

## SIMULATION-BASED COST-BENEFIT ANALYSIS FOR INNOVATIVE COMPONENTS IN LOW VOLTAGE GRIDS

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### ABSTRACT

*The steadily increasing number of distributed renewable energy sources as well as the integration of high loads such as heat pumps or charging procedures of electric vehicles in low voltage grids could cause significant peaks in the power domain – either in generation or consumption – or voltage constraints might be violated. New and innovative components like the Smart Breaker in cooperation with high performant software algorithms could be used to keep the grid within the specified borders. In this paper we introduce a methodology to support the adherence of limits on one hand and show the economic benefit of using the new technologies in contrast to grid reinforcement in two low voltage grids in Linz (Austria) on the other hand.*

### INTRODUCTION

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. In this paper we present an outlook for the next two decades assuming an increase of installed PV-power, heat-pumps, and electric vehicles in two dedicated low voltage grids in Linz, Austria. We show the impact on loading values of the grid infrastructure and potential violations in the voltage domain based on Monte Carlo Simulations. Therefore, realistic power profiles for the grid components are generated on a daily base, distinguishing between residential and commercial areas, seasons, and weather. The load flow calculations are done via quasi-dynamic simulations.

By integrating innovative sensor and actuator components like the so-called Smart Breaker [1] – developed in the Austrian research project *iniGrid* [2] – as well as the combination of central and distributed energy management systems, we present methods for avoiding violations that increases the grid's hosting capacity without traditional grid reinforcements. The paper introduces a traffic light model approach for a very efficient communication of grid information and controlling domestic loads. In addition, a domestic load shifting algorithm based on features of the Smart Breaker is

presented to demonstrate the benefits of using such components.

To show the positive monetary effects of integrating the innovative software and hardware components – installation and maintenance costs on one hand versus grid expansion on the other hand – cost-benefit analysis' are performed for the scenarios and the results are presented.

### FRAMEWORK

Whenever new technologies want to enter a market, the benefits and necessities need to be investigated. The Smart Breaker is one of such technologies, enabling the control of electrical loads and generators by shifting, switching, or scaling power values.

To investigate the impact of this new technology interacting with new algorithms, several simulations are executed – the base scenario represents the actual situation, future scenarios are defined by many assumptions, explained in detail later.

The implemented framework includes a network model, the used loads of the network are dependent on the scenario. Penetration of different technologies (photovoltaic-systems, heat pumps, electric vehicles) can be set and the Smart Breaker functionality together with load shift algorithms can be toggled on and off to investigate the influence of these technologies.

Figure 1 shows an overview of the investigation process, starting with the definition of scenarios and profile generation. The power profiles will be used in load flow calculations as base for comparison on one hand, and as input parameter for the load shift algorithm, generation of new profiles afterwards, and as input parameter for another load flow on the other hand. The results of both load flow calculations will be used as base for the economic analysis.

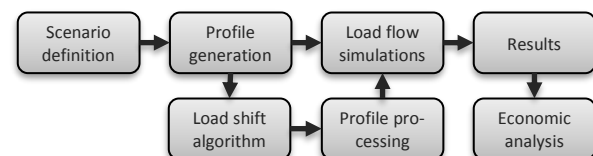


Figure 1: Overview of the investigation process, beginning at the definition of scenarios, followed by profile generation, load shift algorithms, and finally the economic analysis.

## Methodology

The framework is used to perform Monte Carlo based load flow simulations consisting of the following parts:

- i) Profile generation dependent on defined scenarios
- ii) Perform load flow calculations via quasi-dynamic-simulation in Power Factory
- iii) Analyze the created results

The analysis is based on a daily approach. One iteration of the Monte Carlo simulation represents one day.

## Grid topology

Two low voltage network models are used for the analysis, both located in Linz (Austria) with real consumption values available and used in the simulation.

1. *Residential area* representing a rural network with 28 residential customers, with two of them as farmers.
2. *Commercial area* representing an urban network with eleven commercial customers (including a railway station, office buildings, and others) and ten residential customers

## Power profiles

Based on the scenarios and assumptions for PV-penetration, the number of electric vehicles and heat pumps, new profiles are generated for all customers of the examined grids. The following types of load profiles are generated and used within the simulation.

**PV-element:** For the usage of a photovoltaic element, three different profiles are generated, based on recorded real generation data in Austria:

- i) Sunny day with maximum energy.
- ii) Partly cloudy day with 33 percentile energy value among all days.
- iii) Cloudy day with 66 percentile energy value among all days.

Additionally, these profiles are generated for summer, winter, and transition period, shown in Figure 2. Within the simulation the profiles are scaled according to the type of the node and the annual consumption, to have realistic generation values compared to the consumption.

**Heat pump:** Similar to the generation profiles of PV-elements, power profiles for heat pumps are created for three seasons and different weather conditions, based on recorded data from the field, also scaled according to the annual consumption.

**Electric vehicle:** Based on recorded data of charging cycles of several electric vehicles, typical charging strategies are identified and used for generating the power profiles. Residential nodes in the grid are expected to charge cars when people come back from work in the afternoon, whereas commercial nodes are expected to charge cars in the morning. Additionally, typical driving distances are assumed to have realistic energy demand when charging [3].

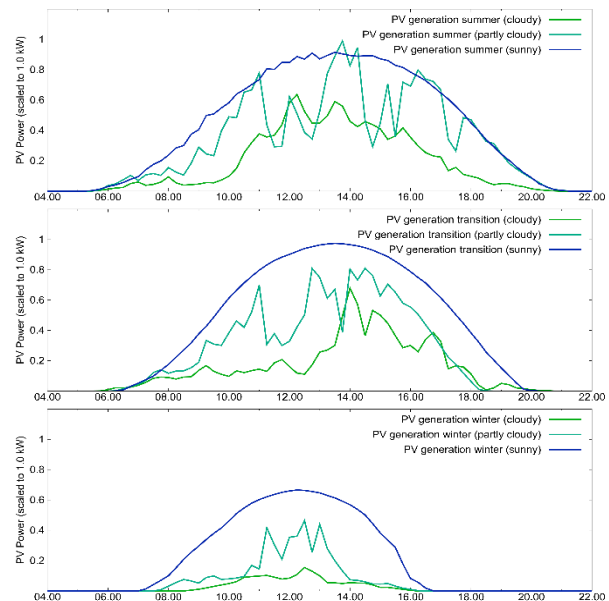


Figure 2: PV Power for summer, transition, and winter with a sunny day, a partly cloudy day, and a cloudy day in each season

**Base load elements:** The load elements represent common loads without any other technologies like heat pumps, electric vehicles, generation units, etc. The profiles are based on standard load profiles and scaled according to the annual consumption.

**Stochastic load behavior:** For the heat pump and electric vehicle elements, a random activation time shift via a kernel is introduced for the power profiles to cover a wider range in possible load situations 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  $\pm 3$  hours because people are supposed to arrive at home within this time span. Commercial customers have a peak at 8 a.m. and a possible time shift of  $\pm 1.5$  hour because people are supposed to arrive at work within this time span [4].

Heat pumps use a finite gaussian kernel. Some predefined profiles are shifted in time with  $\pm 2$  hours possible time shift. PV and base load elements do not make use of a random time shift.

## Scenarios

As already mentioned, the investigation process starts with a base scenario simulating the year 2017, followed by a look ahead in 2027 and 2037. Therefore, the following assumptions regarding the increase of energy demand and the number of installed devices are made.

- i) An increase of 2 % per year was assumed for all base load elements.
- ii) 30 % of all nodes will have a photovoltaic system and/or a heat pump in 2027 and 55 % in 2037<sup>1</sup>.

<sup>1</sup> These assumptions are based on the experience of *Linz Strom Netz GmbH*

- iii) 17 % of all nodes will have an electric vehicle in 2027 and 47 % in 2037 [5].

### Traffic light model as base for grid optimization

In our approach, a traffic light model is used to convey the electrical grid status. This model was introduced first in Germany by the German Association of Energy and Water Industries (BDEW) to reduce the need for grid expansions by means of network flexibility and smart grid concepts [6]. The proposed traffic light model refers to the network status during a specific period and in a specific network cluster and can be described using one of the following colors:

- i) *Green state*: No restrictions from the network.
- ii) *Yellow state*: Potential or actual network shortage or overload of network components occurred.
- iii) *Red state*: The network's stability has been compromised.

The grid status for each network cluster is generated based on the voltage and current/thermal constraints of the network as shown in Table 1. The status in addition to active power limits are generated based on the lowest voltage value in the grid cluster and the highest line loading percentage. The final cluster status and limits is then the worst case of the two.

Table 1: Traffic light model for voltage and current constraints

Grid status	Voltage constraints [p.u.]	Current constraints [loading in %]
Green	> 0.93	< 70 %
Yellow	0.93 - 0.91	70 % - 90 %
Red	< 0.91	> 90 %

The grid status and power limits are assumed to be received for every 15 minutes via local energy management systems in the customer premise. This intelligent component is responsible for load shifting based on the grid state. To decrease the effects of voltage and power fluctuations due to load shifting, a limit oscillation control algorithm is used with the following steps:

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

### Load shift algorithm

The goal of the shift algorithm is to optimize the local consumption by maintaining the grid operator's active power limits according to the grid status. Each customer receives the whole cluster's grid status from the grid operator. Next, a local limit is determined by the local energy management system based on the bus maximum consumption.

The power optimization problem is defined as an integer linear programming problem (ILP) as the power con-

sumption 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. No long-term forecast is considered here [7].

Decisions are made to operate or shift controllable loads (EV, HP) based on the grid status, uncontrollable loads and customer preference constraints are shown in Table 2. The main constraints and the shift window considerations are also explained. The car park time and temperature preferences of the building or apartment are assumed to be given to the local energy management system by the user.

Table 2: Controllable loads operation constraints

Load	Main constraint	Shift window
EV	Finish charging the EV within the shift window.	The shift window represents the EV parking time.
HP	Maintain the temperature within user's comfort zone.	The whole day, depending on user comfort.

The heat pump constraint was not directly based on the indoor temperature. Instead, it was simulated to operate the heat pump for as many times it operated in the base scenario, but in different time slots by segmenting the operation into intervals (maintaining the same energy, indoor temperature while allowing the shifting feature). The traffic light model is interpreted by the shift algorithm as follow:

- i) *Green state*: Heat pump and charging of electric vehicle can run without restrictions.
- ii) *Yellow state*: Heat pump and charging can run if their load is within the power limits; limits can be broken according to customer preferences.
- iii) *Red state*: Heat pump and charging is allowed only if their load is within the limits.

### Simulation results

The results (mean value of maximum infrastructure loading and mean value of minimum voltage at the nodes of all scenarios) for the residential and commercial area of the load flow calculation for 2017, 2027, and 2037 are shown in Table 3. For 2027 and 2037 the load flow was calculated without/with using the new technologies (scenario (a)/(b)). Obviously, the maximum loading can be reduced dramatically (e.g., from almost 134 % of loading to 84 % in the commercial area) by using the Smart Breaker functionality together with the load shift algorithm. Similar improvements can be achieved in the voltage domain.

Table 3: Results of load flow simulation 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.

Scenario	Residential area		Commercial area	
	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

## COST-BENEFIT ANALYSIS

As described above the technical applicability of Smart Breakers for a commercial and domestic area was simulated resulting in possible savings of conventional grid reinforcement. Accordingly, optional grid reinforcements and corresponding costs were evaluated by *Linz Strom Netz GmbH*, considering urban cable installation costs (215 – 265 €/m). Based on these results the following data (Table 4 and Table 5 representing the number of Smart Breakers and buildings within the commercial and residential area) were implemented for the performed cost-benefit analysis.

Table 4: Overview of necessary Smart Breaker numbers (SB) and IT installations (buildings) within the commercial area

Scenario	SB 2027	SB 2037	Buildings 2027	Buildings 2037
MAX	10	21	10	20
MEAN	10	21	9	16
MIN	10	21	6	13

Table 5: Overview of necessary Smart Breaker numbers (SB) and IT installations (buildings) within the domestic area

Scenario	SB 2027	SB 2037	Buildings 2027	Buildings 2037
	2027	2037	2027	2037
MAX	10	21	10	20
MEAN	10	21	9	16
MIN	10	21	6	13

Smart Breaker Capital Expenditures (CAPEX) were set at 305 €/Breaker (no Operational Expenditures - OPEX). Regarding necessary EATON ECI and xComfort components costs were estimated to decrease to 30 % of actual (see Table 6) values (as of economies of scale effects for higher sale numbers). All other component costs were used as shown in Table 6. Avoided grid reinforcement cost calculated to 25,8 k€ in 2027 (141 k€ in 2037) for the domestic as well as to 18 k€ in 2017 (139 k€ in 2037) for the commercial area.

Table 6: Overview of actual component cost

	CAPEX in [€]	Asset life-time [yr]
Conventional breaker	1350	10
CEMS + communication (Raspberry Pi incl. display and router)	166	10
Eaton ECI	310	10
Eaton xComfort - CAEE-02/01	87	10
Eaton xComfort - CBEU-02/03	58	10

Thus, Figure 3 shows economic results for the domestic and commercial Smart Breaker application studies. For both the domestic and commercial case the simulated Smart Breaker functionalities could lead to lower grid cost. It also can be seen, that grid reinforcement costs significantly increase if the hosting capacity of the installed infrastructure is reached.

## CONCLUSION

From economic perspective, the analyzed technology offers significant cost reduction potentials compared to

currently available solutions. Thus, a further tool to increase the efficient utilization of existing AC (as well as DC in the future) infrastructures exists. The applicability of the analyzed technology in Low Voltage grids however depends on the existing grid capacity, location, and rated power of consumption and generation. Also, the grid age plays a central role. Thus, the derived economic project results cannot be generalized.

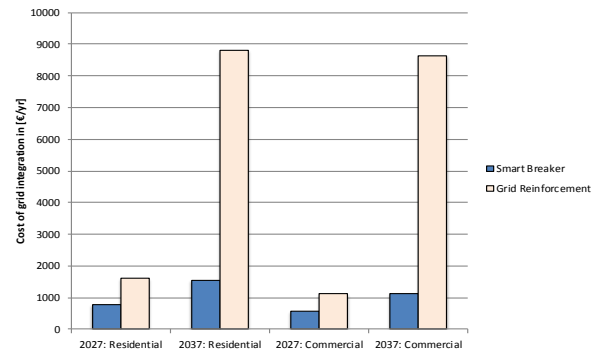


Figure 3: Grid integration cost comparison for the commercial and residential area: Smart Breaker vs. Grid Reinforcement

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