Improved Distribution of Locally Sourced Energy in Smart Grids During Brownouts and in Times of Energy Scarcity

Rolf Egert, Florian Volk, Jörg Daubert, Max Mühlhäuser,
Telecooperation Lab
Technische Universität Darmstadt,
Email: {egert,volk,daubert,max}@tk.tu-darmstadt.de

***Abstract*—Brown-out situations are cases of electricity distribution in which demand exceeds production and transportation capabilities. In contrast to black-outs, energy is available to some extent, but not enough to meet the demand of all consumers. Traditionally, centrally organized power grids with large production capabilities on the one end of the distribution grid and only consumers on the other end are struggling to cope with brown-out situations. In order to achieve a somewhat fair distribution of the available energy, street busses are supplied in a round-robin-like distribution scheme. For that, some streets busses are supplied with energy, while others encounter local black-outs. Due to the round-robin-like scheme, all consumers receive some energy eventually. Modern, ICT-enhanced "smart grids", which also include small and local production capabilities (often-times renewable energy sources like photovoltaic) provide new means of addressing brown-outs. In this paper, we evolve the current round-robin-like scheme further to take the properties of smart grids into account. This affects the fairness of energy distribution, but—in total—increases the amount of supplied consumers. Extensive simulations that are based on real-world street busses of the German electrical grid are conducted. These simulations are conducted with our smart grid simulation tool HOLEG and they indicate improved supply rates during brownouts, even in the presence of volatile local energy production. We extend our model to a hierarchical scheme, spanning from the distribution grid down to household items, for which we imagine fine-grained control capabilities in the future smart grid.**

Keywords–Smart Grid;Micro Gird; Demand and Response; Fairness; Electrical Grid; Optimization.

I. INTRODUCTION

This work is an extension of the authors previous work, *Mitigating Brown-Outs: Fair Distribution of Locally Sourced Energy in Smart Grids* [1].

The current electrical grid is already undergoing a change, which will accelerate even more in the future. Nowadays, the production architecture is based on large nuclear- and fossil-fuelled producers, which are located centrally in the grid. This concept will turn into an architecture that uses *local and distributed* energy resources (DER) in addition to a reduced number of central producers. DERs are based on renewable energy sources, amongst those, the most established ones are solar- and wind-energy. However, this increasing amount of DERs in the electricity production introduces several new problems for the electrical grid. For instance, the flow of electricity can become bidirectional, if the production of the DERs is high [2], which can cause problems in the network infrastructure. Furthermore, in contrast to the fossil-fuelled producers, the production of DERs is dependent on environmental circumstances like the wind and weather conditions. This connection renders the electricity production of the DERs highly fluctuating and thus, difficult to plan for [3]. This unpredictable behaviour in combination with the increased number of producers and consumers that take part in the network, makes it impossible for human operators to control the future grid. Therefore, the establishment of an information and communication infrastructure (ICT) that provides monitoring and control capabilities becomes mandatory. If such a system is integrated into the electrical grid, the concept of a smart grid (SG) emerges.

A big step into the direction of increasing the share of renewable resources in the production of electricity was conducted recently in Germany. There, the *Renewable Energy Sources Act* (EEG) [4] was passed. This act states that, until the year 2025, Germany must generate 40%-45% of the electricity demand by renewable energy sources like solar panels, wind turbines and biomass power plants.

These changes, which the electrical grid is facing in terms of infrastructure, do not fit to the rules and network policies for maintaining controlled operation that are currently in use. A response to these changes, by adapting and establishing new policies and rules according to the new situation, is necessary. A subproblem concerning the outdated rules and policies, and the main focus of this work, is the demand and response (D&R) behaviour of the electrical grid in brown-out scenarios. An energy grid enters a brown-out state if the production capabilities do not suffice to supply the demand of all consumers in the network. This also holds for the black-out scenario; however, the complete absence of electricity introduces additional difficulties, like frequency synchronization. The black-out state is a problem that needs to be addressed separately and is not part of this work.

The German state of the art procedure to cope with the problem of D&R in a brown-out scenario works as follows: If a brown-out state has been entered and cannot be solved by backup power plants or other emergency electricity sources, the network is logically divided into (preferred equally consuming) subnets. Each of these subnets has to be separable and reconnectible to the grid, such that these are allowed to either consume electricity or not. Subsequently, one after another of these subnets is separated from the grid in a round-robin like manner. After each separation of a subnet, the current network stability is measured. If the network has stabilized, the currently active consumers will be supplied for a certain amount of time and a plan is generated that schedules the connected and disconnected time intervals for all subnets in the network. In case the network does not stabilize, additional subnets are disconnected until a demand and supply equilibrium is reached. The round-robin approach guarantees fairness in the brown-out-scenario. This is done by only allowing to disconnect the same subnet for a second time, after all other subnets have been disconnected at least once. In the very end, this method guarantees that each subnet is supplied, as well as disconnected for the same amount of time. Note that the very last round of the disconnection process (which is the round directly before the brown-out situation is resolved) might change the equality of supplied time for the latest supplied groups. However, this will be taken into account in case of further brown-out cases, such that consumers with lower supplied time during the last incident will be preferred next time.

However, the procedure has one major flaw that renders it not suitable for the future changes in the electrical grid. The currently used method does not take the production capabilities of the subnets into account, but enforces equal supplied times for each consumer by deactivating the subnets in a round-robin based manner. However, this also means that the production capabilities, in terms of DERs, which are located in these subnets are deactivated and can therefore not contribute to mitigate problems in the brown-out state. Therefore, this attempt might even promote further destabilization of the network if the prosumers are capable of producing high amounts of electricity, but are simply dismissed by disconnecting them from the grid. To face these challenges of the future energy grid it is important to develop new rules and policies that adapt to the necessities of these future changes. Additionally, with the introduction of ICT and DERs, novel algorithms need to be developed for controlling the new electrical infrastructure and providing fair electricity distribution.

This work is an extension of our previous work [1]. We extend this work in Section III, where a formal model for representing grid levels in an undersupplied state is introduced and a novel fairness metric is described. This model is extended to recursively represent all abstraction levels from micro grids down to individual components in each single house. However, there is no general definition of fairness. As of this, our fairness definition focuses on the following two optimization goals: on the one hand, to provide equal supplied times for all consumers and, on the other hand, to maximize the number of supplied subnets in the grid. Additionally, a time-discrete simulation environment for modelling and testing simplified smart grids (HOLEG) is introduced in Section V. Moreover, HOLEG is used in Section VI to conduct the simulation of an exemplary electrical test network and to evaluate the modelled network. As a use case, a recursively defined model of an low-voltage electrical distribution network is implemented in the HOLEG simulation environment. To be more precise, without loss of generality, each modelled abstraction level encompasses five prosumers from the next lower recursive level. In this work, all four introduced levels are modelled using real measurement data for the consumption and production behaviour of the prosumers. Additionally, the network is only provided with a limited amount of electricity to represent a brown-out scenario.

The remainder of this work is organized as follows. In Section II, an overview over scenarios in the domain of the electrical grid is provided, where fairness is an important goal. In Section IV, fair electricity distribution algorithms are presented. Followed by the paper conclusion of this work in Section VII.

II. Related Work

Fairness is a term discussed in many fields, most prominently in economics [5] and psychology [6]. However, fairness also became an important criterion in application of information technology [7] and especially in the area of scheduling algorithms [8] and resource allocation [9]. In this Section, a selection of work is presented that is concerned with the definitions and fields of application in the SG scenario. One of the most popular fields for applying fairness in the domain of SGs is the area of dynamic demand and response, where demand is dynamically adapted according to different strategies or algorithms to reach certain optimization goals. The approach of [10] uses a daily consumption schedule for the consumers in the network. The loads in this schedule are divided into two categories, namely fixed- and flexible-loads, where the latter can be moved within the schedule. In this work, consumers try to reduce their electricity bill by scheduling their flexible loads in such a way that the overall production cost for energy in the network is reduced. Hereby, fairness is achieved by charging users for electricity based on their contribution to minimize the production costs in the network. In [11], dynamic demand and response management is discussed in the environment of smart objects that can be activated and deactivated dynamically. In this scenario, fairness is introduced by using different scheduling approaches like round-robin or by assigning priorities for scheduling algorithms. The authors of [12] discuss fairness in the sense of a trade-off between the maximization of a consumers utility function (level of satisfaction dependant on the electricity consumption) and the minimization of production costs imposed to the energy provider. Another approach that defines the fairness of an algorithm as a matter of consumer satisfaction is presented in [13]. Hereby, the difference in starting time of so-called *soft loads* is used as a metric. A slightly different fairness notion is used by the authors of [14]; they present a day-ahead energy resource scheduling algorithm using DERs and Vehicle-to-Grid (V2G). To prevent unnecessary battery deterioration of the vehicles, the authors establish pricing levels, which are dependent on the power level of the batteries, to establish a fair remuneration scheme.

Another field of application is the planning of SG communication networks. The authors of [15] use equal quality of service as a fairness metric in their approach of planning wireless mesh neighbourhood area networks (NANs). They discuss fair placement of gateways to ensure an equal number of participants to be covered by each gateway.

Although there is a lot of ongoing work that uses fairness metrics in the SG scenario, the considered scenarios are mainly based on cases of normal operation. In contrast, this work considers the state of the art fairness metric and presents its drawbacks in the SG domain. Moreover, the presented algorithm aims to maximize the use of DERs, while simultaneously maintaining fairness of electricity distribution among consumers.

III. Recursive System Model Definition

In this section, the extended model that is used for the conducted simulations is described in detail. First, the four different recursive levels, *Micro-Grid, Street, House* and *In-House* are introduced. Recursive in this sense means that starting from the *Micro-Grid* level, each lower level is part of the previous one (e.g., each micro grid can contain an arbitrary number of streets). Figure 1 shows an overview of the general recursive structure of the system model. For all levels, a general description is provided. Second, a formal definition of the model constraints and assumptions is given. Finally, the section concludes with the presentation of the fairness notion used in this work.

A. Micro-Grid Level

The first level is the *Micro-Grid level*, which is concerned with individual micro grids that are inter-connected via the transmission grid. In this work, the micro grids are considered to encompass residential areas. Those can be, for instance, larger residential areas in cities that have a connection via an adjustable transformer to the transmission grid. This transformer is responsible for managing the incoming electricity from the transmission grid as well as the outgoing electricity provided by the micro grids. Moreover, the transformer has the ability to connect or separate each individual micro grid from the transmission grid, and thus, control consumption and production behaviour by allowing or declining participation in the electricity distribution. More formally, the micro grid level can be defined as a set of micro grids $MG = \{mg_0, \ldots, mg_n\}, n \in \mathbb{N}$

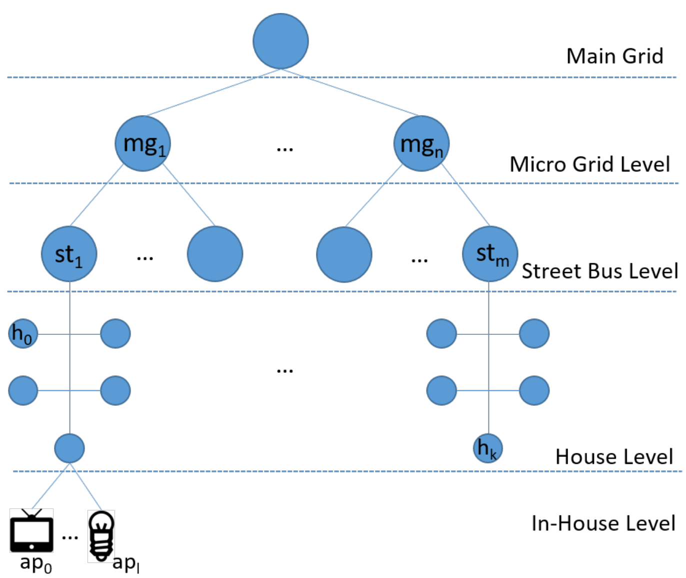

Figure 1. General structure of the model and the individual recursive levels

Each micro grid mg_i has an overall consumption and production. Those values are measured at the transformer that connects the micro grids to the transmission grid. The overall consumption is, in general, the overall sum of all the loads provided by the consumers located in the micro grids and similarly the overall production represents the sum of the production of all producers in the micro grid. Note that all elements in this model are prosumers, which can switch between being a consumer or a producer at different points in time. A producer or a consumer at this abstraction level is represented as a street bus and is explained in the following in more detail.

B. Street Bus Level

The street bus level represents the second abstraction level in our model and can be represented as a set of street busses $ST = \{st_0, \ldots, st_m\}$, $m \in \mathbb{N}$. The set ST represents the street busses that are connected via an adjustable transformer to form a micro grid mg. Each individual street bus again has an overall consumption and production that is defined as the sum of all loads or production capabilities of the houses that are located in the street busses. The adjustable transformer allows to measure the ingoing and outgoing electricity of the individual busses and, additionally, can disconnect and connect busses to control their participation in electricity distribution.

C. House Level

The third abstraction level is described as the house level. On this level, it is assumed that novel technology like Smart Meter Gateways introduce the capabilities to control individual houses, which are connected to the distribution grid. Let H be a set of houses $H = \{h_0, \ldots, h_k\}$, $k \in \mathbb{N}$ that are contained in a single street bus st. The overall load and production of a house h is the sum of all loads and producers that are located in the house. For instance, loads can be devices like fridges and TVs and producers can be locally installed solar panels. Each individual house, again, can be connected and disconnected to control it's participation in the electrical grid.

D. In-House Level

The last abstraction level is concerned with the distribution of electricity to prosumers that are encompassed in a house level prosumer. For instance, this can be all prosumers in a normal house in a city or all the prosumers contained in a building of a factory. Let AP be a set of *atomic* prosumers $AP = \{ap_0, \ldots, ap_l\}$, $l \in \mathbb{N}$, where *atomic* indicates that these producers can not be further divided into lower level prosumers. It is assumed that the Smart Meter Gateway allows a user to connect and disconnect prosumers to supply them with electricity. Note that this domain is currently significantly different from the previous abstraction levels, because the responsibility of the domain belongs to the house owner and not to the electricity provider. A user would have to adapt to the changes that happen on previous abstraction levels to contribute in the mitigation of system problems. The reason for this is that the energy providers are not allowed, or can not influence what a user is doing in his environment and they are not permitted to control the consumption or production behaviour of any components in the house from the outside.

E. Model Constraints and Assumptions

In this section, the constraints and assumptions that are required to define the recursive model used in this work are presented in more detail. First, information about the modelled prosumers as well as load and production calculation over time is provided. Second, the a formal definition of a brown-out state is presented. Finally, the novel fairness notion is introduced.

Let $cons(\cdot, \cdot)$ and $prod(\cdot, \cdot)$ be functions that take as an input a prosumer $x \in Y$ and a timestep t, where $Y \in \{MG, ST, H, AP\}$ and t is taken from the interval $[0, \ldots, T-1]$. The output of $cons(x, t)$ returns the overall load of the prosumer x at the point in time t and the output of $prod(x, t)$ is the overall production. As long as the prosumer is not an *atomic* prosumer, the functions recursively sum up the production or consumption of the next lower recursive level. Without loss of generality it will be assumed for the remainder of the paper that the granularity of the time interval is based on the hours of the day, such that $T = 24$. Any other time interval would be suitable too; especially smaller ones, when taking into account the volatile nature of SGs that include renewable energy sources like photovoltaic and wind power. More formally, those functions are described as follows:

$$prod(x,t) := \begin{cases} \sum_{j=0}^{n} \int_{t}^{t+1} prod(y,t)\mathrm{d}t & if x \notin AP \\ \int_{t}^{t+1} prod(x,t)\mathrm{d}t & else \end{cases} \quad (1)$$

$$cons(x,t) := \begin{cases} \sum_{j=0}^{n} \int_{t}^{t+1} cons(y,t)\mathrm{d}t & if x \notin AP \\ \int_{t}^{t+1} cons(x,t)\mathrm{d}t & else \end{cases} \quad (2)$$

Where n is the number of prosumers y of the next recursive level that are contained in x. Note that these functions are recursively defined to calculate their output based on the result of the next recursive level. The recursive process stops at the in-house level, where the prosumers are *atomic* and the production or consumption of an prosumer can not be based on another recursive sum, but is directly represented as the measured amount of produced or consumed electricity in this timestep.

At every point in time t in a day, a prosumer can be either a consumer or a producer. Let all consumers be represented as a set C and the producers likewise as a set P. A prosumer x is a consumer $x \in C$, if its consumption of electricity is higher than the production provided by its next recursive level prosumers. Whereas, a prosumer is a producer $x \in P$ if the electricity provided by its next recursive level prosumers exceeds the local consumption. A more formal representation of these relations can be expressed as follows:

$$\forall x \in Y \ \{x \in C \,|\, cons(x,t) > prod(x,t)\} \quad (3)$$

$$\forall x \in Y \ \{x \in P \,|\, cons(x,t) \leq prod(x,t) \quad (4)$$

Where $Y \in \{MG, ST, H, AP\}$ defines the recursive level for the calculation of production and consumption. Note that this assignment to a set of producers and consumers is used later in the fairness notion used for the conducted simulations.

In the following, a formal definition for an undersupplied state (brown-out) is provided. At each point in time, a prosumer can either be a consumer or a producer. In case it is part of the set of consumers, it requires more energy than it produces itself; and thus, it needs additional electricity delivered by the previous recursive level. Note that in this work the recursive model starts with micro grids as the first level that is connected to the transmission grid via an adjustable transformer. For the micro grid level the preceding level is simply referred to as the *main grid*. In the case that a prosumer is part of the producer set, the prosumer provides energy to its preceding level.

The general electrical supply situation is considered to represent a brown-out scenario. In this scenario it is assumed that the grid is not able to provide enough electricity to fully supply all prosumers that are connected to the transmission grid simultaneously. Moreover, the electrical grid is in a brown-out state, if a single point in time during the day exists, where the electricity provided by the grid is not sufficient to cover the overall demand of the grid at the same time.

The formal definition of a brown-out state is as follows:

$$\exists t \, 0 \leq t < T \, prod_{Main}(t) < \sum_{i=0}^{n} cons(x,t) \quad (5)$$

Where $prod_{Main}(t)$ represents the amount of electricity the main grid can provide for supplying the prosumers located in the microgrids. Additionally, it is necessary to distinguish the brown-out scenario from the black-out scenario. In contrast to the brown-out state, where the grid is partially supplied, none of the elements of the grid is supplied in a black-out scenario. Without loss of generality, this work focuses on an undersupplied state that is critical (brown-out), but not fatal (black-out) for the grid. In particular, this means that the amount of energy provided by the main grid should at least cover the demand of some of the prosumers located in grid. The assumption for the minimal amount of supply provided by the main grid is that the amount needs to be sufficient to cover the demand of the largest prosumer in the network. A formal definition can be as follows:

$$\forall t \, 0 \leq t < T \ prod_{Main}(t) \geq \max\{cons(x,t) | x \in C\} \quad (6)$$

This definition guarantees that, for each point in time, the main grid provides enough energy to supply a single prosumer in the grid. Without this assumption we may have situations where the electricity is not enough to supply a single prosumer. However, this represents a black-out-state in our model, and is not part of the current work. In addition to the electricity that is provided by the main grid to supply the micro grids, the prosumers in the model may be producers and provide additional electricity for the grid. Note that a prosumer is a producer, if it generates more electricity than it consumes. This can happen if, for instance, a part of the grid contains a high number of DERs like solar panels, wind turbines and similar, as well as batteries and alike. Thereby, solar panels and wind turbines are inherently volatile in availability and power output, while the availability of batteries and other energy storage systems is much easier to plan. In this paper, without loss of generality, we simulate local energy production with solar panels. If a prosumer at any of the recursive levels of the model is supplied, it's DERs are active and contribute to the amount of electricity in the grid. However, if a prosumer is not supplied, the corresponding DERs are deactivated and neither produce nor consume electricity. To successfully supply a prosumer x at time t it is sufficient to provide the amount of electricity, such that the sum of the production of the local DERs in addition to the electricity provided by the main grid equals the consumption of the prosumer. A more formal definition can be as follows:

$$cons(x,t) \leq prod_{Main}(t) + prod(x,t) \quad (7)$$

The function $prod_{Main}(t)$ hereby represents the amount of energy that is centrally provided by the main grid. Changes of state, like from being supplied to being unsupplied or changing from being a consumer to being a producer, can be performed instantly in the digital representation of a system. However, the physical system consists of electrical and mechanical components that have time constraints for changing their state (e.g., electrical switches). To consider these constraints in the discrete simulation model, it is assumed that after a change of status has happened, this new status is kept for one timestep.

To evaluate the fairness in the described model, in the following a new fairness notion is proposed. The currently used metric, which is based on equal supplied time, is not optimal anymore in the presence of future technological changes in the domain of the electricity grid. The transition from centralized to distributed production changes the way how the presence of prosumers influences the performance of the network. However, DERs can only contribute to the system if the corresponding prosumer (e.g., the street where solar panels are connected to the grid), where they are located, is connected to the network. One part of the novel fairness notion is based on the assumption that strategies, which maximize the use of DERs, are able to supply more prosumers than other strategies. To represent this in the fairness notion, the average number of supplied prosumers is used as a parameter. This also includes those prosumers that act as producers at specific points in time due to high electricity production by DERs. In particular, prosumers that are able to sustain themselves are considered to be supplied, even if they supplied themselves and are not depending on external electricity. Furthermore, to include the fairness of handling the consumers, the sum of differences between the supplied time of all consumers is calculated. Therefore, the fairness assumption extended in this metric is again based on the equality of overall supplied time of all consumers. If an algorithm can supply a large number of prosumers, while minimizing the differences in the number of timesteps, in which consumers are supplied, the fairness metric is maximized. To achieve maximum performance of the DERs, prosumers that are producers are not taken into account in the supplied time difference calculation. This is due to the benefit the network gets in terms of produced surplus electricity; and thus, producers are allowed to stay connected. A more formal description of the fairness metric is as follows:

$$\forall i, j \in C \quad f = \max \frac{avg\#ofsuppliedprosumers}{1 + \sum_{i,j \in C} |t_{sup,i} - t_{sup,j}|} \tag{8}$$

where $t_{sup,i}$ represents the number of supplied timesteps for consumer $i \in C$.

IV. Description of (fair) Algorithms

In this section, several algorithms that aim to solve the resource allocation problem for the undersupplied state scenario, are presented. First, a slightly adapted version of the round-robin based approach, which is used in the German electrical grid, is introduced. Second, an iterative algorithm, which does not aim to provide equal supplied times for the prosumers, but indirectly prefers small consumers, is described. Finally, an algorithm that aims to maximize the use of DERs and, additionally, equalises the number of supplied time for each prosumer, is presented.

A. TRR - Traditional Round-Robin

This algorithm is a slightly extended version of the mechanism currently used in the German electrical grid. The Traditional Round-Robin algorithm, which is shown in Figure 2

```
procedure TRR(production, timestep, prosumers)
    for i ← prosumers.length() do
        prosumer ← getLowestUptime(prosumers);
        if prosumer == null then
            break;
        else
            if isSupplyable(prosumer) then
                markAsActive(prosumer);
            end if
        end if
    end for
     return activeProsumers;
end procedure
```

Figure 2. TRR - Traditional Round-Robin.

works in a round-robin based manner and solves the problem of fair supply distribution as follows. The algorithm uses a list of prosumers and the information about the amount of production that is centrally provided by the main grid or the previous recursive level, to determine a subset of supplyable prosumers for the current timestep. Since the algorithm uses a round-robin approach, it is not allowed to activate a specific prosumers for a second time before all other prosumers have been activated at least once. With this design it is ensured that each prosumer stays active and inactive for an equal amount of time. An additional important remark is that this algorithm does not take the surplus electricity, which is provided by local DERs, and its influence on the network into account. To make this approach comparable with the other algorithms presented in this work, the round-robin approach was extended such that surplus electricity production provided by prosumers can be leveraged to supply additional prosumers in the network. Note that the in the currently deployed electrical grid the applicability of the traditional round-robin approach is limited to the second abstraction level (street bus level) using a adjustable transformer. However, it is assumed that with further technical progress this approach will be applicable to the lower abstraction levels as well.

B. IIA - Improved Iterative Approach

The Improved Iterative Approach (IAA), which is shown in Figure 3, iteratively selects prosumers from its list and tries to supply them. In contrast to the original version of TRR (Figure 2) it takes the production of the DERs located in the prosumers and uses it for current production calculations. The algorithm provides a very rudimentary kind of fairness by indirectly favouring producers and consumers with a very low demand. The algorithm works as follows: first, if there still remains unused capacity, iteratively choose a prosumer from the list of prosumers and check if the required demand can be met. If this is the case, then activate the prosumer and add the resulting production capabilities of its DERs to the overall production. If the selected prosumer cannot be supplied in this timestep mark it as unfit. After the algorithm terminates, it returns a list of all prosumers that will stay active in this timestep and all remaining prosumers will be deactivated.

C. UEA - Uptime Equalizing Algorithm

The Uptime Equalizing Algorithm (UEA), which is shown in Figure 4 aims to maximize the use of DERs while maintain-

```
procedure IIA(production, timestep, prosumers)
    while consumption < production do
        prosumer ← getNextProsumer(prosumers);
        if supplyable(prosumer) then
            markAsActive(prosumer);
            production += prosumer.getProduction();
        else
            markUnfit(prosumer);
            if AllProsumersProcessed then
                return activeProsumers;
            end if
        end if
    end while
end procedure
```

Figure 3. IIA - Improved Iterative Algorithm.

```
procedure UEA(production, timestep, prosumers)
    while consumption < production do
        for all prosumer ∈ prosumers do
            if isSelfSustaining(prosumer) then
                markAsActive(prosumer);
                production += prosumer.getProduction();
            end if
        end for
        prosumer ← getMinUptimeProsumer(prosumers);
        if supplyable(prosumer) then
            markAsActive(prosumer);
        else
            markUnfit(prosumer);
        end if
        if AllProsumersProcessed then
            return activeProsumers
        end if
    end while
end procedure
```

Figure 4. UEA - Uptime Equalizing Algorithm.

ing equal supplied times for the prosumers. To achieve this, the algorithm distinguishes in a first step between consumers and producers. To make this distinction the algorithm uses the definition provided in Section III-E. Second, all producers are activated and their local production capabilities are added to the overall electricity provided by the previous level or the main grid. This is possible, since the definition of the brown-out-scenario states that there is enough centrally produced electricity to supply least a single individual prosumer. After the activation of the prosumer, the local DERs are providing enough energy to fully cover the local demand and thus make the prosumer self-sustaining. After all the producers are activated, the algorithm chooses a prosumer that is currently inactive and has a minimal amount of supplied time. In the next step, the algorithm checks if the selected prosumer can be supplied using the currently available production. If this is the case, the prosumer is activated, otherwise it is marked as unfit. After all prosumers are supplied or marked as unfit, the algorithm returns a list of prosumers that will stay active during this timestep and all remaining ones will be deactivated.

V. Simulation Environment for Algorithm Development and Evaluation

Testing of novel algorithms is a mandatory task to ensure correct functionality; however, it is also task not easily done in the domain of electricity distribution. Due to the necessity of continuous operation, testing can not be done on the currently deployed electrical grid. Another possibility for conducting tests is the construction of physical testbeds that represent a part of the grid. However, those testbeds can become expensive quite fast and, additionally, only cover a part of the overall grid, which may neglect cascading effects. A more suitable strategy for testing novel approaches is modelling and simulating the environment in a digital manner.

In this section, a simulation environment for energy grids based on a holar structure is introduced. This simulation environment, called HOLEG [16], is a previous work of the authors and allows to model and simulate the behaviour of a simplified electrical grid. In particular, HOLEG makes the following contributions:

- Simplified representation of an electrical distribution grid based on a holar approach.
- Detailed modelling capabilities for network components. It allows to model all types of components ranging from large producers, to connection lines and houses, up to individual components like small solar panels, TVs and alike.
- It provides an API that allows to develop novel optimization algorithms using the Java programming language. Those algorithms can then be run in a time-discrete fashion in the HOLEG environment.
- Many plotting capabilities for a diverse set of metrics for the evaluation of the simulation (see Figure 7)

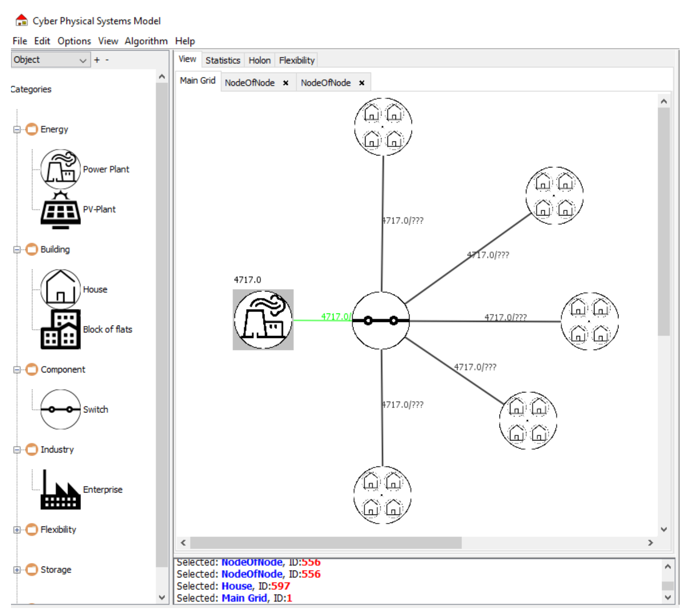

Figure 5. View of the Micro-Grid level modelled in HOLEG. The power plant represents the main grid which is connected to a switching node that connects or disconnects the individual micro grids

In this work the HOLEG simulation tools purpose is twofold. One of the purposes is the generation of a simplified environment that allows to model typical components of an electrical grid in a detailed manner, which can be seen in Figure 5. Moreover, the individual components of the network needed to be fully customizable. Figure 6 shows the the in-house level with the different prosumers displayed in the table at the top right corner. The graph below allows the user do define the consumption or production behaviour of the component over the total simulation time.

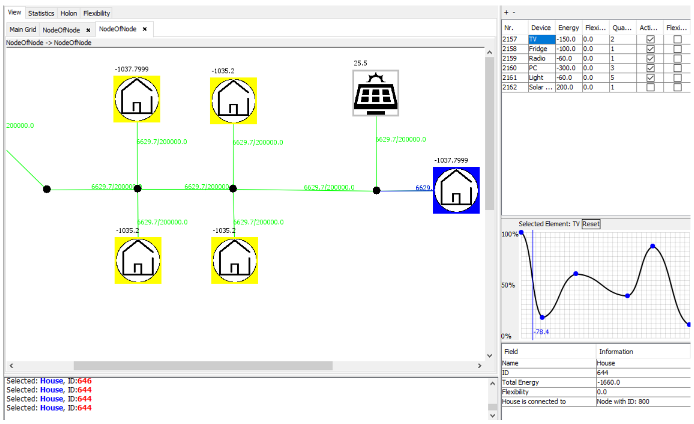

Figure 6. View of the house level modelled in HOLEG. On the right side the in-house level is displayed as a table of elements contained in the highlighted house. On the bottom right side, the consumption and production behaviour can be manipulated by modifying the graph

The more important feature provided by HOLEG is it's capability of running optimization algorithms in a time-discrete fashion during the simulation of the network. In particular, in each step of the simulation, the algorithm is executed while being able to access and manipulate all individual components in the network. The impact of the algorithms decisions can then be observed in real-time and, additionally, be represented in metric plots. In this work HOLEG is used to run the different fair algorithms on an example network and to observe the effects on the network. The detailed setup for the simulation is described in the next section.

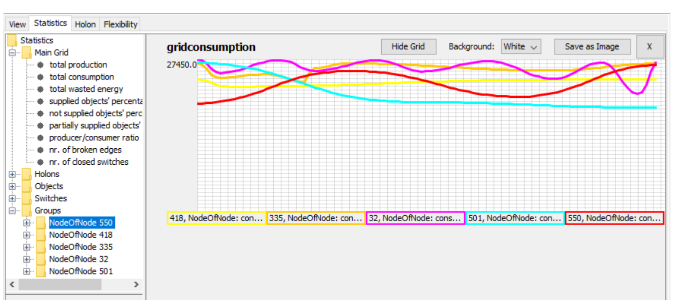

Figure 7. The statistics view of HOLEG allows a user to track and plot diverse data about the different prosumers or groups in the network. In this picture the consumption behaviour of the five micro grids is presented as the coloured graphs

VI. Simulation of the Algorithms

In this section, the conducted simulation is explained. The goal of this simulation is to evaluate the performance of the presented algorithms in a realistic scenario. Moreover, the simulation aims to evaluate the performance in the presence of our presented fairness metric. First, the general simulation setup is introduced. Second, the datasets that are used for demand and supply are described. Third, the simulation execution and corresponding results are presented. Finally, the results of the simulation are discussed.

A. Simulation Setup

The complete simulation was conducted using the capabilities provided by the simulation environment HOLEG [16]. HOLEG allows to build large hierarchically structured networks. The individual recursive levels can be modelled by using HOLEGs grouping capabilities to form subnets that hide the representation details of the underlying subnet. Each of those subnets then represents a lower hierarchical level in the model. The complete model, which is explained in Section III is modelled using HOLEG. More precisely, all four abstraction levels were implemented and each level encompasses five prosumers from the next lower abstraction level (e.g., the first abstraction level contains five micro grids and each microgrid contains five streets). Note that HOLEG is not limited to this amount of abstraction levels or prosumer numbers, but can model arbitrary topologies. To generate a more realistic scenario the values for consumption and production are loaded from external datasets. For this setup, two different load profiles for streets and one production curve of a solar panel are used. The lower level consumption configuration was modelled to align with the real data for the street. This means that the consumption of the devices located in the houses were adapted to fit the consumption data from the real measurements. Figure 8 shows HOLEGs capabilities to model individual load curves for the different devices located in the houses. For simulating a brown-out scenario, the central production is derived using (6). This allows that in each step of the simulation there is enough energy provided by the previous level to supply at least one prosumer.

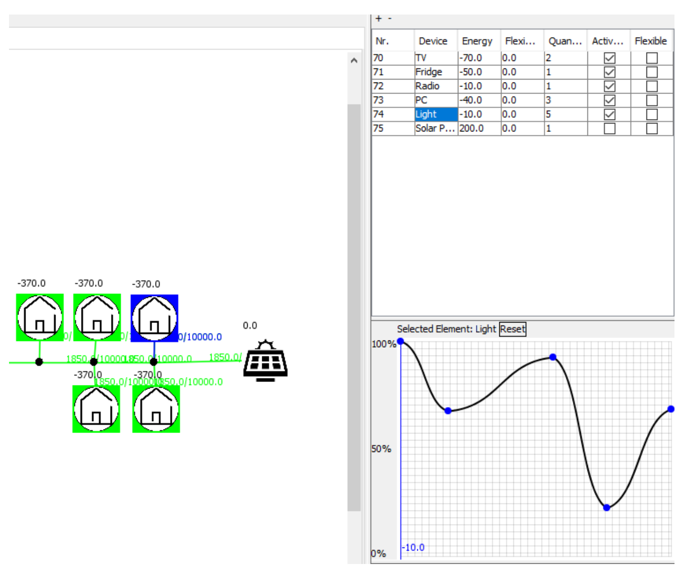

Figure 8. HOLEG allows to model arbitrary components located in the house and configure their consumption and production behaviour using individual load/production curves.

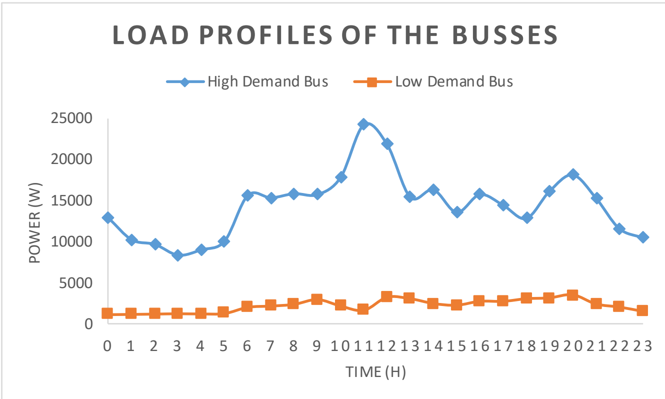

Figure 9. Load curves of the high/low demand busses connected to the adjustable transformer in Saarland (Germany).

1) Load Set: For realistic load data of prosumers in residential areas, real recordings of an adjustable transformer are used. The consumption for the lower recursive level was modelled in such a way that it fit to the overall consumption of the streets. This transformer is located in Saarland in Germany and it is connected to several streets containing housing areas. The real time data was monitored every second and the hourly average of the data is used for the simulation process. Two different load sets are used for simulation. One of the sets was generated by monitoring a larger street and represents a prosumer with a very high electricity demand, whereas the second set represents the consumption of a smaller street. Figure 9 shows the load curves of the street busses for a day.

2) DER Production Set: For modelling realistic production behaviour, real-world solar panel production data is taken from Kronberg, Germany. Figure 11 shows the production curve of the solar panel over a day. The solar panel has a capacity of 4.51 kWp and the recordings are provided in an hourly resolution. For the simulation, one of the previously mentioned solar panels is assigned to the prosumer in the low demand scenario and three to the in the high demand scenario.

B. Simulation and Results

The simulation consists of 1,000 iterations, where in each iteration, a new scenario is generated. In each iteration, the production and consumption values are allowed to randomly deviate by $\pm 10\%$ from the data set values to induce additional variation between the busses. During the simulation, each of the algorithms presented in Section IV is executed and compared in each run. The active prosumers in each run, are prosumers that stay online in the current timestep, either, because they are self-sustaining, or are supplied by the energy provided by the previous abstraction level. Moreover, the full simulation process is conducted for both, the high demand set as well as for the low demand set.

1) Low Demand Bus Results: This section presents the results for the simulation of the low demand dataset. Figure 12 shows the average results for 1,000 simulation runs with the data set of the low demand bus. From this set, the consumption data for the five street-level prosumers is derived and used for evaluation. The setup for the street level scenario is displayed in Figure 10, where exemplary two busses are displayed in more detail. The green bus is currently connected to the

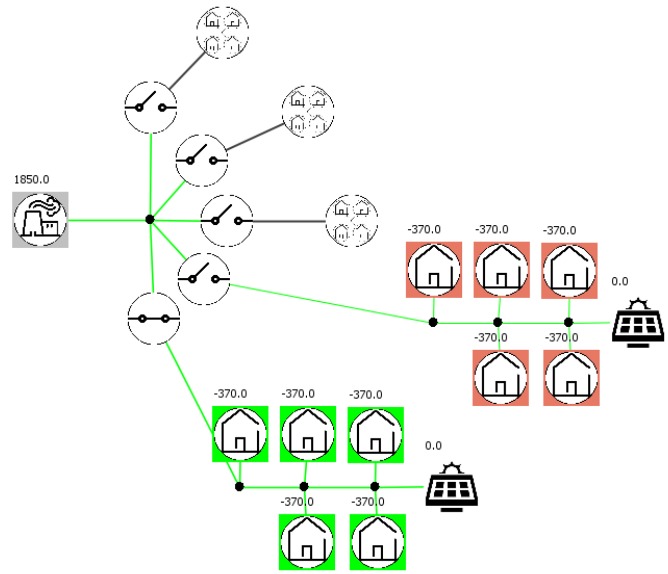

Figure 10. Representation of the street bus abstraction level in the low demand scenario modelled in HOLEG. The bottom two street busses are displayed with extended details to show what lower level prosumers are located in the streets.

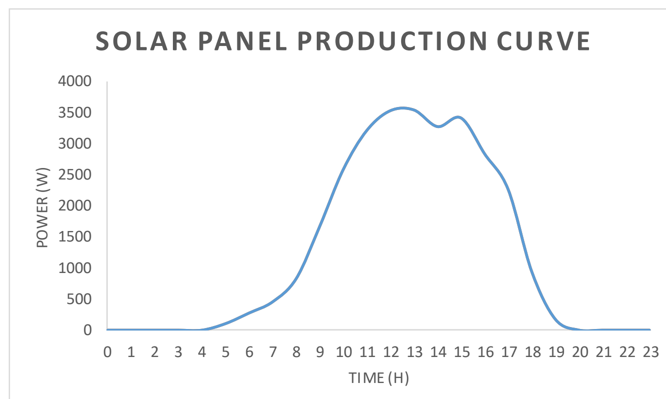

Figure 11. Production profile of a 4.51 kWp solar panel located in Kronberg Germany.

grid and is fully supplied by the electricity provided by the the higher abstraction level. The second bus, coloured in red, is disconnected through an open switch and thus, not supplied. Note that the current consumption (negative value) or production (positive value) is displayed above the individual prosumers. Figure 12 shows the average number of supplied components during the corresponding time of the day for each of the algorithms.

The graph shows a significant performance drop of all algorithms starting from 5am in the morning. While the TRR algorithm can not really cope with this situation, IAA and UEA perform better. This is due to the consumption behaviour of the busses. While the overall production stays the same for TRR, the demand of the busses increases during the morning until about 12pm. As this gap grows with each timestep, busses must be deactivated to keep the consumption below the production provided by the MG. Most of the time, TRR is only able to

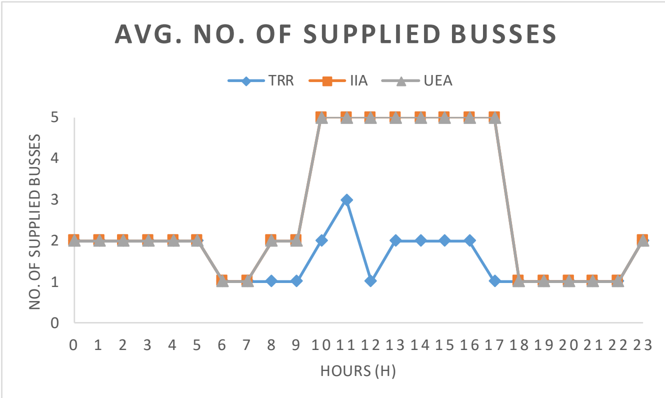

Figure 12. Average number of active low demand street busses during a time interval of 24 hours.

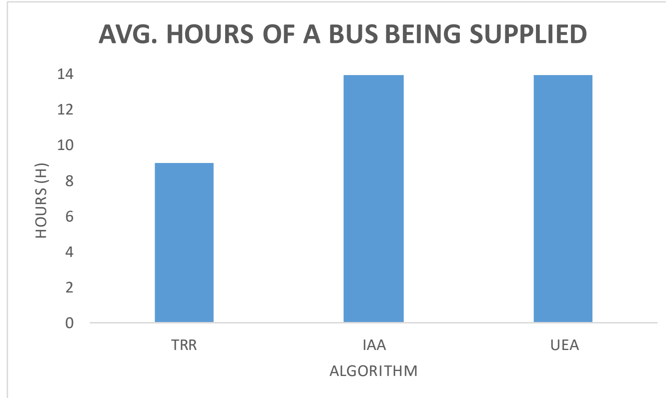

Figure 13. Total average number of how long busses were active during a day using the different algorithms in the low demand scenario.

supply between one and two busses while the rest remains deactivated.

IIA (Figure 3) and UEA (Figure 4) perform equally in this scenario as shown in Figure 12. Since both algorithms use the electricity provided by the solar panel located in the busses, the main difference is the way they choose the next candidate that should be supplied. IIA iteratively chooses the next element in its list of busses and its performance thus depends on the ordering of the busses, whereas UEA performs two steps: first, it activates all prosumers that are real producers in the current time step to uses their production for supplying additional busses. Second, it chooses the least supplied element out of the set of real consumers as a next candidate. The equality in performance of UEA and IIA, is due to the ratio between the required supply of the low demand busses and the provided electricity of the solar panels. The supply for the low demand bus deviates between 1,000Wh and 2,500Wh. In contrast, the solar panel is capable of producing 1,500Wh - 3,000Wh of electricity between 9am and 1pm. With this, the production of the solar panels highly likely exceeds the consumption of their individual busses during peak hours and the busses change from being consumers to being producers. Therefore, most of the prosumers in the low demand scenario become producers, and thus, the ordering of the busses for IIA does not influence the outcome anymore. Moreover, with the assumption provided in (6), each individual bus can be supplied and since most of them are producers, they are self sustaining. If every consumer becomes a producer, the iterative selection of elements equals the first activation step of UEA. This can be seen in Figure 12 at around 9am where IIA and UEA significantly increase the number of supplied components, as well as in the average uptime of busses shown in Figure 13. At about 6pm, the production of the solar panels can be omitted and, therefore, all algorithms perform equally.

The main difference between the algorithms becomes apparent if they are evaluated using the introduced fairness metric presented in (8). As mentioned before, a simple equality approach, like the one provided by the round-robin algorithm, is not suitable anymore for future distributed electricity production. Figure 14 shows the performance of the algorithms with regard to the fairness metric.

As mentioned in Section III, this metric is based on the average performance of the algorithms while treating all consumers

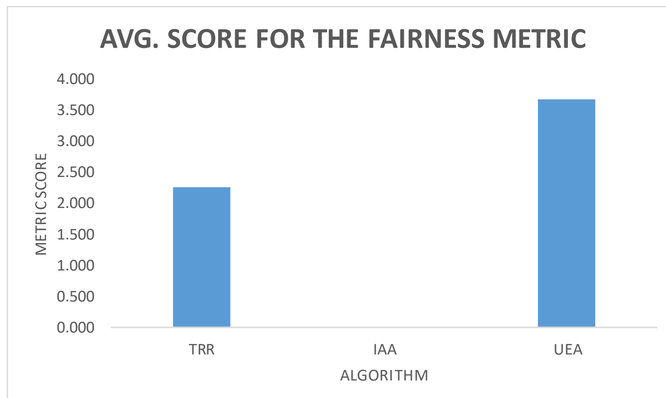

Figure 14. Average metric score of the algorithms in the low demand scenario.

equally. TRR performs quite well, because it is purely based on a round-robin approach. This minimizes the denominator of the fraction in the metric. IIA scores a rounded value of 0. In spite of outperforming TRR with regard to the average supplied time of busses, IIA does not use any techniques to equalize the supplied times of busses. However, this drastically increases the sum of differences in the metrics denominator and thus decreases the metric score. UEA on the one hand maximizes the use of real producers and, on the other hand, favours the bus with lowest supplied time. This leads to small differences between the supplied times, as well as it leads to a good performance with regard to average hours of supplied busses.

2) High Demand Bus Result: Figure 15 shows the average results of 1,000 simulation runs. For providing equal starting positions for both scenarios, again five different busses are derived from the dataset and their values are allowed to deviate from the original data by $\pm 10\%$. However, since the demand of the bus is around ten times as high as the demand of the low demand scenario, the number of solar panels in each bus is set to three. If only one solar panel is located in each bus, they would not be able to influence the outcome of the simulation because the maximum production of the solar panel is significantly lower than the demand of a single bus. Therefore, it is assumed that, in a larger bus in a residential area with a high demand, the number of installed solar panels is higher than in a low demand area.

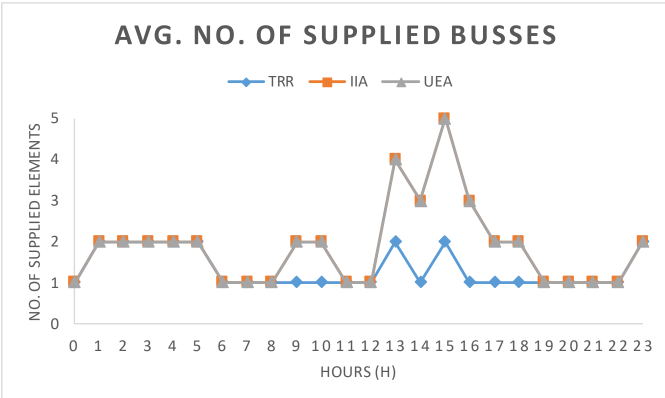

Figure 15. Average number of active high demand street busses during a time interval of 24 hours.

Most of the time TRR (Figure 2) is only able to supply between one and two busses. This is possible due to our assumption about the centrally provided energy and, additionally, due to the missing use of the surplus production of the DERs. The two algorithms that use the production of the DERs again perform equal in the simulation with regard to the average of supplied busses. The rapid changes in the performance of algorithms IIA (Figure 3) and UEA (Figure 4) at 12pm is due to the demand spike that can be seen in Figure 9 at the same time. This is a moment, in which the electricity provided by the DERs simply did not suffice and additional busses had to be deactivated.

The application of the fairness metric in the high demand scenario shows similar results as in the low demand scenario. IIA and UEA perform equal with regard to the average uptime of the busses, whereas TRR performs worse due to the missing use of DERs. With regard to the fairness metric, the overall value decreased due to the smaller number of supplied busses, but still TRR and UEA perform better than IIA.

VII. Conclusion

The results of this work indicate that, with the introduction of a widespread monitoring infrastructure and the increasing installation of DERs in the electricity grid, traditional algorithms and their corresponding definition of fair electricity distribution are outdated. Traditional load shedding based on round-robin selection used in Germany, in case of brown-out phases, is compared to novel algorithms that use the electricity provided by local DERs to improve the quality of service. Therefore, a simulation of an electrical grid in a low-voltage residential area is conducted.

The presented method, however, is not limited to the low-voltage scenarios. The current work showed that a recursive approach that encompasses all different levels of an electrical grid, ranging from the micro grid level down to the house level, is feasible. Moreover, further development of smart meter technologies will even allow to apply the presented method to in-house appliances and, therefore, provide detailed regulation capabilities for distributing electricity. This in-house area however, is a fundamentally different from the other levels in the electrical grid, since energy providers are not allowed to connect or disconnect individual components in peoples homes. Novel ideas and solutions that encourage a user to actively take part in the development of the future energy grid are necessary to make the whole potential of this recursive level accessible for demand and response handling.

As long as real testing of novel applications is restricted by outdated policies, laws and regulations, novel simulation techniques can help to understand the behaviour and impact of novel algorithms and methods in the electrical domain. The model used in this work was implemented in HOLEG, a simulation environment that allows to model simplified electrical grids.

While this paper had the German regulations in focus, future work will encompass and compare international laws and regulations. Our results indicate a lot of optimization potential in brown-out scenarios when local energy producers can be leveraged. In future, we intend to further explore this potential, especially with regards to volatile energy producers and local balancing of production and consumption, in order to reduce the influence of constantly changing energy levels on the transmission grid.

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