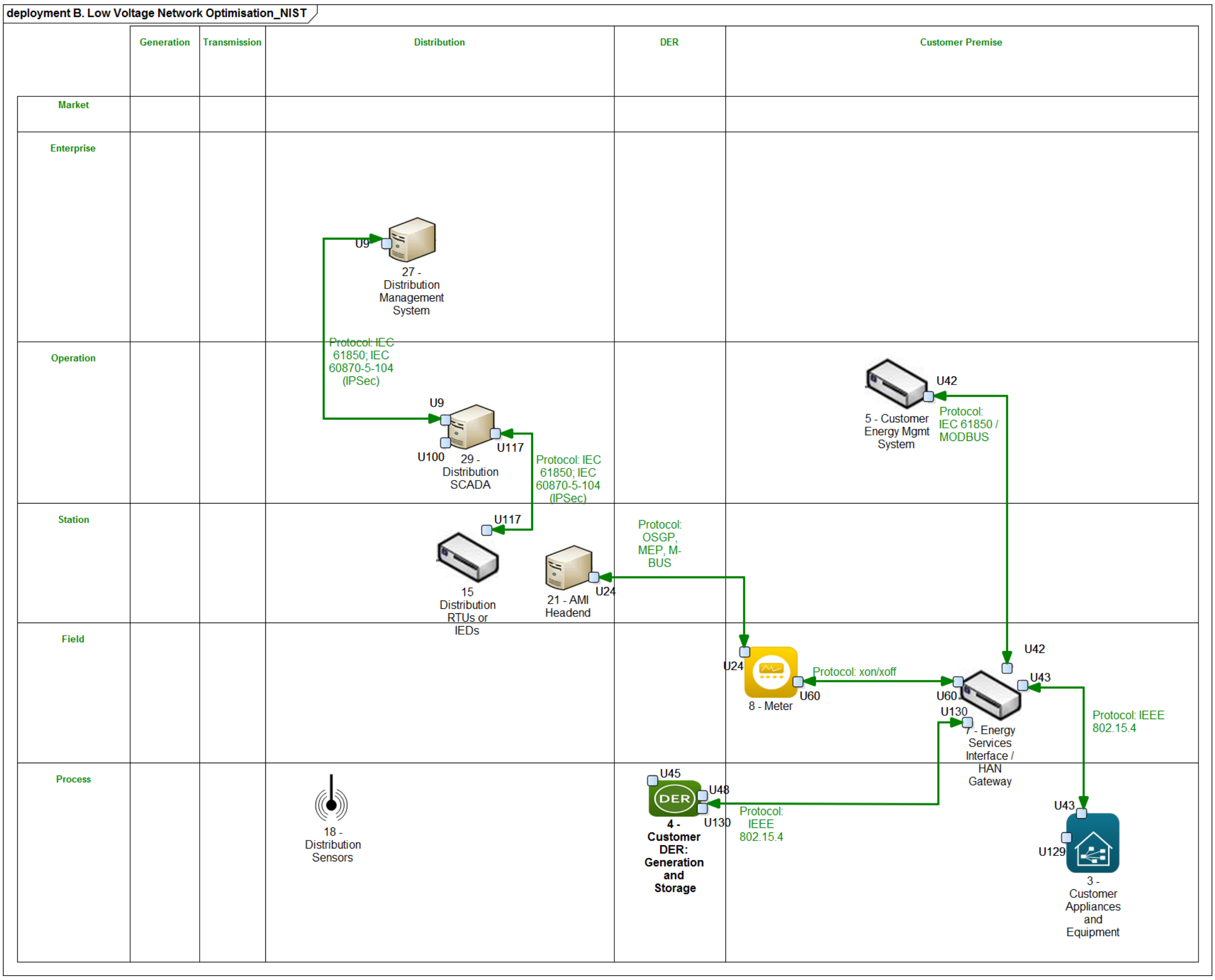


Figure 33: SGAM communication layer for use case B, including NIST actors

3.4.6.3 Technical measures and controls

Figure 34 below shows requirements and proposed security measures for use case B. The last step of the process is to derive the security controls from the architecture proposed in standard IEC 62351, in this case the Substation Control case. Since the security at customer premises has been covered in previous use case, we have not included it here. We have focused on the controller at the secondary substation and its connection with distributed energy generation and storage. As shown in Figure 34, at the substation controller, the strong authorization, virus protection, logging and monitoring is requested. In addition, all the information from the distributed resources and sensors should pass through DMZ, e.g. data acquisition headend at the substation premises. Furthermore, the role based access control (RBAC) should be implemented at substation controller.

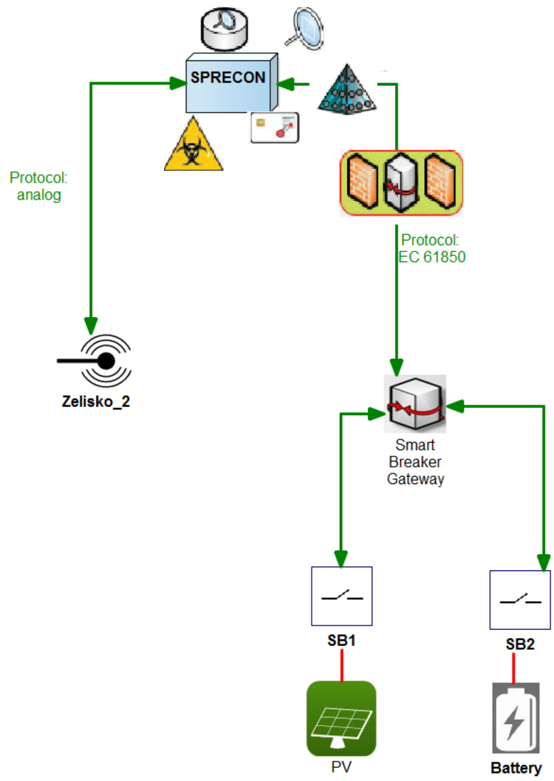


Figure 34: Use Case B SGAM components with security controls mapped from IEC 62351-10

3.4.7 Risk analysis

The implementation of the iniGrid use cases did not follow exactly the proposed architecture. In particular some of the security measures could not be implemented and thus not all requirements outlined in the present document can be met. Nevertheless, to assess what security functionality should be considered when implemented in the field a risk analysis on one of the use cases was conducted in order to identify the most critical parts of the architecture. The analysis was done based on use case B.

The risk analysis methodology was inspired by the methodology proposed by the FP7 project SPARKS. In order to identify the risks of attacks a process of seven steps needs to be followed as described in [11]. The SPARKS risk management process, is based on the information security risk management process that is standardised through ISO/IEC 27005. This standard process has been slightly changed in order adopt the generic process to the smart grid domain.

One of the goals of the risk analysis was to assess how the introduction of the smart breaker changes the security of the distribution grid. In order to identify potential changes, the risk analysis conducted by AIT and Linz Strom Netz in the project Smart Grid Security Guidance (SG2) was used as reference taking into account the smart breaker as a new component.

The threat catalogue used for the risk analysis is based on the BSI IT-Grundschutzkataloge [12]. Within the project SG2 this generic threat catalogue was consolidated with a special focus on smart grids. Threats not relevant in smart grids have been removed from the catalogue and some of the threats have been merged. A list of 67 threats remained that were used in the iniGrid risk analysis. Finally, the of impact and likelihood of attacks was estimated based on expert knowledge during several interviews with experts from Linz AG, AIT und TU Wien.

3.4.7.1 Main findings

The main finding of the risk analysis was that the highest risks are for several reasons associated with the operation of the Customer Energy Management System (CEMS). The CEMS is the main component to receive control commands from SCADA and to send commands to the smart breaker via the smart breaker gateway. It is connected to SCADA and the Internet.

The CEMS is connected to the Internet to enable remote connections of the costumer for management purposes or for e.g. letting the site participating in a Virtual Powerplant (VPP). Internet connection can be considered to be the main attack vector. Being exposed to the Internet it would be crucial for the customer to use up-to-date software and to apply software patches regularly to fix vulnerabilities and prevent attackers from gaining unauthorized access to the CEMS. However, the DSO has no mean to enforce software updates as the CEMS is under full control of the customer.

Assuming for security reasons only one-way communication between CEMS and SCADA is possible an attacker cannot gain access to SCADA from CEMS. Nevertheless, an attacker can launch an attack on the communication channel between CEMS and SCADA namely smart metering communication using power line communication (PLC) or wireless communication infrastructure. PLC in provides only low bandwidth and is highly susceptible to Denial of Service (DoS) attacks.

In general attacks to a single CEMS will have only very limited local impact, e.g on the feeder the customer is connected to. If the smart breaker is not disconnecting a load this could induce an overload situation where overload protection could trip to disconnect the feeder und thus causing an outage. A more severe attack scenario would be an attack to large number of CEMS' simultaneously. The attacker would be able to gain access to a lot of devices running e.g. the same software and thus able to switch on and of significant loads causing grid overload or instability.

3.5 Definition of rollout concept

This chapter deals with rollout concepts for the new and innovative components, in particular in finding scalable solutions in planning, rollout, and operation with the constraint of having a minimum of individual engineering effort.

The developed rollout concept aims at addressing all issues linked with installation and maintenance of a high number of devices. The implementation of well-defined installation and maintenance procedures is vital for the success of high volume devices like the Smart Breaker or other intelligent sensors and actors in the electrical network that rely massively on communication.

During the process of requirements analysis and specification, the following main technological areas have been identified that need for proper solution concepts:

While in most power grids the quantitative relation between primary substations and secondary substations is in the range of about 1:10, this in turn means that nowadays only about 9 % of automation devices are installed when being compared to "fully automated grids" in the Smart Grid vision. Hence, efficient rollout concepts are needed in order to:

- Reduce the engineering cost per device/per system.

- Enable the supervision and maintenance of a high number of devices within a distributed network.

Integrate appropriate cybersecurity technologies in order to not threaten the digitalized grid by underestimating cyber threats and proper countermeasures in control devices.

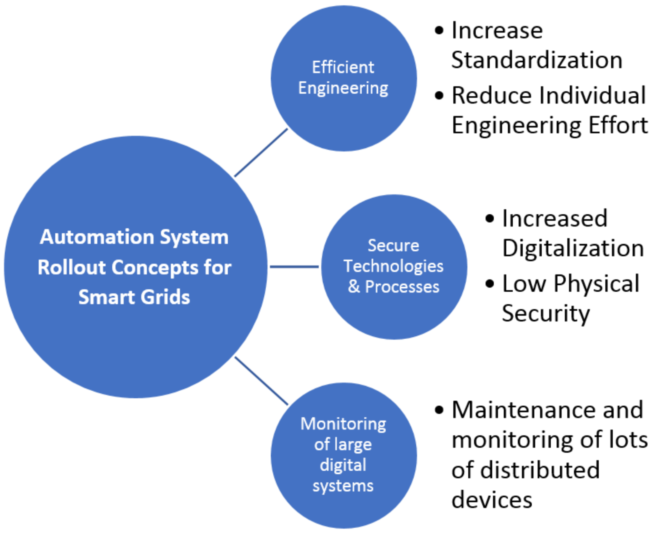


Figure 35: Requirements to Rollout Concept

After having identified these technological areas, a lifecycle-analysis has been performed in order to show which states an automation system takes from production to long-term operation, and at which points in time the rollout concept comes into play.

In the end, out of the identified lifecycle, concrete technological advancements have been specified that are needed in order to satisfy the efficient rollout – these are called "Building Blocks". For the sake of practical prove, these technologies have been integrated into prototype SPRECON devices. An overview on them is given in Figure 36.

Figure 36: Technological Features (Building Blocks) Needed for Rollout Concept

It is important to mention at this point, that national and international reference architectures as well as standards have been taken into account in order to properly select these building blocks. While especially IEC standards such as IEC 62443 and IEC 62351 have been considered, reference architectures such as results from the national RASSA research project as well as the renowned SGAM model have been methodically integrated.

Planning and Operation Processes

The typical lifecycle of a component in the energy automation domain follows a sequence of 3 steps: requirements specification and device ordering, system engineering and device configuration, and finally device operation and maintenance.

Therefore, this work package developed an extended lifecycle model which satisfies an efficient and secure rollout concept. In the end, two main ideas have been integrated into the lifecycle:

When using template-based engineering with typicals (see the proper building block in the figure above), the overall configuration effort is reduced as only project-specific configurations need to be done by the customer upon device commissioning. This is only possible, if proper templates can be created, i.e. if it is possible to find common configurations among a high number of possible projects/installations/devices.

In means of security, two points needed to be considered, namely a proper handling of cryptographic material that already starts during production process, as well as fine-grained access control concepts – which all have been integrated into the developed building blocks.

Through the prototypic implementations, these ideas have also been proven in real automation products.

3.6 Grid Simulation

Due to the steadily increasing number of distributed renewable energy sources, new challenges in distribution grids arise, e.g., the avoidance of power peaks caused by generation from photovoltaic systems or wind generators on one hand. On the other hand, the integration of upcoming electric vehicles and heat pumps might lead to high loading values or deep voltage drops. Within a comprehensive and detailed grid simulation, the current situation in two low voltage (one representing a residential area, the other one representing a commercial area) grids in Linz (Upper Austria) was analysed (base-scenario), followed by an outlook for the next two decades with realistic assumptions regarding the number of PV-installations, heat pumps, electric cars, and general load increase for each grid. Figure 37 shows the commercial grid, modelled in PowerFactory.

Base-Scenario: As already mentioned, the first step was the load flow simulation of the actual situation in the two low voltage grids (in 2017). Therefore, the annual consumption was used for the customers, different seasons and weather conditions were used, as well as realistic power profiles for the different load types, heat pumps, PV modules, and electric vehicles.

Future Scenarios: For the future scenarios (2027, 2037), the following assumptions were considered in the load flow calculations:

- An increase of 2 % per year was assumed for all load elements.

- 30 % of all customers will have a photovoltaic system and/or a heat pump in 2027 and 55 % in 2037[1].

17 % of all customers will have an electric vehicle in 2027 and 47 % in 2037 [13].

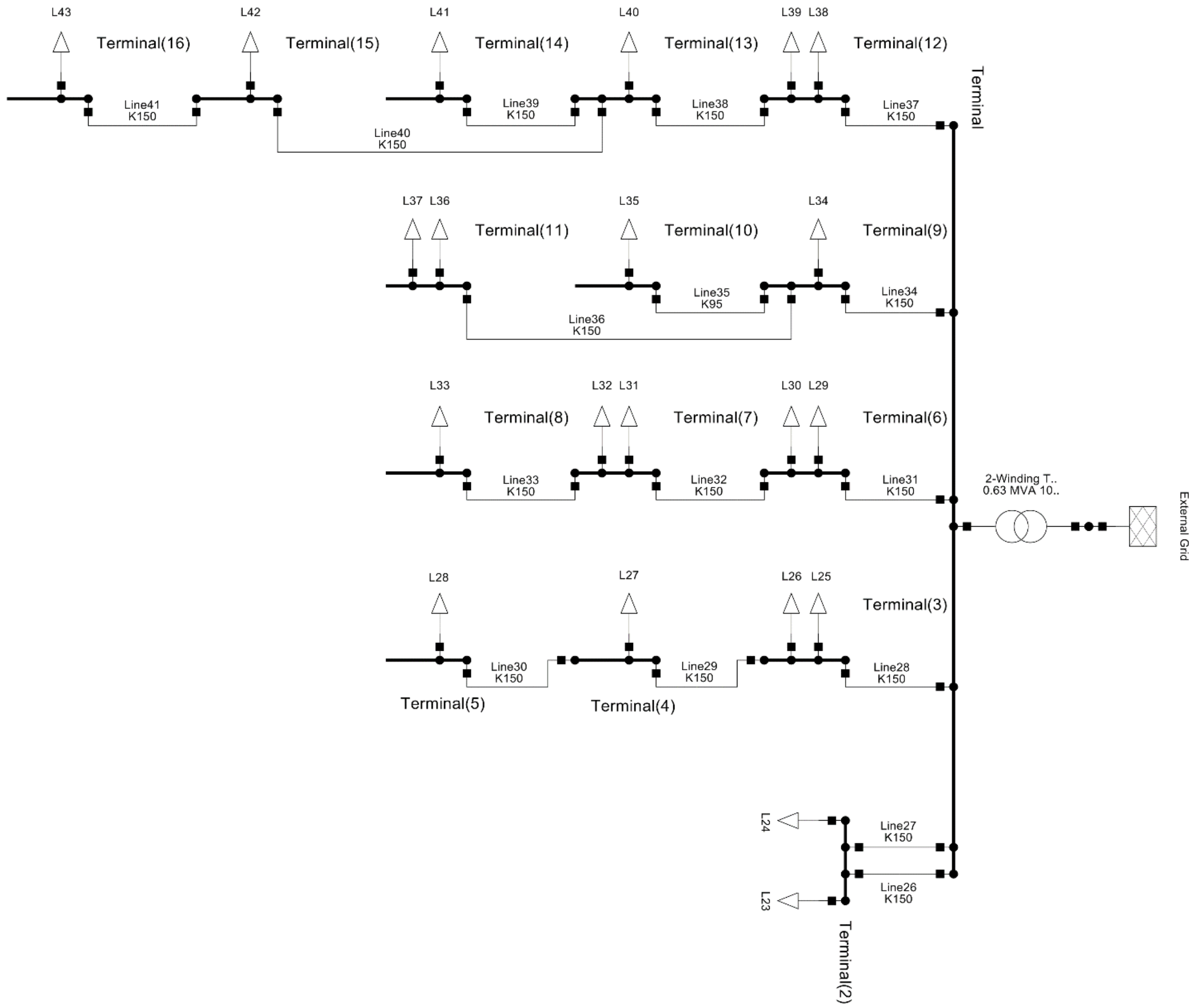


Figure 37: Commercial area (low voltage grid in Linz).

3.6.1 Traffic light model as base for grid optimization

The grid information was based on the traffic light model [14] where every state has a colour (green, yellow and red), in addition to active power limits. The grid was first divided into different sectors that would have the same grid information. This was done since the grid operator is interested in violations occurring in grid clusters and not in single customers. The load clusters are created based on the grid topology where every feeder line was considered as a single cluster, as shown in Figure 38,Figure 39 with two clusters for the household area and five for the industrial area.

[1] These assumptions are based on the experience of Linz Strom Netz GmbH

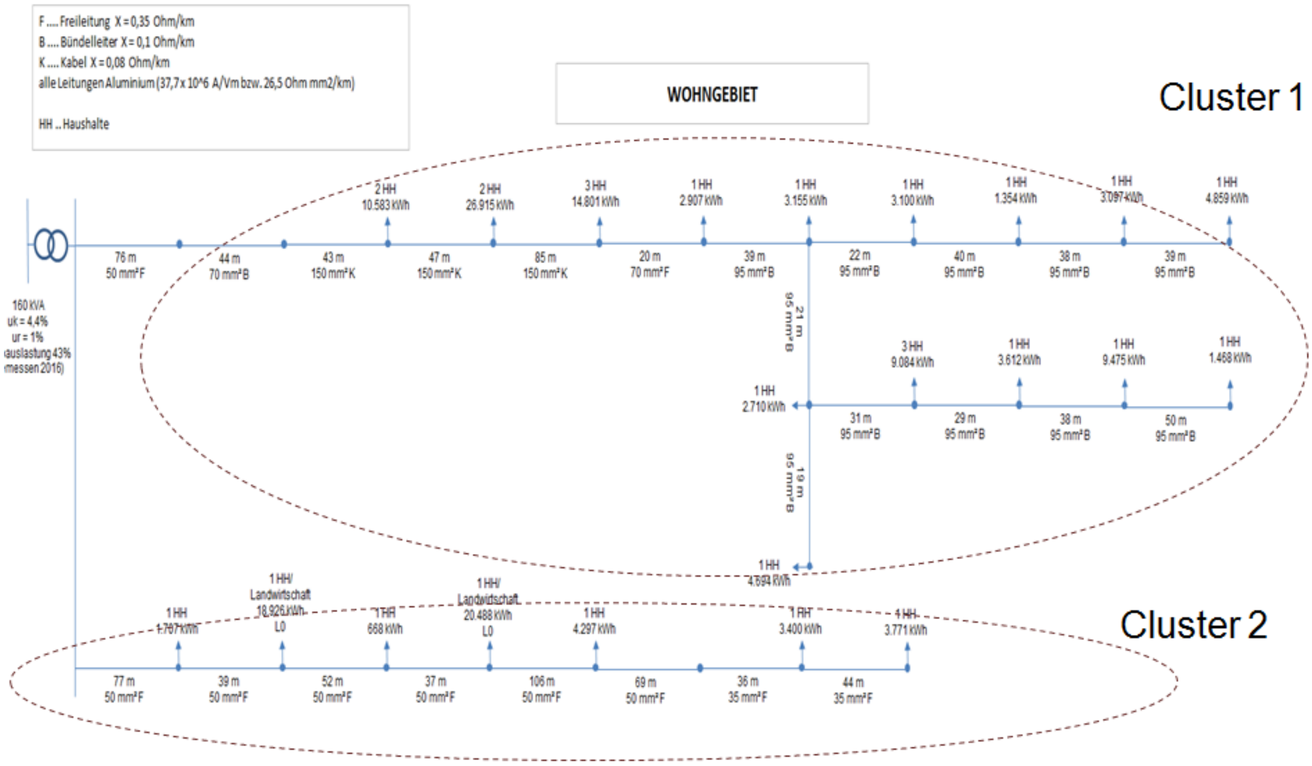


Figure 38: Household area grid clusters

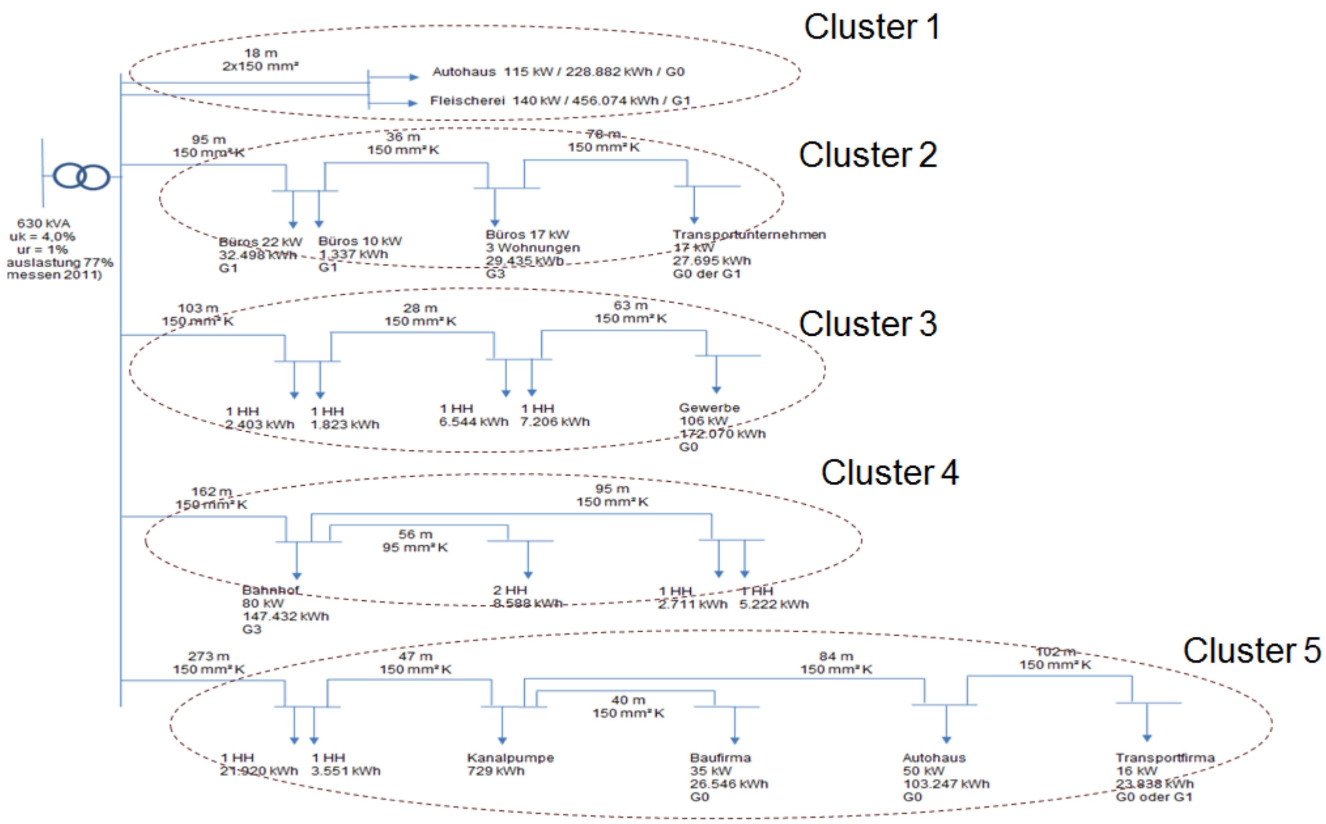


Figure 39: Industrial area grid clusters

Active power limits are generated for the upper limits, while lower limits were not considered due to the control algorithms in modern PV inverters that control high voltages locally. Voltage and current constraints were considered for the grid limits and status.

For voltage limits, the grid information will be generated based on the lowest voltage in the grid buses. The low voltage indicates high load consumption and is hence considered an indicator to generate the upper grid limits.

The grid status was accordingly based on the lowest bus voltage in one cluster as follow (see Figure 40):

- Green: voltage higher than 0,93 p.u.
- Yellow: voltage between 0,93-0,91 p.u.
- Red: voltage lower than 0,91 p.u.

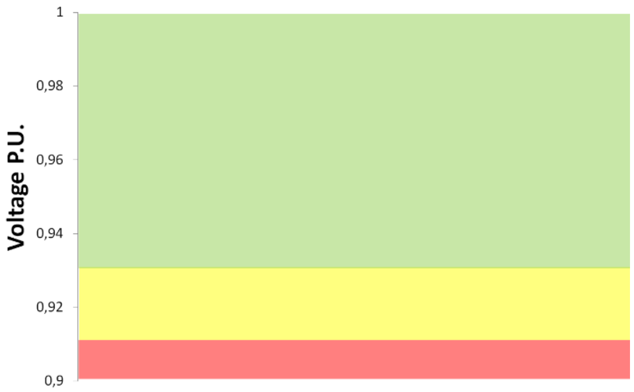


Figure 40 Voltage grid status limits

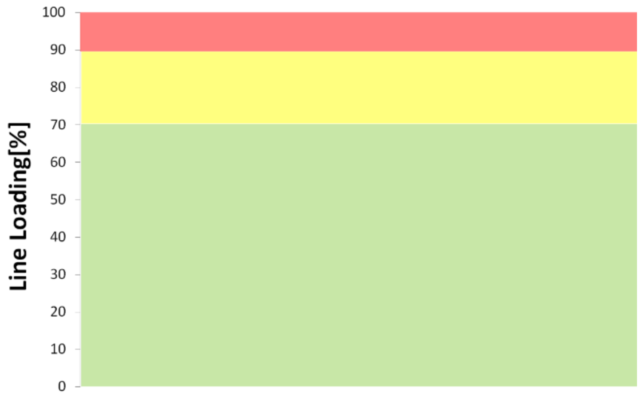


Figure 41 Line loading grid status limits

Calculations were then made to check the power consumption value that changes the voltage to the acceptable value for each cluster (higher than 0,93 p.u.). The calculation was done by using a PID controller where the set point is a bus voltage of 0,93 p.u. and a bus voltage-power transfer function. The consumption in other clusters is fixed for this calculation. This resulted consumption is the active power limit from voltage constraints.

For the current/thermal limits, the grid information will be generated based on the highest line loading percentage. The high current indicates high load consumption and is hence considered an indicator to generate the upper grid limits.

The grid status was accordingly based on the highest line loadings in one cluster as follow (see Figure 41):

- Green: Line loading lower than 70%.
- Yellow: Line loading between 70-90%.
- Red: Line loading higher than 90%.

Calculations were made to check the power consumption value that changes the line loading to the acceptable value for each cluster (lower than 70 %). The calculation was done by using a PID controller where the set point is a line loading of 70 % and a line loading-power transfer function. The consumption in other clusters is fixed for this calculation. This resulted consumption is the active power limit from current constraints.

After generating the grid information for both voltage and current constraints, the final grid information for the grid cluster were chosen based on the following criteria:

- The cluster's final active power limit will be based on the lowest of the voltage and current constraints.
- The cluster's final grid status will be the highest of the voltage and current constraints.

Limits Oscillation Control

Limits oscillation control was implemented to decrease the effect of voltage and power fluctuations due to load shifting.

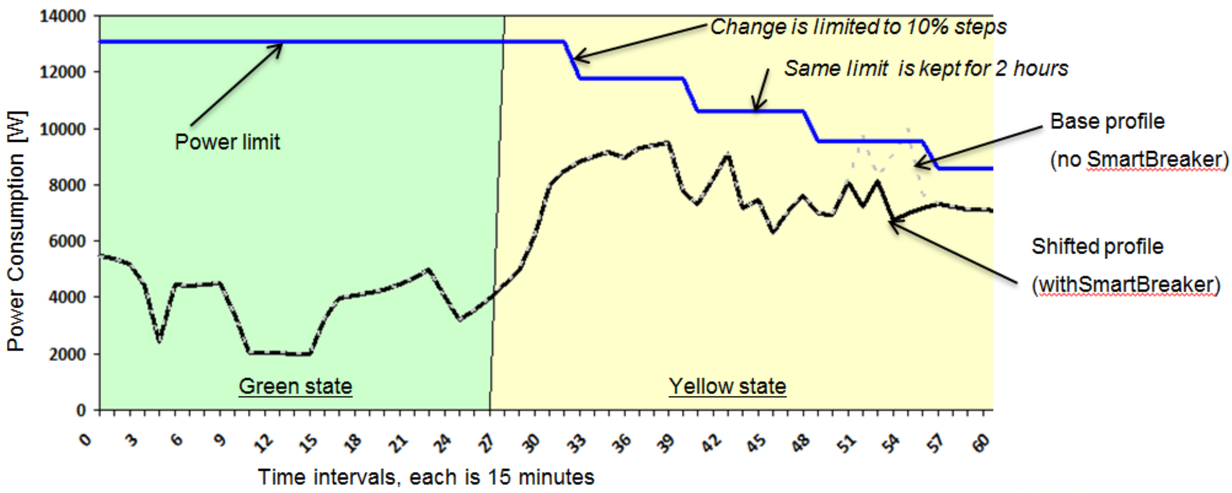


Figure 42 Limits oscillation control example

The steps considered can be shown in Figure 42, the blue line represents the active power limit and the straight and dotted lines represent the base and shifted profiles respectively. The oscillation control considered the following criteria:

- The power limit is restricted to only 40 % of the initial cluster limit.
- If the grid status is not changed for the next cycle, the power limit is kept at the same value for the next 2 hours. Only if the grid status changes from green to red or yellow, a new limit is forced.
- The power limit rate of change is kept at maximum 10 % from the previous one.

3.6.2 Load shift algorithm

Each load profile considers different variations of PV generation, heat pumps (HP), and electric vehicles (EV). The profiles represent one day which was extended (00:00 until 05:45 in the next day), to give EVs realistic time to charge after midnight. Hence, two loads are considered for shifting (EV and HP) while other loads are considered as non-controllable and are always running.

The shift algorithm is proposed to reside within the CEMS located in each customer premise and was based on the domestic demonstrator algorithm presented in the Deliverable D7.1. Each CEMS receives the whole cluster grid information from the grid operator. Next, the local limit is determined by the CEMS based on the bus maximum consumption. The CEMS takes decision based on grid information and customer preference constraints (to finish the task in the allowed shift window). The CEMS takes decisions to

Run or Stop the controllable loads (EV, HP) for the next 15 minutes with no information about the future (no load forecast).

The traffic light model was interpreted as follow:

- Green: no Limits from the grid. HP and EV can run without restrictions.
- Yellow: HP/ EV can run if their load is within limits, limits can be broken in special cases (explained next for each controllable load)
- Red: HP/ EV can run only if their load is within limits.

The operation constraints for each controllable load were considered as shown in Table 2. The main constraints and the shift window considerations are explained also.

Table 2 Controllable loads operation constraints

Controllable load	Main constraint	Shift window
EV	Finish charging the EV within the shift window.	The shift window is assumed to be given to the CEMS by the user and represent the EV parking time.
HP	Maintain the temperature within user's comfort zone.	The whole day, depending on user comfort.

For the EV, if the charging causes a limit violation in yellow state, it will be shifted except if there is no enough time left in shift window (Figure 43). As the input is an already made load profile, the HP constraint was not directly based on the indoor temperature (as is the case in the domestic demonstrator). The main constraint considered was to operate the HP for as many times it operated in the base scenario, but in different time slots (maintaining the same energy and allowing shifting feature). As shown in Figure 44, the HP working was divided into intervals, from start time to the next start time. In the load profile in Figure 44, the HP works in two time slots, each with a different shift window. If the HP load causes a limit violation in yellow state, it will be shifted except if there is no enough time left in shift window.

The high consumption of the EV in future scenarios means that whenever number of EVs are charging at the same time, this triggers a yellow or red status in the grid cluster. This leads to load oscillations, as when the status is green most CEMS would decide locally to charge the EVs which triggers a red grid status, in the next cycle all charging will stop meaning the status would be green in the cycle after that. The grid oscillation control proposed can limit this behaviour, but without communication between CEMSs the issue will not be completely solved.

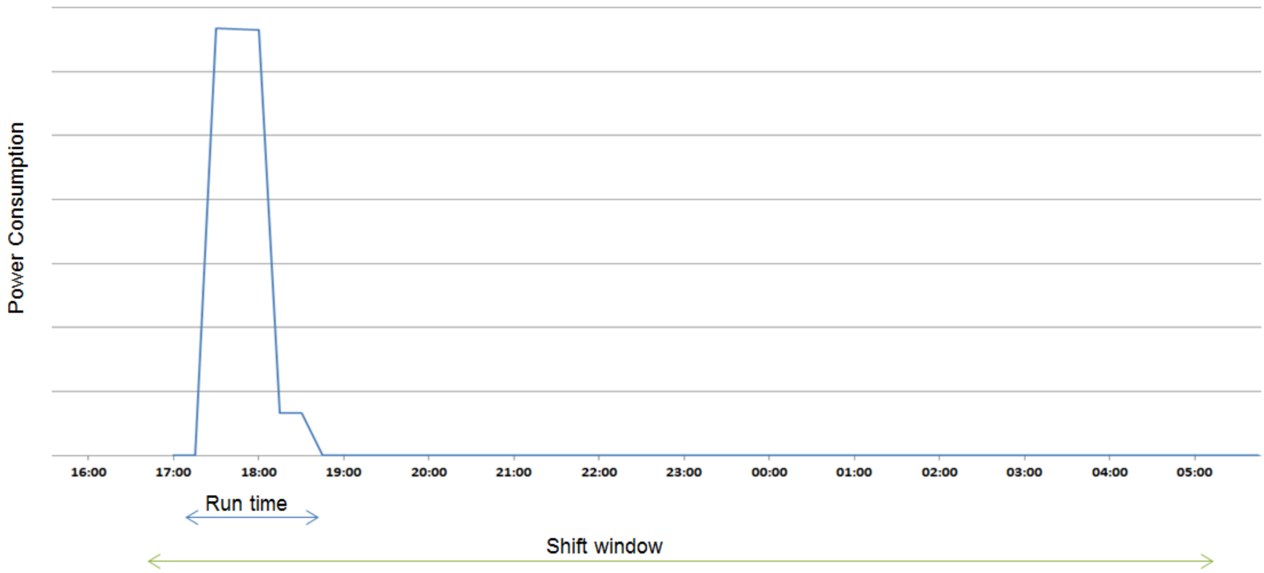


Figure 43 Electrical vehicle shift window

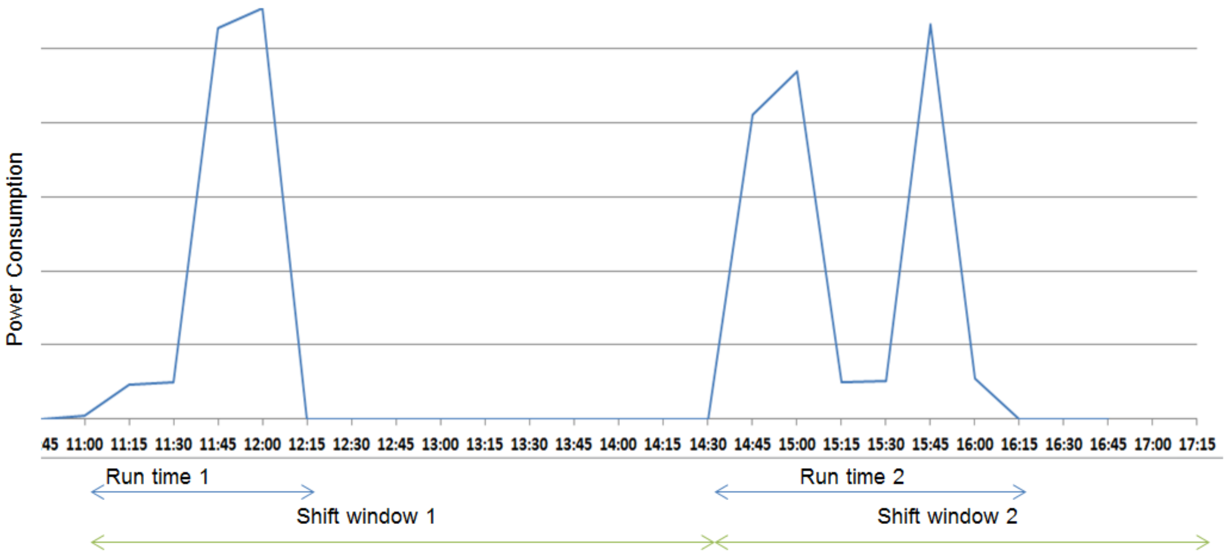


Figure 44 Heat pump shift window

3.6.3 Methodology

Within the project, a framework was implemented to create the necessary power profiles, choose customers with electric vehicle, PV, or heat pumps, and to perform Monte Carlo based load flow simulations, whereas one iteration of the Monte Carlo simulation represents one day.

For the heat pump and electric vehicle elements, a random activation time shift via a kernel was introduced for the power profiles to cover a wider range in possible load situation with the Monte Carlo approach. Different kernels are used for both elements. Electric vehicles use a triangular kernel. Residential customers have a peak at 6 p.m. and a possible time shift of +/- 3 hours because people are supposed to arrive at home within this span. Commercial customers have a peak at 8 p.m. and a possible time shift of +/- 1.5 hours because they are supposed to arrive at work within this time span [15]. Heat pumps use a finite gaussian kernel. Some predefined profiles are shifted in time with +/- 2 hours possible time shift. PV and baes load elements do not make use of a random time shift.

3.6.4 Simulation results

The results (mean value of maximum infrastructure loading and mean value of minimal voltage at the nodes of all scenarios) for the residential and commercial area of the load flow calculations for 2017, 2027, and 2037 are shown in Table 3. For 2027 and 2037 the load flow was calculated without using the new and innovative components in scenario (a), whereas in (b), the Smart Breaker, Customer Energy Management System, Load Shift Algorithm, etc. was assumed to be implemented. Obviously, the maximum loading can be reduced dramatically (e.g., from almost 134 % of infrastructure loading in peak times to 84 % in the commercial area) by using the new approaches. Similar improvements can be achieved in the voltage domain. The comparison of the commercial area in 2037 between scenario (a) and (b) is shown in Figure 45.

Table 3: Results of load flow simulations for residential and commercial area for 2017, 2027, and 2037. In scenario (a) new technologies are not used, in (b), the Smart Breaker, load shift algorithm, etc. are implemented.

	Residential area		Commercial area	
Scenario	**Loading [%]**	**Voltage [p.u.]**	**Loading [%]**	**Voltage [p.u.]**
2017	13.0	0.931	29.6	0.932
2027 (a)	30.2	0.904	79.5	0.894
2037 (a)	69.9	0.840	133.9	0.839
2027 (b)	19.8	0.921	69.7	0.903
2037 (b)	27.5	0.906	84.0	0.889

The results of the simulation were investigated in the cost-benefit analysis resulting in possible savings in comparison to conventional grid reinforcement. The exact numbers are provided in the project deliverable D2.1 (Section 4.2 Low Voltage Network Optimization) in the appendix.

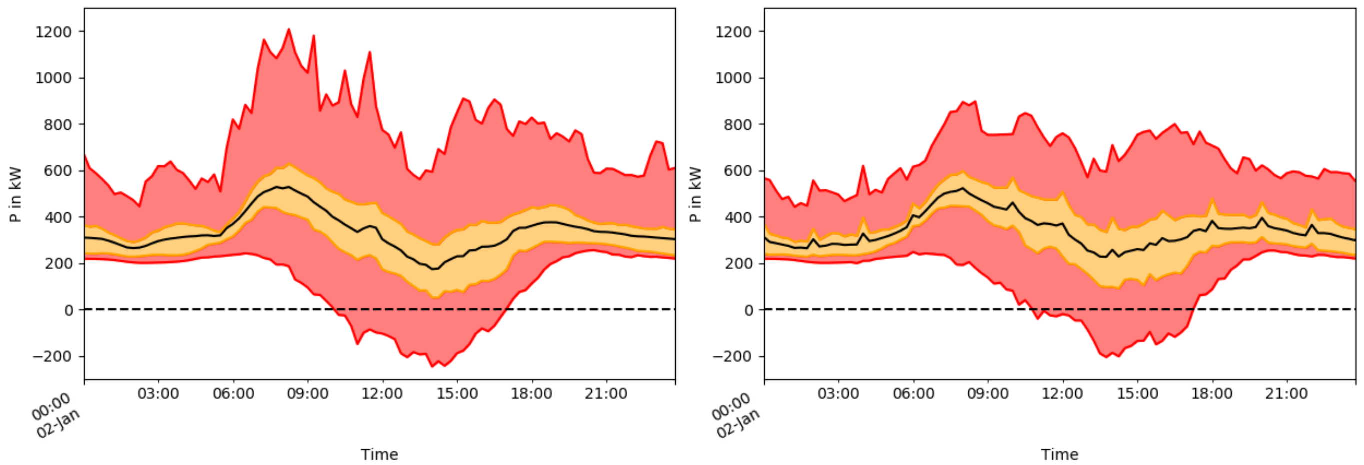


Figure 45: Summed load in the commercial area assumed in 2037 without the new technologies (left) and by integrating the Smart Breaker, Load Shift Algorithm, etc. (right).

3.7 Lab Validation of hard- and software components

After the components have been successfully developed and tested in simulations and in-house laboratories, the system validation phase in the AIT SmartEST lab war performed. Additionally, it was necessary to implement a proprietary Customer Energy Management System (CEMS) responsible for receiving grid information (traffic light signal) and boundary values (voltage and loading) as well as for communicating with the Smart Breaker Gateway for controlling the connected loads. Details about the Customer Energy Management System on one hand and the description and results of the lab validation will be presented in the following subsections.

3.7.1 Prototype Setup

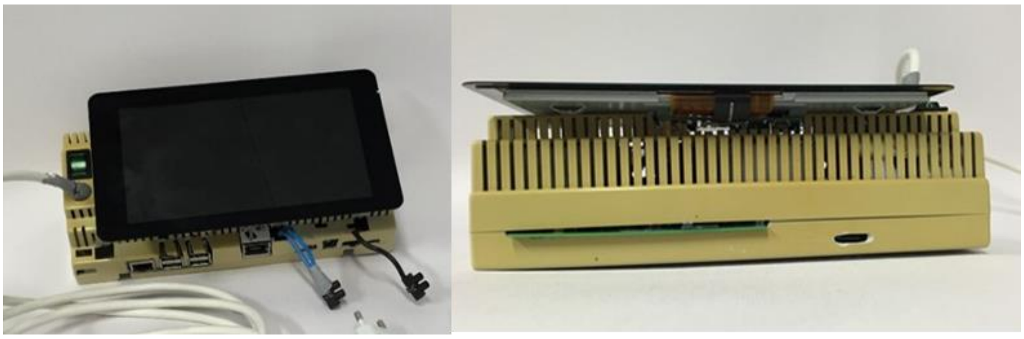


Figure 46: CEMS prototype housing containing Raspberry Pi and touch screen

In order to validate the new hardware components, we developed a prototypical CEMS that can mitigate between the grid demands and local demands from the consumer side, allowing us to test out the different usage scenarios outlined in the use cases presented in section 3.7.3. For the development of the CEMS and for the mocking of other systems, Raspberry Pis were used. In order to make the setup portable, which was especially important for the various dissemination activities that included demonstration of the hardware, we decided to build a minimal prototype setup into a single housing, as shown in Figure 46. This component was also used as control device during the SmartEST Laboratory tests.

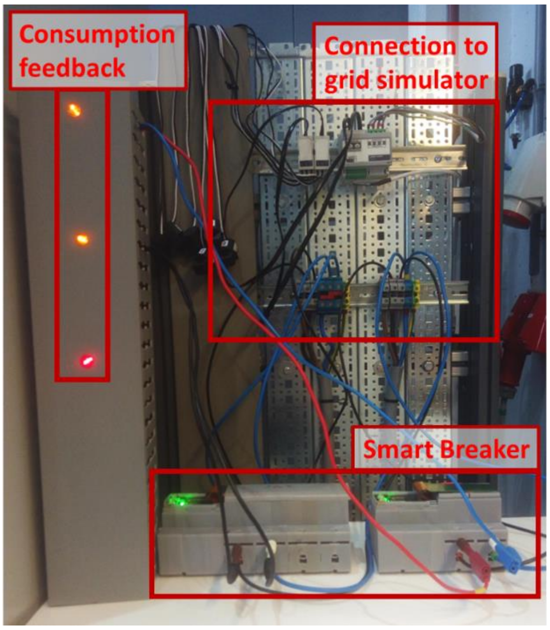


Figure 47: Prototype setup for a single testcase

The instalment for the various testcases differed, depending on the actually required components. A typical setup is shown in Figure 47, consisting of a CEMS (not visible in the picture), two Smart Breakers, connected to the grid simulator and controlling an array of LEDs to visualize the actual power flow. The laboratory setup, of course, also measured the power flow, but having visual feedback within the setup seemed appropriate.

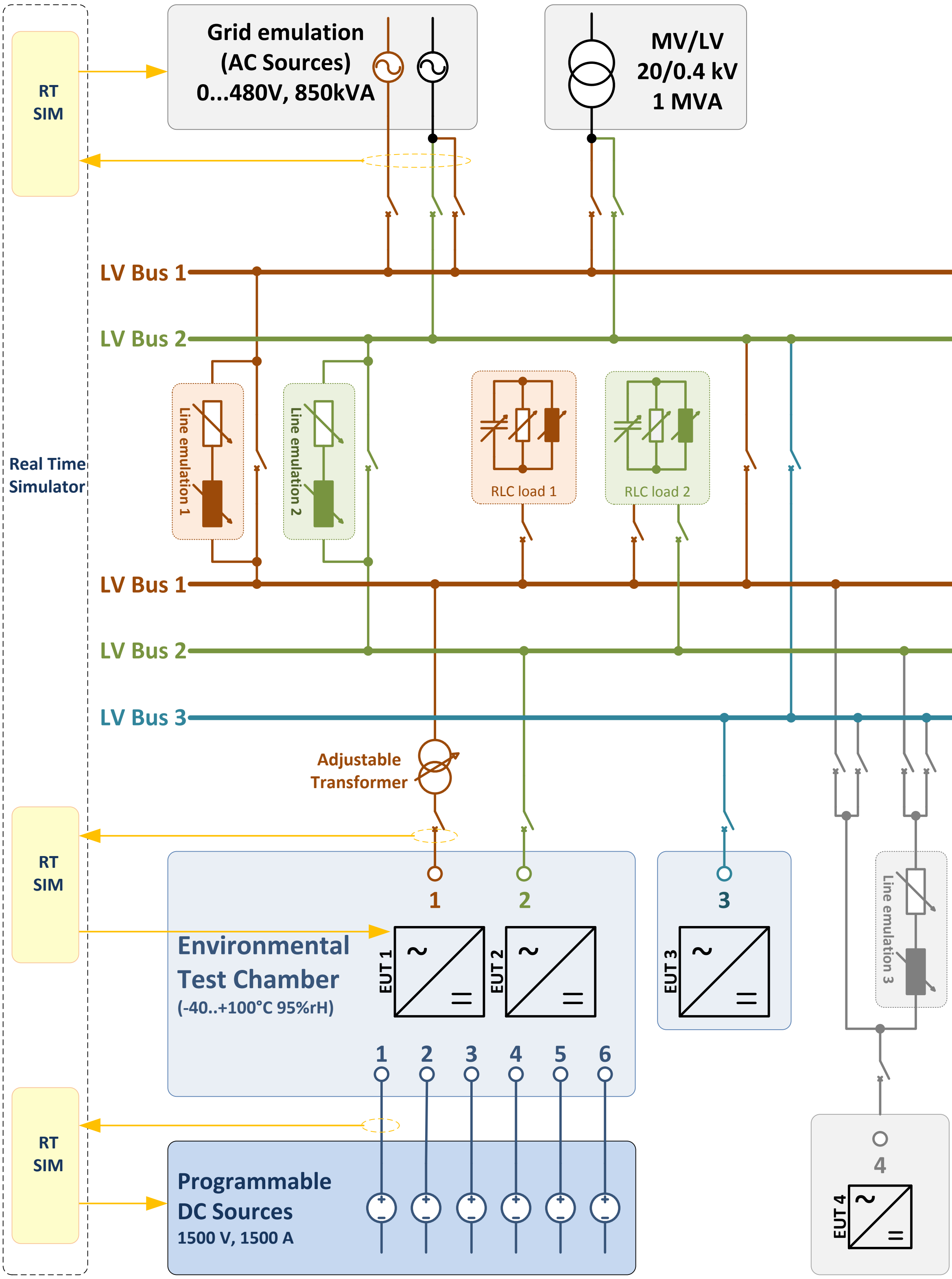


Figure 48: Simplified SmartEST schematic

3.7.2 Laboratory Setup

Figure 48 shows the simplified schematic of the AIT SmartEST laboratory which was used for various test cases, described in the subsequent sections.

3.7.3 Validation

Our test cases, for the laboratory validation, where derived from the use cases presented earlier. The different use cases cover different aspects of possible future smart grid applications. Since the laboratory setup cannot simulate all of these aspects, only parts of the five use cases are covered by our test cases. We designed the test cases to cover as much of the developed prototype functionality as possible, under the restrictions imposed the testing site. The result was a total of 7 individual test cases that cover the functionalities required to implement the use cases outlined in this document. A detailed description of the functionalities, their relation to the use cases and details on their implementation are available in Deliverable 6.1. The following subsections will outline the goal of each test case and, where appropriate, conclusions based on the test cases outcome. Whenever no conclusion is give, the test case execution has simply covered the full range of aims, set out in the goals description.

3.7.3.1 Test Case 1.1

Goal of this test case is to demonstrate the CEMS capability to support grid stability in a simple form. To this end, the test case demonstrates the CEMS capability to enable or disable the connection of a single static consumer to the grid, depending on grid stability information provided by a centralized system. The CEMS should not simply connect or disconnected based on the grid state directly, but instead adopts the bandwidth limitations transmitted by the SCADA system (in form of traffic light signals) for the different grid states and adhere to these restrictions upon entering a specific grid state.

3.7.3.2 Test Case 1.2

Goal of this test case is to demonstrate the CEMS capability to support grid stability in a simple form. To this end, the test case demonstrates the CEMS capability to enable or disable the connection of a single consumer to the grid during a period of high, but still manageable, grid strain. The CEMS is supposed to demonstrate its ability to allow a single consumer access to the grid, as long as it does not violate the bandwidth restrictions currently set by the DSO or TSO. The main difference to Test Case 1.1 is that now, the loads are varied, instead of adjusting the bandwidth restrictions.

Conclusion

The test performed as expected, but illustrated a general problem with pre-define consumption values in a priority list. Since the system does not yet “learn” the consumption values, a fixed, lower-than-actual consumption value, would result in regular attempts to enable the Smart Breaker, even though the actual consumption will always violate the current limits. In some setups the repeated enable-attempts could potentially be harmful to the connected hardware. This problem becomes more sever when we consider industrial setups where even a short connection attempt of a very large consumer could push a struggling grid section into serious problems.

This aspect of this test is base for our recommendation to improve flexibility and complexity of the methodology used to determine a consumer load-upon-connection, e.g. by using machine learning to predict load profiles.

3.7.3.3 Test Case 1.3

This is the first test case involving two breakers controlled by a single CEMS. The goal here is to demonstrate the CEMS ability to control both breakers, from a defensive start scenario, i.e. both breakers start the test in a disables mode. The CEMS should activate the breaks in the expected sequence. The second part of the test should show the breakers ability to maintain bandwidth restrictions in a multi-breaker scenario, aggregating the consumption of both consumers to determine if the CEMS violates the restrictions or not. Finally, the test should show the CEMS ability to react to dynamic changes in the consumption behaviour of the participating consumers. Upon increased consumption of one of the consumers, the CEMS should deactivate the less important device, to maintain the more important consumers for as long as possible. When the more important consumer has fulfilled its task and reduces its consumption, in our test this is done manually by the tester that sets the consumption to zero, the CEMS should re-enable the less important consumer, since there is now enough bandwidth available.

3.7.3.4 Test Case 2.1

This is a variation of the setup in Test Case 1.1 using two breakers in a single CEMS, but this time the variant component is not in the local part of the setup (i.e. not in the consumers) but in the centralized part, the SCADA. The goal here is to demonstrate the CEMS ability to control multiple breakers, from a defensive start scenario, i.e. both breakers start the test in a disabled mode, during changes in the grid state. The CEMS should first activate the Smart Breakers in the expected sequence. The second part of the test should show the breakers ability to maintain bandwidth restrictions in a multi-breaker scenario, aggregating the consumption of both consumers to determine if the CEMS violates the restrictions or not. Finally, the test should show the CEMS ability to react to dynamic changes in the grid state by activating an additional consumer as soon as the bandwidth restrictions allow it.

3.7.3.5 Test Case 2.2

The goal of this test case is to demonstrate the CEMS ability to autonomously participate in grid stability measures by reacting appropriately to voltage drops in its grid-segment. The CEMS should first activate the Smart Breakers due to free consumption capacity on the consumer site. Then, the tester will cause a voltage drop on the simulated local grid-segment. As a reaction, the CEMS should shed its consumer during the following control cycle in order to help stabilize the grid-segment. The CEMS should also consider a hysteresis range to the voltage bandwidth, i.e. the CEMS should not re-enable the consumer immediately as soon as the voltage climbs slightly above threshold. Assuming a sufficient number of participants shedding their load, the simulated grid-segment will be manually reset to valid voltage value and the CEMS should re-connect the previously shed consumer.

Conclusion

The CEMS performed as expected. This test showed that the current CEMS implementation is capable of autonomously reacting to voltage bandwidth violations by shedding loads. The test also showed how hysteresis can be used to avoid oscillation effects on the consumer level.

During development of this test case however, we realized that distributed autonomous reactions, like the one performed in this test case, could also lead to problematic behaviour. If enough houses on a grid section participate and the shedding happens (almost) simultaneously, the grid section could start to “oscillate”. Simple delay mechanics like randomized wait periods before shedding could help – but also hinder in case of emergency situation, by delaying the consumption reduction. The proper coordination of these distributed, low-level reactions should be of interest to future Smart Grid research. The hysteresis approach can avoid oscillation on a consumer level, but might not be adequate for the grid-segment level, since the range in which the voltage might oscillate could be too big.

3.7.3.6 Test Case 2.3

The goal of this test case is to demonstrate the CEMS ability to assist the local substation controller in grid stabilization measures by allowing the SCADA system to impact the configuration of distributed local producers in order to stabilize grid voltage. The CEMS should first activate the SBs due to free consumption capacity on the consumer site. Then, the tester will cause a voltage drop on the simulated local grid-segment. Simultaneously, the SCADA system, in reaction to the voltage drop, increases the reactive power of photovoltaic systems at participating CEMS. This should stabilize the grid sufficiently to avoid load shedding. Then a simulated change in weather conditions will reduce the possible output of the PV system and the voltage will degrade bellow the voltage threshold, causing the CEMS to shed its load. In the final part of the test, the weather conditions will improve again and the CEMS will be able to re-connect its consumer, due to the stabilizing effect of the PV system.

3.7.3.7 Test Case 5.1

The goal of this test case is to demonstrate the CEMS ability to handle a combination device that can switch between producer and consumer state (referred to as “prosumer”). The CEMS should first activate two Smart Breakers (in the correct sequence) due to free consumption capacity on the consumer site. Then the SCADA system will indicate grid strain by sending a yellow traffic light state with a bandwidth limit that is would not be able to support the local consumer by itself. The CEMS should react to this problem by switching the battery on one of the connected Smart Breakers from consumer state (loading) to producer state (unloading). With this additional local production, the CEMS should maintain the ‘actual’ consumer for as long as possible, during the yellow traffic light state. As the battery eventually runs out, the CEMS will need to disconnect the consumer. After the SCADA system changes the grid state back to green (stable) the CEMS should re-connect the consumer and battery (in proper sequence).

3.7.4 Conclusion

The laboratory tests showed the prototypes ability to fulfil the requirements put out by the use case descriptions. We tested these aspects using prototypes of the actual hardware components, especially the Smart Breakers and Smart Metering devices available at the lab site. We further tested the ability of our prototypical controller implementation to provide the necessary behaviour, especially in regard to:

1) Local consumption optimization
   Involved in most test cases in form of connecting optional Smart Breakers to maximize the current consumption, as long as there is no violation of bandwidths; but especially covered in test cases 2.3 and 5.1 where the local PV and battery systems where used to maintain local consumers
2) Priority lists

Involved in most test cases, but especially important for test case 5.1 where the correct sequencing of battery and consumer is important (to avoid loading the battery while an actual consumer would lay dormant)

3) Grid stabilization
Implemented in threw aspects: (1) first by the reaction to grid state messages, in form of traffic light signals, especially significant for test cases 1.2, 1.3, 2.1 and 5.1; (2) second by autonomous reaction of the CEMS to voltage violations in the local grid section, appearing in test case 2.2 and (3) third by passing on specific configurations directly to participating distributed producers, exemplified in test case 2.3 by the Q(U) function provided to the PV system

The CEMS required communication with various components from various sources, e.g. Smart Breakers, Smart Meters, a SCADA system and in some cases common remote sensors and actuator, which worked well in all tested scenarios. From this we conclude that the communication framework OpenMUC, which was used as central communication layer and connection point for additional software components, is suitable for such a task, where flexibility in configuration and extendibility of existing drivers is important for the control device. The CEMS was furthermore deployed on a Raspberry Pi 3 during all test cases, giving clear evidence that the final deployment of control devices, capable of performing the tasks outlined in project iniGrid, does not necessarily require expensive, specialized equipment but can, even with state of the art security considerations in mind, be performed on in-expensive off-the-shelf hard- and software components.

3.8 Field trials

After the components have been successfully validated in the laboratories (in-house component validation and system validation with Smart Breakers, Customer Energy Management System, loads, generators, real network topology – validated in the AIT SmartEST laboratory, see Section 3.7), a comprehensive field validation phase started. In contrast to the initial plan to implement a field validation setup (Smart Breakers to control loads and generation units) in Linz, a field test was setup in the exhibition of Sonnenwelt Großschönau. This test was performed for several months – further details are presented in Section 0. An important preparation work was the implementation of the Domestic Smart Grid Controller and the validation in the University of Applied Sciences Upper Austria in Wels – controlling real loads with the Smart Breaker (see Section 3.8.1). The third part of the field validation was the Medium Voltage Sensor test in a real replica of an air-insulated switch gear (equipped with actual current sensors, the new medium voltage sensors, and IT automation infrastructure) at the AIT (see Section 0).

3.8.1 Domestic Smart Grid Controller

A domestic smart grid ready prototype system was developed in FHOÖ consisting of all significant parts of the considered smart grid system. This demonstrator focuses on the validation of the use of the Smart-Breaker system in active load management in households. The concept of demand response was based mainly on a grid information model. This model was centred on a traffic light model for distribution grids which reflects the status of the network according to a specific colour (green/yellow/red). Guideline conditions with the maximum and minimum active power limits were also included.

Two personal computers (see Figure 49) communicating via Mbus and LAN technology were used in a Hardware-in-the-loop technique (HIL) to run an accelerated simulation with continuous hardware feedback. This setup is implementing actual smart grid component simulating the customer energy management system (which has to be implemented into a domestic system in order to optimize the energy consumption) as well as the smart meter including the emulation of the grid operator commands. This setup assumes that a smart meter with two-way communication capabilities is present in the customers' premise to allow the grid to communicate information via the traffic light model.

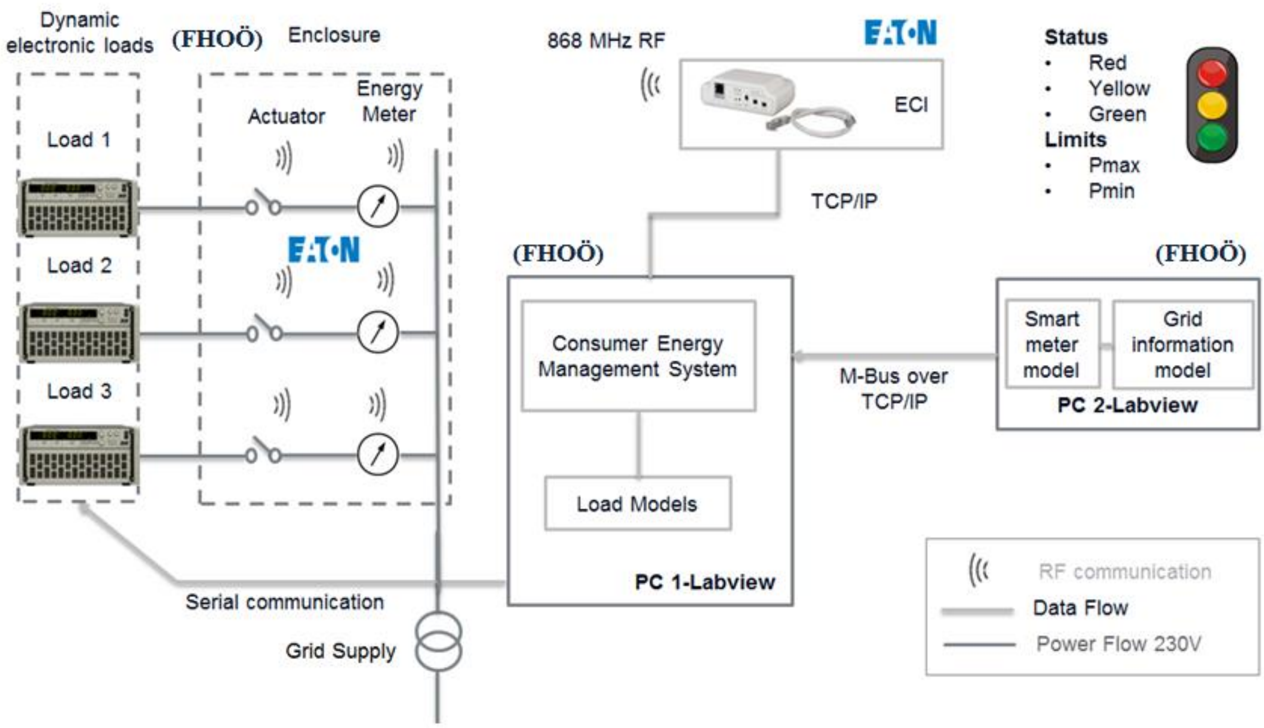


Figure 49 Current lay out of the domestic smart grid ready prototype system.

Three dynamic electronically loads are acting as an electrical vehicle (charging of the car), a washing machine, and a heat pump system. Other controllable loads (a dryer and a dishwasher) and a photovoltaic system, in addition to non-controllable loads, were simulated in PC1. The power consumption was derived from load and thermal house models developed for this project and implemented by means of LabView software. The required input meteorological data is yield from historical recordings from the University of Applied sciences in Wels PV and meteorology data recording system.

The SmartBreaker communication hardware was modelled by real components applying the same technology as used for the SmartBreaker technology. Because of availability restrictions, real SmartBreaker were not installed. However, actuators and energy meters that have a similar communication technology (also from EATON) were implemented to give a realistic behaviour of the system.

The traffic light model was interpreted in the domestic demonstrator as shown in (Table 4). The grid situation is indicated by red, yellow, and green colours. In case of the red colour the consumer has to operate his system within an energy band strictly. In case of green and yellow status the energy consumption will be optimized with respect to energy costs (an appropriate optimization algorithm has been developed and implemented into the simulation software). This was done by defining priorities for the customer preferences and the grid active power limits communicated by the grid operator.

The customer preferences differ according to the controllable load as follow:

- Heat Pump: maintain indoor temperature within preferred temperatures.
- Washing appliances (washing machine, dryer and dishwasher): finish task within the customers defined shift window. Once task starts, it has to finish the operation without any interruptions due to internal physical limitations concerning the quality of the washing or drying.
- Electric vehicle: charge the vehicle within the car's parking time.

Table 4 Traffic light model description and CEMS objectives

Grid Status	Status Description	CEMS Algorithm Objective
Green	No restrictions from the network	Maximize self-consumption. (utilize local PV generation)
Yellow	A potential or actual network shortage or overload of network components	Try to keep limits (Following first customer preferences then grid limits)
Red	Grid's stability has been compromised	Follow limits (Following first grid limits then customer preferences)

The grid information is communicated to the CEMS is through the smart meter. Here, the CEMS acts as a master and the smart meter as a slave in an M-Bus topology. The M-Bus protocol is a European standard for the networking and remote reading of utility meters. It opens an opportunity for communication inside the customer premises between the smart meter and other devices. The smart meter should have a direct communication with the secondary substation to send the grid information. Nevertheless, this communication path is not considered in this demonstrator.

The control algorithm is located in the local CEMS. The control algorithm was realized by considering the problem as an optimization problem with the grid information and customer preferences as inputs. The outputs of the algorithm are on/off signals for the controllable loads and the local PV generation. The optimization problem is defined as an integer linear programming problem (ILP) as the power consumption is a linear function. The choice variables take only one value if chosen (integer variables) i.e. each load has only one value of power consumption if chosen. The CEMS fetches the grid information, customer inputs and power measurements to makes a decision for controllable loads operation state for the next 15 minutes; hence no long-term forecast is included. The objectives of the control algorithm change depending on the grid status. Those objectives are shown in Table 4.

Results

The long-term hardware in the loop (HIL) simulation is made for ten representative weeks; two summer weeks, two winter weeks, three fall weeks, and three spring weeks. The results of the HIL simulation are presented here in two sections, long-term statistics about the number of peaks in the considered household. The second section shows detailed results of the behavior of the system in short term periods of one day.

Long-term Results

The long-term simulation results are presented for three different simulations to prove the concept of the control algorithm for different customer behaviours. The simulations are made for the ten representative weeks and each contains 6720 intervals, each interval represents 15 minutes of actual time (about 32 seconds simulation time). With the HIL accelerated simulation, a whole year can be simulated in two weeks. Due to hardware constraints (switching times, settling times, etc.) the simulation could not be accelerated further.

Table 5. Peaks caused by controllable loads and net consumption for 10 simulation weeks

Simulation	Controllable load peaks (%)	Net energy consumed for 10 weeks (kWh)
Simulation 1	41 %	1630
Simulation 2	37 %	1650
Simulation 3	35 %	1780

In Table 5, the percentage of load peaks caused by controlled loads and the net energy consumed is shown. It was found that approximately 40 % of peaks in the consumption are caused by controllable loads, which gives a good potential for load shifting. The three simulations have different results due to the randomness scheduling of the controllable loads used (based on user's statistics and behaviour for different loads).

Table 6. Number of peaks caused by loads for 10 weeks (in 15 minutes intervals).

	Simulation 1		Simulation 2		Simulation 3	
Grid Level	Yellow Out of 3146 intervals	Red Out of 1480 intervals	Yellow Out of 3414 intervals	Red Out of 1685 intervals	Yellow Out of 3146 intervals	Red Out of 3146 intervals
Total peaks	229	124	250	183	273	126
Base load peaks	121	37	112	80	125	53
Controlla-ble load peaks	108	71	138	103	148	73
Shifted controllable load peaks	72 (66 %)	64 (90 %)	62 (45 %)	98 (95 %)	73 (49 %)	61 (83 %)

In Table 6, the limits violations in yellow and red grid levels are presented in detail. The resulted data shows the total number of peaks occurring in 15 minutes intervals. In addition, the presented data differentiates between peaks caused by base loads (critical loads with cannot be controlled) and peaks caused by controllable loads (which can be shifted). In the yellow grid level, 40 % to 70 % of the controlled loads are successfully shifted to periods of lower consumption. In the red grid level, more than 90% of controlled loads are successfully shifted to periods of lower consumption.

In Figure 50 simulation results for one week in spring are shown. The colours in the background represent the grid level based on the traffic light model. The dotted lines show the power consumption without using load shifting measures, while the straight lines show the power consumption with the use of the load control algorithm. The maximum and minimum power limits are also indicated with the blue lines. The red circles indicate the successfully shifted peaks by the algorithm. The load profile appears to be changing rapidly as this simulation is taking load readings in only 15 minutes intervals.

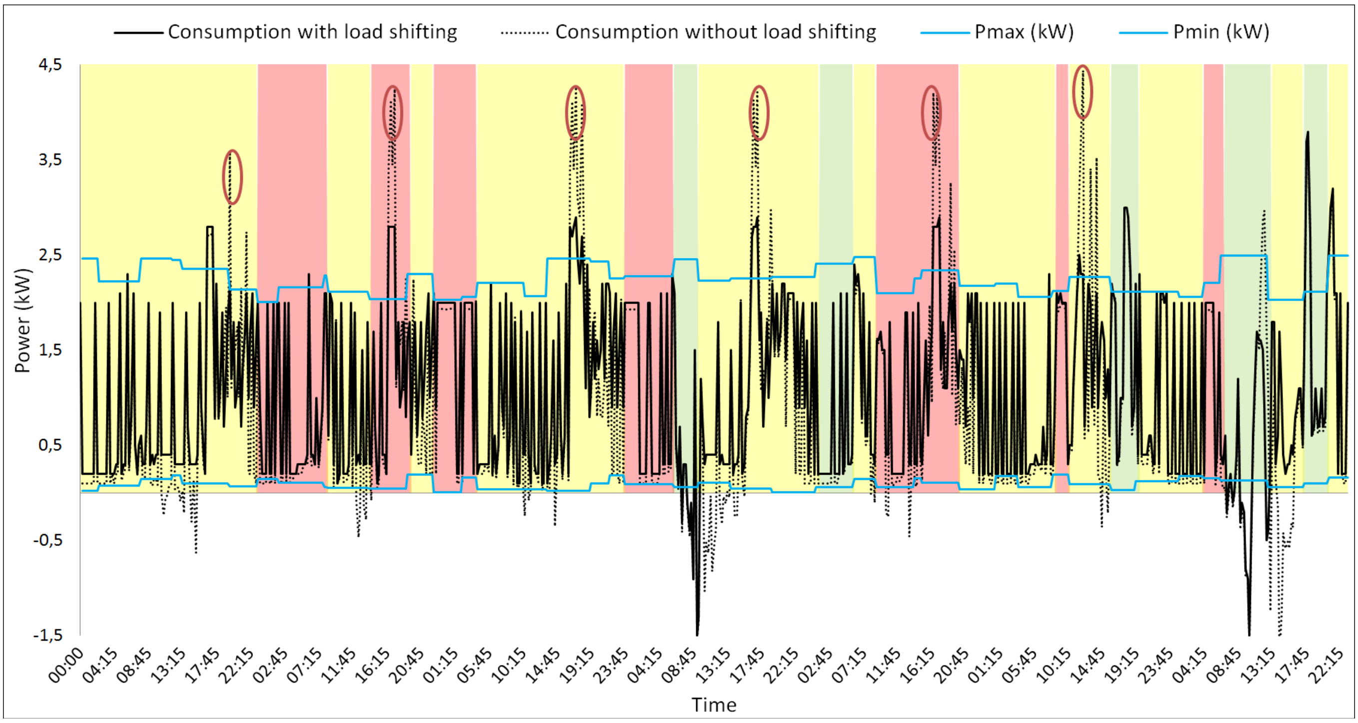


Figure 50. Load Profile comparison for a spring week, colors in the background represent the grid level based on the traffic light model.

Short-term results

In this case study, results for a Friday in summer are shown. In this day, three loads operated: an electric vehicle, a washing machine, and a dishwasher. Each load has a specific task time and commitment window in which the user prefers the task to be finished. The electric vehicle was plugged to the charging station at 14:45 and it needed 3.75 hours to be fully charged. The dishwasher and washing machine were plugged in at 19:15 and 22:00 respectively with different task times. Both appliances were operated immediately after being plugged, although the grid level was red in the case of the washing machine. This is due to the fact the overall load at that time was low and limits would not be violated.

The results of this case are presented in Figure 51 to Figure 54, colours in the background represent the grid level based on the traffic light model. In Figure 51, the consumption with load shifting and the base load (dotted line) profiles are shown in kW with the grid power limits. The base load represents the consumption of the non-controllable loads, while the consumption with load shifting shows the overall consumption of the household including the base load, the PV generation, and all controllable loads. The positive values in the load profile indicate flows from the grid and negative indicate flows back to the grid.

(Figure 52) shows how the electric car charging is shifted away from periods where the base load is high to avoid breaking the upper power limit (point 1 in Figure 51). In Figure 52 to Figure 54 the 3 controllable loads consumption is shown in kW. The black area shows the power consumption and the times the load actually operated, while the gray area indicates the commitment window; the period in which in which the user prefers the task to be finished. For the electric vehicle, the commitment period corresponds to the time the vehicle is parked in the house, for the other appliances the window is set by the customer.

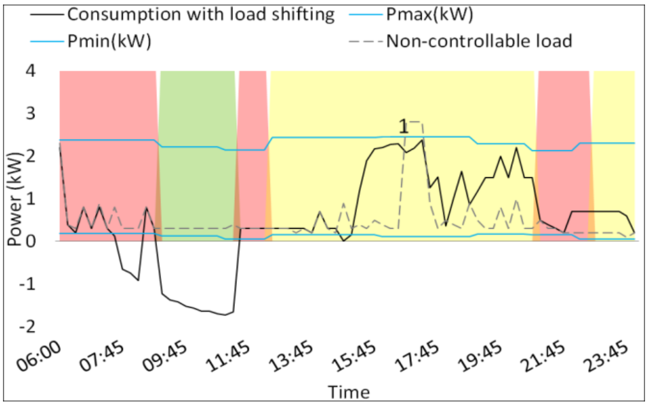


Figure 51. Load profile

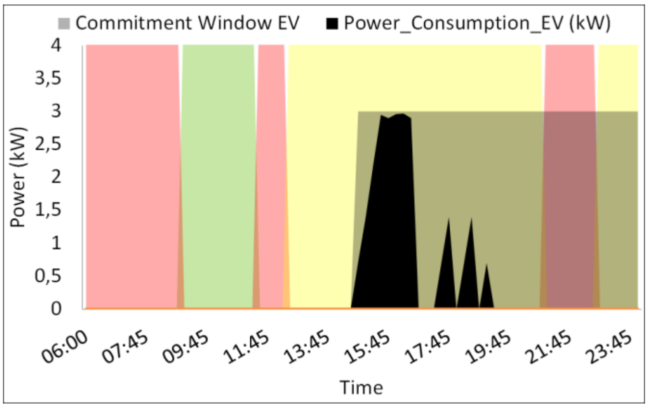


Figure 52. Electric vehicle profile

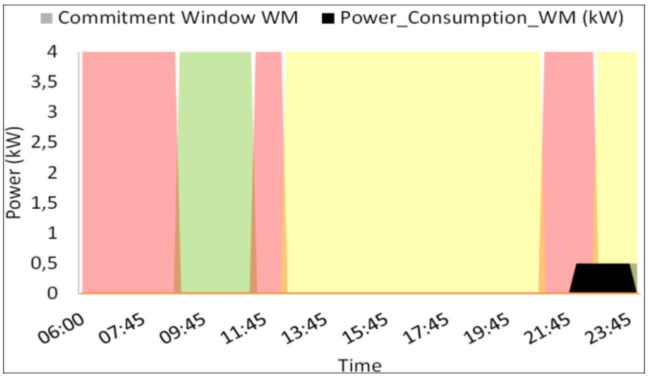


Figure 53. Washing machine profile

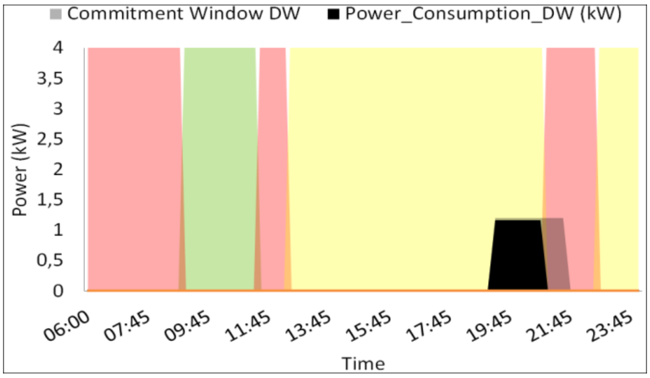


Figure 54. Diswasher profile

3.8.2 Field Validation in Sonnenwelt Großschönau

The field validation in the museum “Sonnenwelt” in Großschönau provided comprehensive data about the performance of the designs and soft- and hardware components developed in project iniGrid. The field test covered three different use cases (not to be mistaken with the iniGrid use cases developed during the requirements analysis phase), which will be introduce, together with the test environment, in the next sub-section. After this we present the results obtained with the use case, covering quantitively savings and non-quantifiable insights, like the successful integration of grid state signals with local control in a realistic setup. Finally, we will provide a short conclusion on the results gathered within the use case.

3.8.2.1 Setup

The field testing site was a museum with approximately 30.000 visitors per year. The site provides a flexible exhibition setup with various topics, often from the energy domain. Figure 55 shows photographs of the testing sites outside, on the left, and a snapshot of an exemplary exhibition on the right. The site has a yearly energy consumption of 45.000 – 48.000 kWh and houses a 82 kWp PV system. The field test only covered a small portion of the site, which makes the actually achieved savings far below the consumption values given above.

Figure 55: Field testing site "Sonnenwelt", from the outsite (left) and from within an active exhibition (right)

The field test deployment contained four Smart Breakers and an Ethernet Communication Interface (ECI) to access them, a router, a Raspberry Pi 3 including a touch display, four motion detectors, an air quality sensor and a manual switch that can be used by human operators to trigger the system. Figure 56 shows photographs of these physical components and, in case of the Smart Breakers, the ECI and the router their enclosed housings.

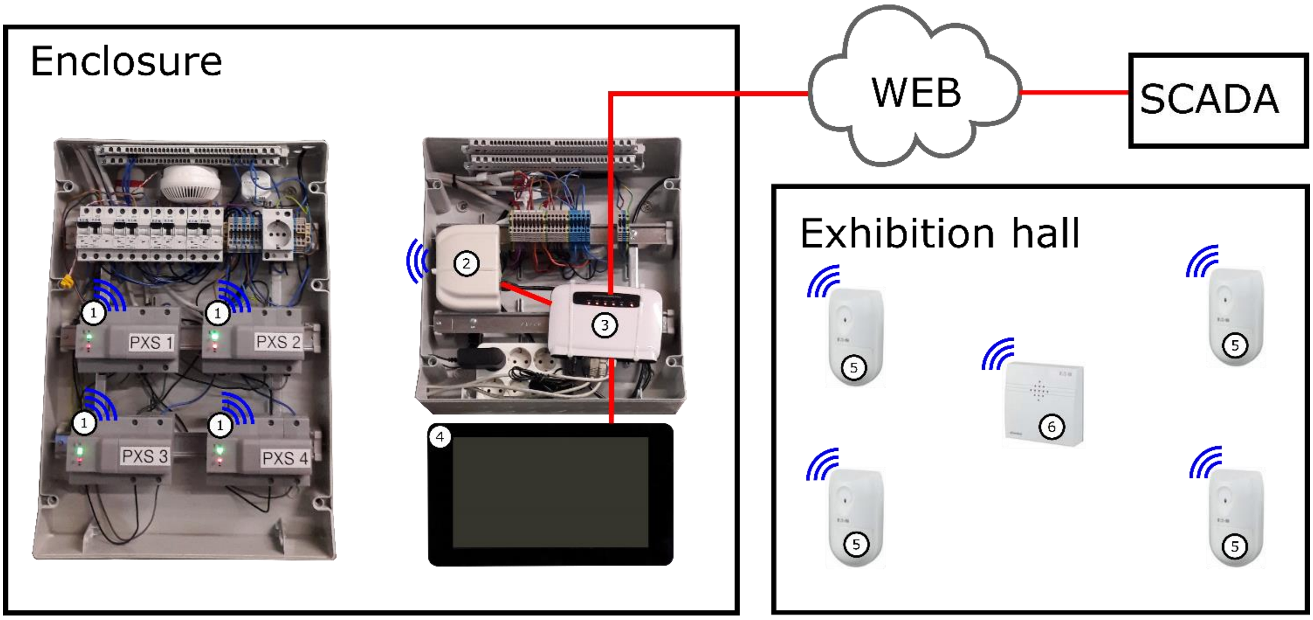


Figure 56: Field test setup: (1) Smart Breakers, (2) Ethernet Communication Interface, (3) router, (4) Raspberry Pi, (5) motion detector, (6) air quality sensor

In addition to the iniGrid prototype hardware, some dedicated metering equipment was deployed, one month ahead of the field test, to provide base line measurements to compare against. The dedicated metering equipment was also used to determine the consumption savings presented in the next subsection and, utilizing analysis and and simple visualization like the one provided in Figure 57, the gathered metering data was also used during the testing phase to help debug the system in case of problems.

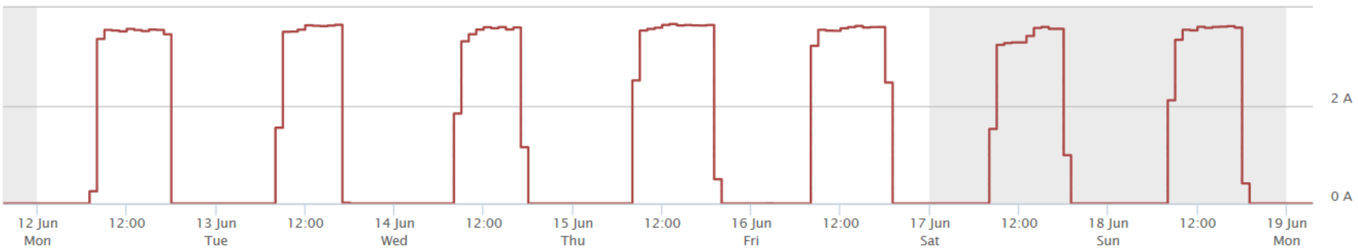


Figure 57: Exemplary visualization of the power ventilation systems power consumption during baseline measurements

The field test setup was completed with a laptop and some secondary communication equipment that allowed remote deployment of new software versions and enhanced debugging support, for example in form of a package sniffer for the radio communication between devices.

3.8.2.2 Field test use cases

The field test was divided into three use cases, illustrated in Figure 58.

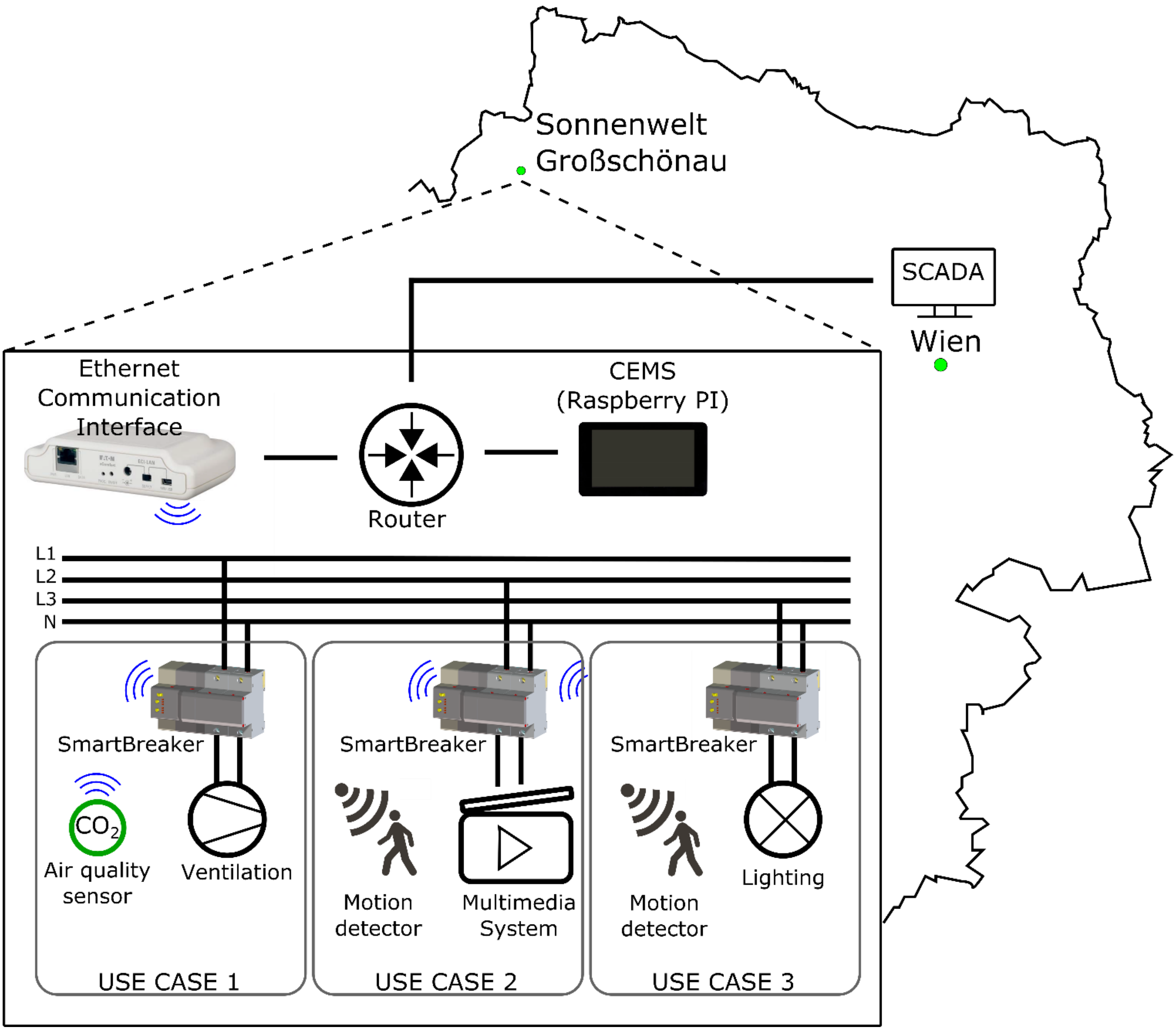


Figure 58: Field test setup [16].

The first use case defined new control requirements for the ventilation system:

1. Ventilation based on a binary signal from a movement sensor
2. Ventilation triggered by human operator in case of emergency
3. Configurable daily operation periods (deactivating the system outside of museum hours)
4. Air quality based ventilation
5. Maximum down-time specification to avoid “stale air”
6. Configurability of the threshold and various running times.
7. Integration with the traffic light system from a remote SCADA

Point 7. specifies a simple proof of concept that intends to show that the local control algorithms developed for the CEMS prototype can successfully interact with grid state information provided by a SCADA, which could be easily replaced by a primary or secondary substation using the same communication protocols.

The second use case specified the control of various multimedia instalments in a single zone of the museum. The goal in this use case was to enable the equipment only on demand, i.e. when visitors where near that could have observed the presentations. During instalment, it turned out that the start-up time of some devices was up to 30 seconds, which required the extension of the activation radius from the current zone to the three neighbouring zones. To determine activity in the zones, movements sensors from the existing light-control system need to be integrated with the CEMS prototype.

The third use case specified the control of the lights in a single zone of the museum. Unexpected difficulties regarding the museum cabling strategy resulting in this use case requiring additional movement sensors instead of using the already available movement sensors on site.

3.8.2.3 Results

All three of the above introduced use cases showed good results. An overall comparison of baseline consumption and the improved consumption is given in Figure 59.

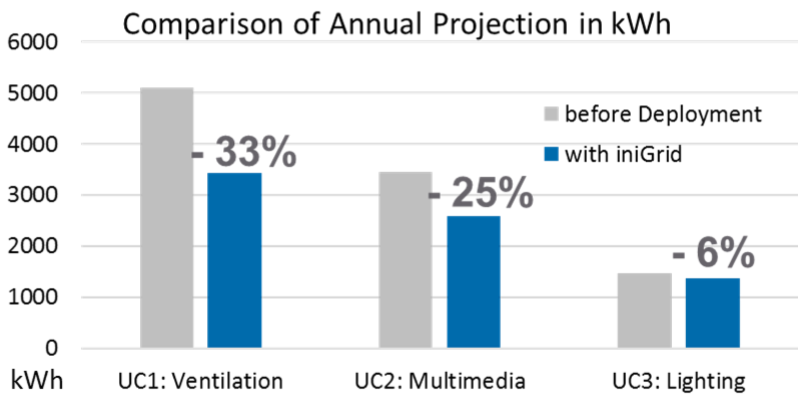


Figure 59: Comparison of projected annual energy consumption with and without CEMS

As the comparison graph shows, the consumption reduction varies strongly from use case to use case.

Ventilation use case: the ventilation use case provided the best performance increase. This result was expected as the baseline strategy for ventilation at the testing site was permanent ventilation during the operating hours of the museum. Introducing the various additional control trigger, also explained in more detail in Deliverable 6.1 in section 7.3 Grid Communication Core Implementation. During the test period the use case did prove the hardest to configure however, since the various parameters of the control, e.g. the threshold of measured air quality that would trigger ventilation and the different ventilation lengths, need to be adjusted to the demands on site, which where only observable while the exhibition was visited. It therefore required use a few feedback rounds from the local guides, regarding the air quality during visits, before the optimal settings where identified. Please note that the settings where deter-mined defen-sively, starting with a lower level and then increased, we therefore do not consider the measured savings skewed by having been take during time of bad air quality. Furthermore, in cases of air quality violations, the local guides where provided with an emergency ventilation option that they could trigger manually. We do not provide air quality measurements of the deployment site, since the data would not be comparable to other air quality measurements, but was only used to specify a threshold that fits the actual sensor deployment (which does not directly translate to a comparable value for CO2). For these reasons we also did not perform any baseline measurements for air quality.

Multimedia use case: the multimedia use case showed a good reduction in energy consumption, which is based on an improvement similar to the ventilation use case. The baseline multimedia strategy was also permanent enabling of the equipment during exhibition hours. The implementation of this use case pro-vided the additional challenge that the used equipment required 30 to 60 seconds to start up, which we countered by widening the trigger area for the equipment to neighbouring zones. Using more specialized multimedia equipment with shorter start up times could improve these results further.

Lighting use case: the lighting use case only showed a slight improvement in energy consumption, which is easily explained by the fact the baseline control strategy is identical to the strategy implemented during the field test. In Both cases, the lights are triggered by strategically placed motion sensors. We still consider this result important, as it shows that our approach can measure up to currently available commercial building automation system, as the one used in Großschönau during the baseline period. The slight con-sumption improvement visible in Figure 59 is owed to the slightly tighter timings implemented in the CEMS, in comparison to the values used in the field test setup.

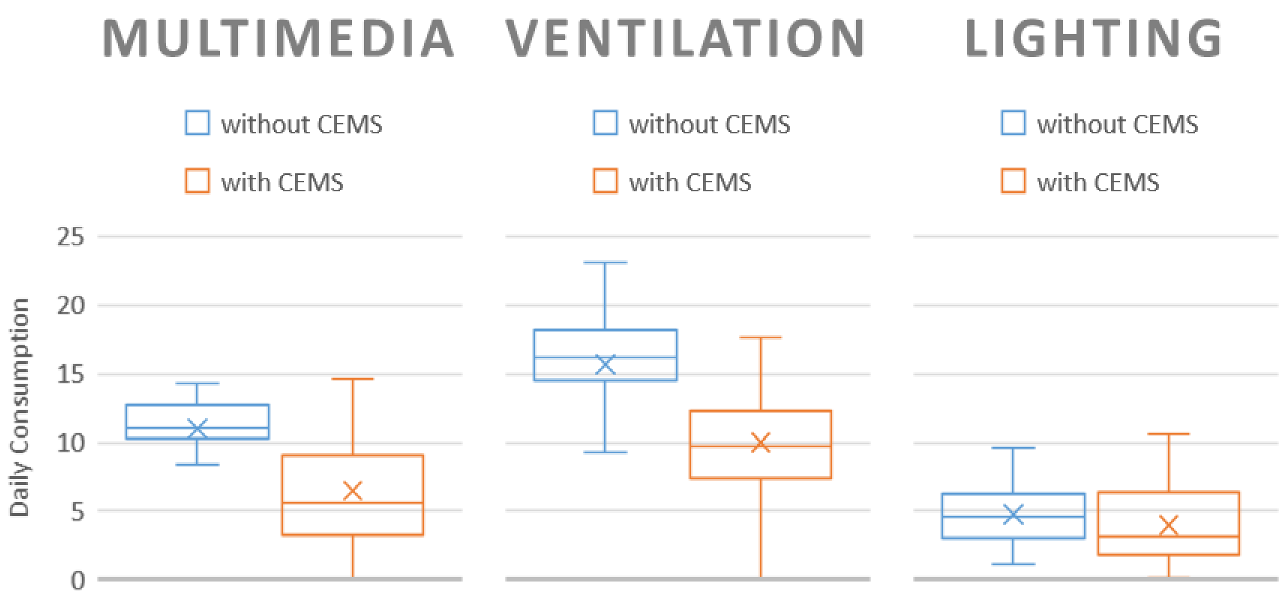


Figure 60: Daily consumption with and without CEMS

Figure 60 shows a more detailed analysis of the measured consumption data during both, the baseline and the testing period. This illustrates how the measurements cover a wider range of values during the testing period, since the strategies use where more elaborate and adapted better to the actual activity times of the exhibition and since the museum does not have constant visitor flow, the new strategies result in a much stronger variation of values. Please note, that the values in Figure 60 only represent measurements taken on days where the exhibition was open for visitors.

3.8.3 Air-insulated switch gear test (Medium Voltage Sensor)

In the iniGrid project it was planned to simulate and test the capabilities of the new medium voltage sensor for air-insulated switch gears. Therefore, a reconstruction of an existing air-insulated switch gear has been equipped with the new medium voltage sensors as well as with already existing current sensors of ZELISKO GmbH. A picture of a real switch gear is shown on the left side in Figure 61, the recreated switch gear, already equipped with the sensors is shown on the right side of Figure 61.

Figure 61: Real switch gear in Linz, Upper Austria (left), iniGrid switch-gear replica (right)

The model of the transformer station was based on real stations in Linz, in particular, the same dimensions are used and a real circuit breaker was integrated. Two important aspects had to be considered within the construction phase:

1. The rack needed to be mechanically stable. It had to carry the weight of the components (disconnector, voltage sensor, cables, etc.) and to withstand the electrical forces in case of short circuits.
2. The cell had to be similar to the original construction in a representative transformer station in Linz to get significant results (comparable to the situation in Linz) from the experiments. Exterior influences like capacitances to the surrounding walls and components needed to be as similar to the actual situation as possible.

The new developed medium voltage sensors were mounted – one for each of the three phases in addition to existing post insulators, not directly at the switching mechanic. The voltage sensors were contacted to the switches by means of separate, additional busbars. In addition, a current sensor for earth fault detection was mounted on the middle phase of the replica of the switch gear.

In combination with the automation infrastructure of Sprecher Automation, the voltage has been measured without any influences (as baseline) and during an artificial earth fault afterwards.

In order to validate the practical functionality and accuracy of Zelisko's medium voltage sensors, a test case has been specified that concerns earth-fault detection. This test case has been chosen as it is a classical use-case in distribution grid automation and at the same time challenges high accuracy from the measuring equipment. Therefore, the aforementioned switch gear rack has been used within AIT's SmartEST Lab, adding a prototype of Sprechers distribution automation system "EDIR" together with Zelisko's voltage and current sensors. These ingredients finally built up the setup for the test case. Also, for these investigations there is practically no difference between a test in the laboratory vs. tests in a real power-grid (e.g. from Linz AG), while creating an earth fault is indeed only feasible to be done within the lab. Hence, this test case is perfectly suited to be performed in the SmartEST lab.

The test-setup is summarized in Figure 62: Test setup., showing the overall topology of the simulated grid together with the added components for measurement and automation.

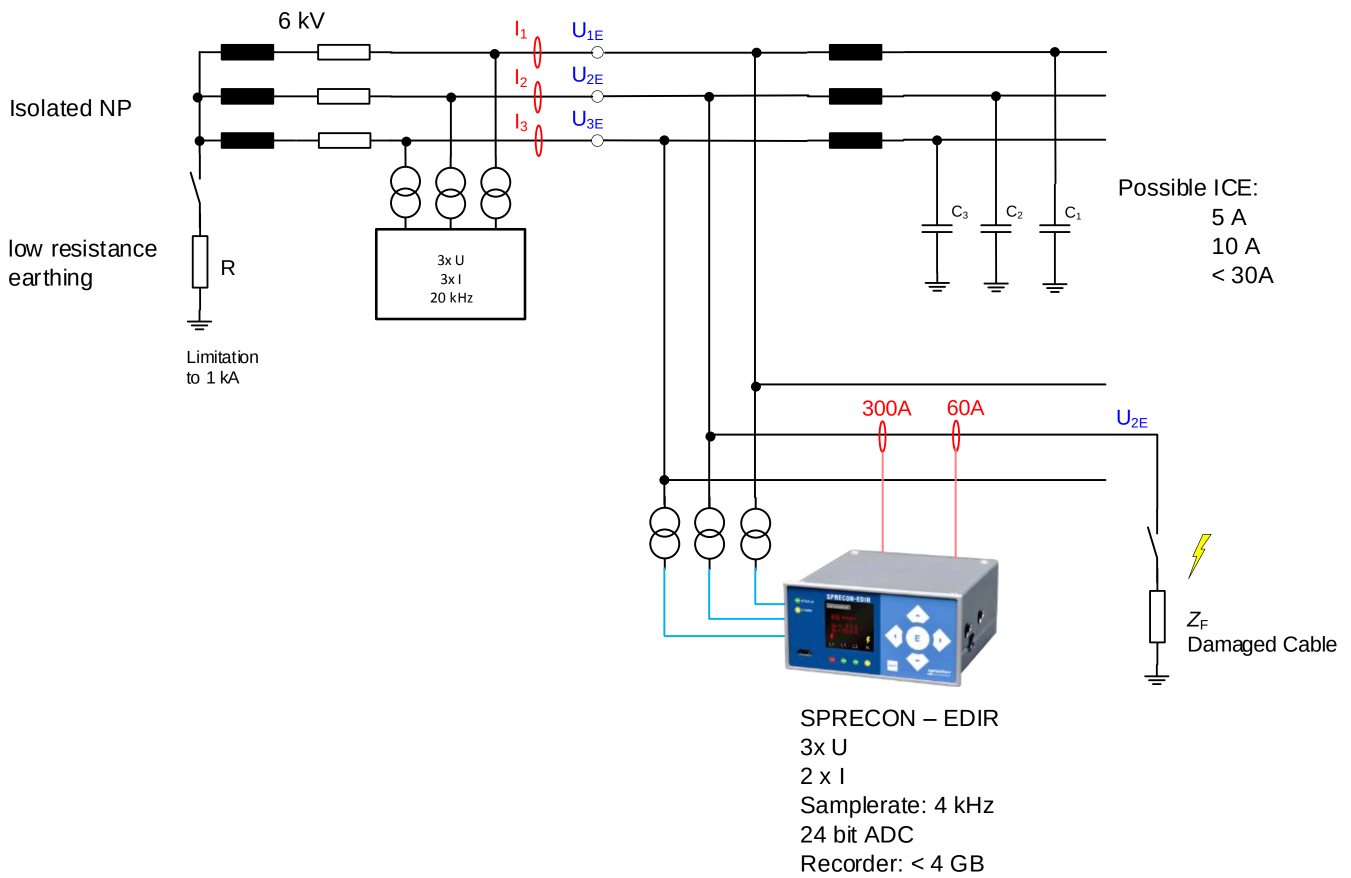


Figure 62: Test setup.

These practical test validations clearly showed the power of the developed iniGrid components in order to be used in distribution automation. Exemplarily, the validation proved the capability of the developed measurement system to correctly identify earth-faults. This use-case is not only very challenging to the developed sensoring and measurement equipment but is also of increasing importance to future distribution grids. As the share of cables continuously increases in distribution grids due to decentralization, the occurrence of earth-faults is expected to increase as well. Hence, this is a very important validation use-case for future smart grid control systems.

3.9 Cost/Benefit Analysis

Within the iniGrid project also the economic impact of developed sensor and actuator components on the cost/benefit ratio of smart grid approaches for renewable system integration as well as efficiency increases were analysed. Therefore, all IniGrid use cases were economically rated for achievable cost and benefits and compared to conventional solutions without implementing developed iniGrid technology. Accordingly, all investments of each solutions were calculated as yearly cost (annuities) considering a specific evaluation period, interest and price change rate.

4 Conclusion

Within the project iniGrid, new innovative sensors and actuators were developed, validated in simulation and in various laboratory tests, and eventually deployed in a realistic environment in field trials. The highlight of the project was the so-called Smart Breaker, combining the function of several independent devices into one single device. The second innovative component was the medium voltage sensor which can be easily retrofitted into existing infrastructure. Additionally, necessary software components were developed in the project, in particular, a load shift algorithm, an entire Customer Energy Management System with local intelligence, etc. Existing devices (e.g., Sprecher IT solutions) have been modified to fulfil the requirements of the new devices. To enable the deployment of the new software and hardware component, a future-proof automation architecture has been defined, a risk analysis has been performed, and an efficient rollout concept has been evolved. Last but not least, several use cases were investigated in the project – some of them in simulation, others in lab validation and in the field – and a cost-benefit analysis was performed, showing a high monetary potential for the application of the new and innovative components.

Based on performed cost / benefit analyses (see also chapter 3.9) selected results are shown in the following figures, at medium voltage level possible cost saving effects were analysed for a theoretical implementation of iniGrid technology in the performed field tests of the research project DG DemoNetz Validierung[2]. As can be seen in Figure 63 for the Vorarlberg (Großes Walsertal) case cost savings of up to 57% referred to the original results seem possible for the implemented DG connection scenarios. This is mainly due to lower MV sensor cost (see developed Zelisko Sensor), lower space requirements in the station as well as lower operational cost. Furthermore, communication asset cost could be much lower due to an expected lifetime of 20 years of the Sprecher system (compared to 10 years in DG Demonet Validierung).

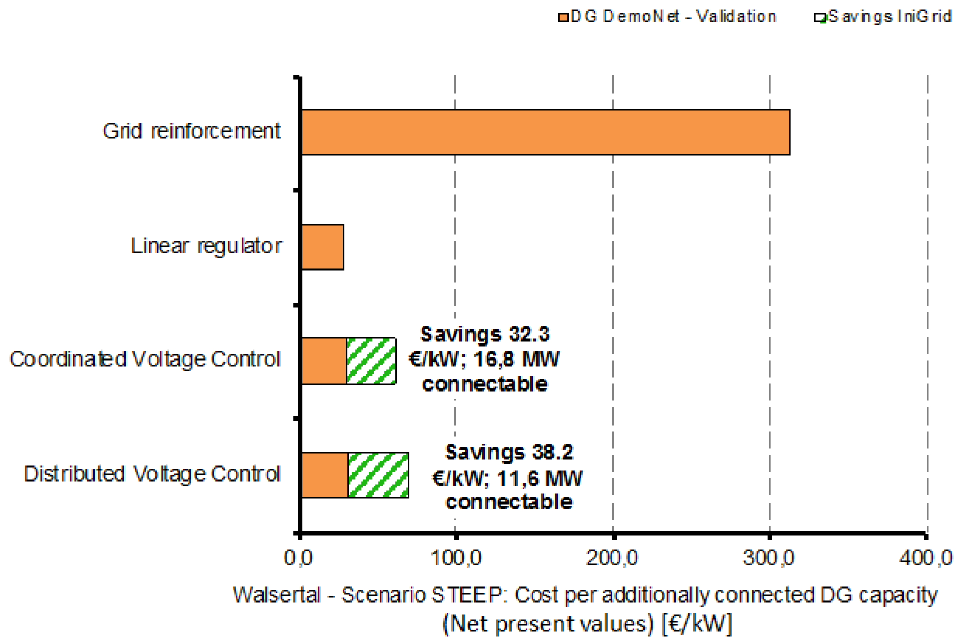


Figure 63: Results of economic evaluation for Use Case C – Großes Walsertal scenario STEEP

[2] See https://www.ait.ac.at/themen/smart-grids/projects/dg-demonetz-validierung, last visited 16.5.2018

At low voltage level, results of the performed iniGrid Field test in Großschönau show, that the developed technologies could offer a positive cost-/benefit ratio at commercial appliances. As can be seen in Figure 64 the yearly surplus of achieved electricity consumption savings (2636 kWh realised in field test) lies at approximately 140 € if the Eaton Air sensor is not considered. On contrary, the yearly loss for a conventional realisation of the implemented energy efficiency measures (control of Multimedia, Lightning and Ventilation installations at the exhibition area in Großschönau with total consumption of 12.2 MWh/yr) would be around 330 Euros. The Break-Even point lies at 1760 kWh/yr for the iniGrid solution (see Figure 65). These values increase to 1900 kWh/yr if the Air Sensor is considered.

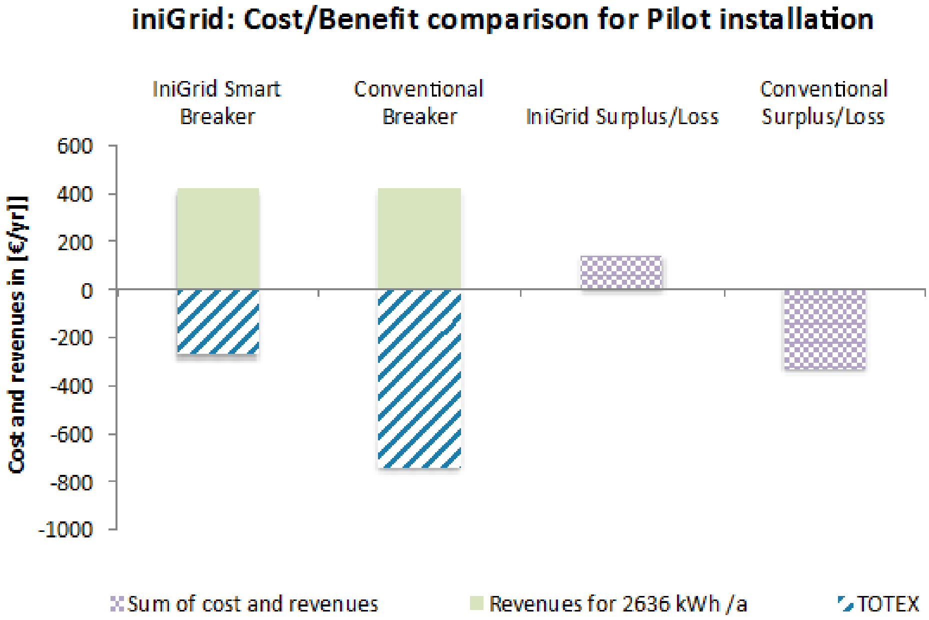


Figure 64: Results of economic evaluation for the iniGrid field test

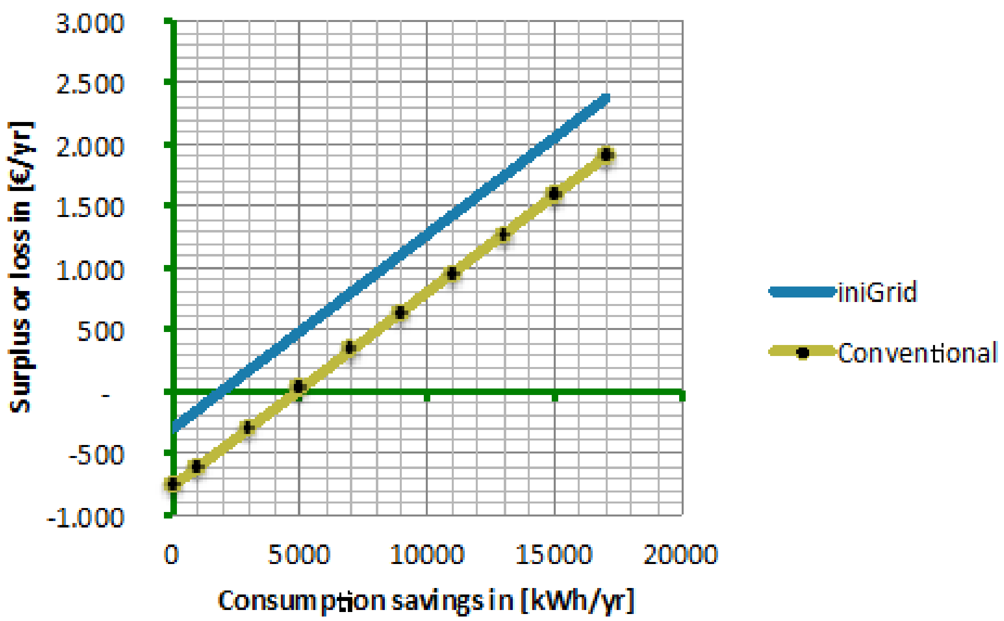


Figure 65: Results of break-even analysis of the iniGrid field test

In general, developed iniGrid technology offers significant cost reduction potentials compared to currently available solutions. From Smart Grid perspective, iniGrid technology offers a further tool to increase the efficient utilization of existing AC as well as future DC infrastructures. Furthermore, derived economic project results lead to the following findings:

- iniGrid technology can already be economically feasible at selected fields of application (e.g. Smart Breakers in commercial appliances as in Sonnenwelt Großschönau).
- The developed technologies offer space requirement (mainly Smart Breaker), component lifetime (Sprecher IT solution) and operational cost advantages (all iniGrid technology) which have significant positive economic impacts. Accordingly, iniGrid technologies could avoid grid reinforcements more easily.
- The developed Sprecher IT solution seems to be more applicable for high power use cases (e.g. at industrial or Medium Voltage level).
- At domestic level, the developed Raspberry Pi systems work well and at low cost. However, if license cost for the implemented software are applicable, economic benefits are reduced significantly. Even more, In-Home-Displays and Smartphone Applications increase the necessary revenues (to reach break-even point) by approx. 10% within the analysed case studies.

The applicability of iniGrid technology in Medium and Low Voltage grids however depends on the existing grid capacity, location & rated power of loads / generation. Also, the grid age plays a central role. Thus, the derived project results cannot be generalised.

5 Exploitation

The consortium expects the new technologies as base for future grids and new developments. With the aid of this project, the next level of electric power distribution technology could be explored. The development of the Smart Breaker led to a lot of recognition within Austria but also outside the borders. A huge set of IP was created which will be used for securing future investment. The Smart Breaker could be part of new DC-applications. Especially in applications with battery storage, new possibilities arise, which could be investigated in further research projects. Several lab-tests as well as the integration of the Smart Breaker in the field validation in Sonnenwelt Großschönau showed the correct functionality and behaviour of the device, as well as the straightforward installation process within existing infrastructure.

Within this project it was shown that it is feasible to implement medium voltage resistive dividers in structures which are similar to regular post insulators. Furthermore, it was shown that it is possible to handle the parasitic capacitances. Therefore, with optimizations in design and components, depending in customer requests, the medium voltage sensor is a solution for the monitoring of medium voltage in air insulated switchgears. This air-insulated voltage sensor is suitable as original equipment and for retrofitting of air-insulated switchgears. The sensors don’t have to be calibrated, because the output signal (acc. to IEC60044-7) is guaranteed over the lifetime. Innovative design eliminates ambient influences from electrical and magnetic fields.

The involvement and development of the Customer Energy Management System, being able to run on a low-cost hardware as the Raspberry Pi, enabled to involve and encourage students to participate in the field of Smart Grids. The construction of the portable prototype, being able to run on its own by nearly a plug and play principle, enabled the exploration at various sides, exchange the board with the partners, as it has happened for the security analysis, plus enabled the dissemination of the iniGrid project at many events in an interactive way. The choice of the usage of the OpenMUC framework enabled to develop a reliable and powerful tool to control loads, while receiving commands from a Supervisory Control And Data Acquisition system or third party controllers, as it has been validated by the fruitful cooperation with the consortium partners during the carried out tests in lab and field.

A comprehensive generic framework was developed for the simulation (load-flow analysis) of low voltage grids, involving the new hardware technologies as well as the consideration of new algorithms for load shifting, activating of flexibilities etc. This framework was used to investigate future grid situations and can be re-used in other research-projects.

The implementation of the domestic smart grid demonstrator has brought new insights and tools for the development in this area. Moreover, students can develop new laboratory practices and teachers introduce this on their curriculums. Concerning the interactive smart grid demonstrator, it presents the opportunity to introduce smart grid concepts and technologies developed by iniGrid in a comprehensible way to public

During the project it was possible to collect valuable experience in cost-/benefit relations of developed components and field test settings. Thus, a widened consulting product portfolio is available for future activities – on one hand for clients searching for energy efficiency increases and on the other hand for DSOs and energy providers in the area of Smart Grids.

6 References

[1] M. Faschang, M. Nöhrer, J. Stöckl und F. Kupzog, „Extensible co-simulation framework for electric vehicle charging infrastructure testing," in *Smart Grid Communications (SmartGridComm), 2014 IEEE International Conference on*, 2014.

[2] F. Kupzog, R. Schwalbe, W. Prüggler, B. Bletterie, K. Serdar, A. Abart und M. Radauer, „Maximising low voltage grid hosting capacity for PV and electric mobility by distributed voltage control," *e & i Elektrotechnik und Informationstechnik,* pp. 188-192, 2014.

[3] M. Stifter, R. Schwalbe, W. Tremmel, B. Bletterie und H. Brunner, „Experiences of Coordinated Volt/Var Control Algorithm for Medium Voltage Networks with High Share of Distributed Generation," in *Innovative Smart Grid Technologies (ISGT Europe)*, 2012.

[4] R. Eichler, „Next generation network analysis applications for secure and economic integration of distributed renewable generation in distribution grids," in *22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013)*, 2013.

[5] Smart Grid Coordination Group, „Smart Grid Reference Architecture," Eur. Comm. Stand. Bruss. Belgium, 2012.

[6] NIST, „NIST IR 7628 - Guidelines for Smart Grid Cyber Security - Volume 1 - Smart Grid Cyber Security Strategy, Architecture, and High-Level Requirements," 2014.

[7] Österreichs Energie, „Anforderungskatalog Ende-zu-Ende Sicherheit Smart Metering," Wien, 2014.

[8] F. Cleveland, „IEC 62351 Security Standards for Power System Information Infrastructure," 2012.

[9] M. Uslar, C. Rosinger und S. Schlegel, „Security by Design for the Smart Grid: Combining the SGAM and NISTIR 7628," in *Computer Software and Applications Conference Workshops (COMPSACW), 2014 IEEE 38th International*, Vasteras, Sweden, 2014.

[10] International Electrotechnical Commission (IEC), „Power systems management and associated information exchange - Data and communications security - Part 10: Security architecture guidelines," Gneva, Switzerland, 2012.

[11] SPARKS consortium, „D2.2 Threat and Risk Assessment Methodology," 2015.

[12] Bundesamt für Sicherheit in der Informationstechnik, „IT-Grundschutz-Kataloge," Bonn, 2016.

[13] F. Pötscher, R. Winter und G. Lichtblau, Elektromobilität in Österreich Szenario 2020 und 2050, Wien: Umweltbundesamt GmbH, 2010.

[14] B. B. d. E.-. u. W. e.V., „BDEW Roadmap - Realistic Steps for the Implementation of Smart Grids in Germany," BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., Berlin, Germany, 2013.

[15] P. Widhalm, Y. Yang, M. Ulm, S. Athavale und M. C. González, „Discovering urban activity patterns in cell phone data," *Transportation,* pp. 597-623, July 2015.

[16] W. Hauer, S. Kollman und S. C. Wilker, „Low-voltage grid automation - Lessons learned during field tests Großschönau, Austria. Impulses from project iniGrid," in *ComForEn 2017*, Haus/Ennstal, Austria, 2017.

[17] „SGAM Toolbox," 2014. [Online]. Available: http://en-trust.ad/downloads/sgam-toolbox/.

7 Further dissemination activities

7.1 Conference contributions

1. Stephan Hutterer, Johann Meindl, Wolfgang Hauer, Friederich Kupzog: "Secure Integration and Rollout of IEC 61850-Based Smart Components in Secondary Substations Within the iniGrid Project"; The 23rd International Conference and Exhibition on Electricity Distribution (CIRED 2015), 15.-18.06.2015.
2. Marcus Meisel, Evangelia Xypolytou, Alexander Wendt: "Ergebnisquerschnitt durch ausgewählte Smart Grids Projekte"; 14. Symposium Energieinnovation (IEWT 2017), Graz, Austria, 10.-12.02.2016.
3. Georg Kienesberger, Stefan Wilker, Alexander Wendt, Marcus Meisel; "iniGrid – Integration von innovativen verteilten Sensoren und Aktuatoren in Smart Grids"; 10.-13.05.2016 Smart Grids Week, Linz, Austria.
4. Marcus Meisel, Stefan Wilker, Matthias Wess, Alexander Wendt, Thilo Sauter: "ICT Emulation Platform Setup Demonstration of Smart Grid Component Prototype Examples", 21st IEEE International Conference on Emerging Technologies and Factory Automation ETFA 2016, 6.-9.09.2016, Berlin, Germany.
5. Marcus Meisel, Stefan Kollmann, Stefan Wilker, Alexander Wendt, Lampros Fotiadis, Friedrich. Bauer, Georg Kienesberger, Demo Abstract: Demonstration of new sensor and actuator equipment for distributed grids, Computer Science - Research and Development, Springer-Verlag, Berlin-Heidelberg, 2017, S. 1 - 3.
6. Marcus Meisel, Stefan Wilker, Stefan Kollmann, Alexander Wendt, Lampros Fotiadis: "Smart Breaker Prototypes and Customer Energy Management System for the Smart Grid"; Microelectronic Systems Symposium MESS 2018, 12.-13.4.2018, GMS Gesellschaft für Mikroelektronische Systeme im OVE, Vienna, Austria; ISBN: 978-3-903249-01-0
7. Stefan Kollmann, Marcus Meisel, Stefan Wilker, Thilo Sauter: „Using Smart Breakers for Demand Side Management in Smart Grids", (accepted, to be published in:) The 27th IEEE International Symposium on Industrial Electronics 12-15 June 2018, Cairns, Australia
8. Wolfgang Hauer, Michael Bartonek: "A Novel Low Voltage Grid Protection Component for Future Smart Grids"; 51st International Universities Power Engineering Conference UPEC 2016; 6.-9. Sept. 2016; Coimbra, Portugal; 978-1-5090-4650-8.
9. Mark Stefan: "iniGrid – A brief description of the main activities and project goals"; 5th D-A-CH+ Energy Informatics Conference 2016; 29-30.09.2016; Klagenfurt, Austria; ISBN: 978-3-85133-090-8.
10. Mark Stefan: "iniGrid – Integration of innovative distributed sensors and actuators in smart grids"; 5th D-A-CH+ Energy Informatics Conference 2016; 29-30.09.2016; Klagenfurt, Austria.
11. Nathalie Prüggler, Friederich Kupzog: "Ergebnisse der ökonomischen Bewertung ausgewählter iniGrid Technologieanwendungen"; 10. Internationale Energiewirtschaftstagung; 15.-17.02.2017; Wien, Austria.

12. Wolfgang Hauer, Michael Bartonek, Mark Stefan: "iniGrid – Smart Breaker: An Innovative Component for Future Low Voltage Power Distribution"; Smart Energy Systems Week Austria 2017; 15.-19.05.2017; Graz, Austria.
13. Oliver Jung, Stephan Hutterer, Mark Stefan, Ewa Piatkowska: "iniGrid – Novel Smart Grid Applications Security Aspects and Rollout-Concept"; Smart Energy Systems Week Austria 2017; 15.-19.05.2017; Graz, Austria.
14. Mark Stefan, Wolfgang Prüggler: "iniGrid – Integration of Smart and Innovative Components into Distribution Grids"; Smart Energy Systems Week Austria 2017; 15.-19.05.2017; Graz, Austria.
15. Alexander Wendt, Stefan Kollmann, Marcus Meisel, Stefan Wilker, Mark Stefan: "iniGrid – Local Intelligence for Active Customer Energy Management Systems"; Smart Energy Systems Week Austria 2017; 15.-19.05.2017; Graz, Austria.
16. Kenan Askan, Michael Bartonek, Fabio Brucchi, "Comparison Between 1200V 5th Generation SiC MPS Diode and Silicon Power Diode in DC/AC Hybrid Circuit Breaker", Proceeding of PCIM 2017, pp. 824–831, Nuremberg, Germany, 2017
17. Wolfgang Hauer: "Technologiesprung in der Energieverteilung: Halbleiter-basiertes Schalten, Schützen und Messen von Stromflüssen – Projekt iniGrid"; Smart Energy Systems Week Austria 2017; 15.-19.05.2017; Graz, Austria.
18. Stefan Kollmann, Stefan Wilker, Marcus Meisel, Alexander Wendt, Lampros Fotiadis, Thilo Sauter: "Local Intelligence for a Customer Energy Management System equipped with Smart Breakers"; 13th IEEE International Workshop on Factory Communication Systems; Communication in Automation (WFCS 2017), 31.05-02.06.2017, Trondheim, Norway.
19. Mark Stefan, Paul Zehetbauer, Khalil Hamad, Andres Moreno, Wolfgang Prüggler, Roland Sperr: „Simulation-based Cost-Benefit Analysis for Innovative Components in Low Voltage Grids"; Workshop 2018 on Microgrids and Local Energy Communities (CIRED 2018), 07.-08.06.2018, Ljubljana, Slovenia.
20. Khalil Hamad, Andres Moreno, Peter Zeller. "Smart grid demonstrator for a household with active load management"; Communications for Energy Systems ComForEn 2017, 05.-06.10.2017, Haus/Ennstal, Austria.
21. W. Hauer, S. Kollmann and S. C. Wilker, "Low-voltage grid automation - Lessons learned during field tests Großschönau, Austria. Impulses from project iniGrid", ComForEn 2017, 05.-06.10.2017, Haus/Ennstal, Austria.
22. Khalil Hamad, Andres Moreno, Peter Zeller. "iniGrid smart grid interactive demonstrator"; World Sustainable Energy Days (WSED), 01.-02.03.2018, Wels, Austria.
23. Kenan Askan, Michael Bartonek, Klaus Sobe, "Surge Current Capability of IGBTs used in Low Voltage Hybrid Circuit Breaker", Proceeding of CIPS, Stuttgart, Germany, 2018 (to be published)
24. Kenan Askan, Michael Bartonek, Klaus Sobe, "Design and Development of an Integrated Power Module Used in Low Voltage DC/AC Hybrid Circuit Breaker", Proceeding of PCIM, Nuremberg, Germany, 2018 (to be published)

7.2 Interactive smart grid demonstrator

The main aim of this demonstrator is the development and implementation of an interactive smart grid console that offers an interactive explanation of how grids work and introduces new state of the art technologies in the field of smart grids developed by the project. The demonstrator aims to serve both people involved in energy sectors as well as the general public. This demonstrator introduces a simulated distribution grid that contains residential and industrial areas, a photovoltaic plant and a wind farm. The demonstrator shows the power flow and direction in the network lines, the amount of generation from renewable sources and the amount of consumption in the residential and industrial areas. The simulation reflects the network status in different seasons and days by changing the time of the day in an accelerated manner where every 15 minutes in the grid is about 3 seconds in real-time. The status of the grid at any given time is reflected based on the traffic light model. In this demonstrator, the user can interact and control all these different components of the grid to see how changing them affects the grid and how smart grids can be used to help balance the grid.

Figure 66: Interactive smart grid demonstrator overview

The demonstrator contains software models that reflect the simulated grid, user input and visualization hardware. The different components can be seen in (Figure 66) where the users can interactively control the PV production with a cell phone light, control the wind generation by blowing in a small fan, activate the smart grid mode with the Smart Breaker switch and use a touch screen to change the season and the load consumption.

This demonstrator was presented first at the Ars Electronica Festival 2017 in Linz. After this event it was transferred to the Welios Science Center (Wels) and integrated in the exhibition for about two months. At the end of the iniGrid project, the demonstrator was moved and integrated into the exhibition in Sonnenwelt Großschönau where it is still available for the visitors.

8 Appendix

- D2.1 – Cost/benefit analysis and economic performance of iniGrid.
- D4.1 – Secure automation network architecture
- D6.1 – Set of smart grid functionalities

Further documents can be requested at the consortium (contact in Section 9).

9 Contact

9.1 Project Management

DI Dr. Mark STEFAN
Research Engineer
Electric Energy Systems
Center for Energy

AIT Austrian Institute of Technology GmbH
Giefinggasse 2 | 1210 Vienna | Austria
T +43 50550-6640 | M +43 664 88964900
mark.stefan@ait.ac.at | www.ait.ac.at

9.2 Project Homepage

www.inigrid.at

9.3 Project Consortium

- AIT Austrian Institute of Technology GmbH
- Eaton Industries (Austria) GmbH
- Infineon Technologies Austria AG
- Zelisko GmbH
- Sprecher Automation GmbH
- Technische Universität Wien – Institut für Computertechnik
- Fachhochschule Oberösterreich – F&E GesmbH
- Linz Strom Netz GmbH
- MOOSMOAR Energies OG