A Formal Holon Model for Operating Future Energy Grids during Blackouts

Siavash Valipour[1], Florian Volk[1], Tim Grube[1], Leon Böck[1], Ludwig Karg[2] and Max Mühlhäuser[1]
[1]*Telecooperation Lab, Technische Universität Darmstadt, Hochschulstr. 10, Darmstadt, Germany*
[2]*B.A.U.M Consult GmbH, Gotzinger Str. 48/50, München, Germany*

Keywords: Smart Grid, Micro Grid, Smart City, Blackout, Islanded Operation, Holon Model, Energy Network, Decentralized Power Sources.

Abstract: Modern energy grids introduce local energy producers into city networks. Whenever a city network is disconnected from the distribution grid, a blackout occurs and local producers are disabled. Micro grids circumvent blackouts by leveraging these local producers to power a fixed subset of consumers. In this paper, we evolve micro grids to Holons, which overcome the need for fixed subsets and power as much of the city network as possible. We contribute a formal model of Holons and investigate the impact of the Holon concept in a simulation with 10,000 randomly generated city networks. These city networks are based on parameters obtained from a real-world test site in a medium-sized German city. Our results show that the Holon approach can supply an average fraction of 22.08% of any city network, even when fixed micro grids would fail to power the city network as a whole.

1 INTRODUCTION

In the event of distributed small energy providers, for example, photovoltaic systems, new challenges for energy grids arise.

The classic scheme of combined energy transmission and distribution networks (*energy grids*) is given in Figure 1. The power stations that generate energy are located in and connected via the so-called *transmission grid*, a network of high voltage transmission lines. The power is transported to the consumer, e.g., households, via the *distribution grid* and *city networks*. Thereby, a city usually consists of multiple city networks, all of them are independently connected to the distribution grid. All grids are connected with distribution substations that transform high-voltage energy in lower-voltage energy and vice versa.

Energy grids are undergoing paradigm changes in producing, distributing, monitoring, and metering electricity. Modern, so-called *smart grids* evolve the traditional energy grid by the addition of communication infrastructure in order to optimize the efficiency of the grid. Thus, producers and consumers can coordinate their production and consumption of energy with each other.

Especially, local energy producers are introduced into city networks. For example, photovoltaic systems (PV systems), combined heat and power plants, as well as wind power stations supply power to the energy grid. Therefore, new challenges and opportunities in distributing power arise for energy grid operators. Our paper focuses on continued operation of parts of city networks during blackouts.

1.1 Blackout Handling

A failing distribution substation usually cuts off the entire city network behind it from the distribution grid. As a consequence, the city network experiences a power outage, a *blackout*. Even though local energy producers might exist inside city networks, these producers are disabled during a blackout and cannot supply energy on their own, as they conventionally depend on the synchronization to the energy grid in order to maintain grid stability. Local emergency energy sources, as, e.g., batteries and diesel generators are only available to those households that operate the respective sources.

1.2 Holon Approach

This paper adopts the Holon approach, as it is being developed in the project PolyEnergyNet, a project

Valipour, S., Volk, F., Grube, T., Böck, L., Karg, L. and Mühlhäuser, M.
A Formal Holon Model for Operating Future Energy Grids during Blackouts.
In *Proceedings of the 5th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS 2016)*, pages 146-153
ISBN: 978-989-758-184-7

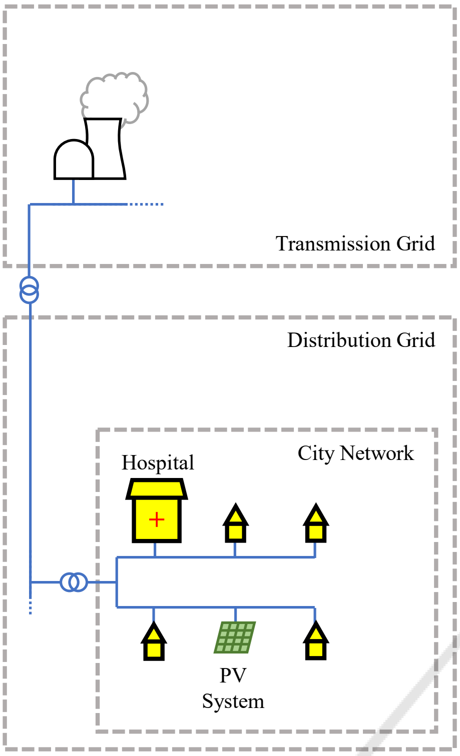

Figure 1: Combined energy transmission and distribution network.

concerned with a resilient and secure energy supply of tomorrow. The adopted model presented here, investigates a possibility to operate parts of city networks independently from the distribution grid by leveraging energy producers located inside the city network (cf. Figure 2). Our aim here is to supply as many consumers as possible with energy during a blackout. Moreover, prospectively, Holons are thought to enable prioritization of consumers so that – in case of energy scarcity – the most critical parts of city networks (hospitals and similar) can be kept active while only consumers of low importance are affected by the blackout. Furthermore, Holons should prefer renewable energy sources over conventional ones.

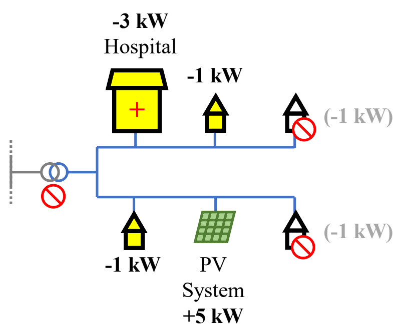

Figure 2: A disconnected city network is partly supplied by a local PV system.

1.3 Paper Structure

This paper is structured as follows: work related to our approach is reviewed in Section 2. In Section 3, we present a formal model of the Holon approach, introduce the involved stakeholders, and discuss constraints. Our approach is evaluated in the subsequent sections. Therein, Section 4 presents the evaluation setup, including a real-world test site, which is under construction in a medium-sized town in Germany. The results of the evaluation are summarized and discussed in Section 5. Section 6 concludes and presents our upcoming research.

2 RELATED WORK

Many approaches for evolving the energy grid to *smart grids* (Amin and Wollenberg, 2005) exist. Most of these approaches target energy-efficiency and demand side management to achieve higher energy grid stability and cost-reduction (Hashmi et al., 2011; Fang et al., 2012).

This section first reviews work related to our approach in Section 2.1 and, later in Section 2.2, discusses the approach of *micro grids*, which we see as an evolutionary base for the Holon approach.

2.1 Smart Grids

The term *smart grid* is, ampong others, well explained by Amin in (Amin and Wollenberg, 2005). Both Hashmi et al. and Fang et al. survey smart grid technologies and approaches in (Hashmi et al., 2011) and (Fang et al., 2012), respectively.

With regards to the stability of smart grids, Guérard et al. propose a grid model based on dynamic graphs to detect and handle network errors within smart grids (Guérard et al., 2015). Our approach specifically targets network errors that isolate city networks and require isolated operation (here: *islanded operation*) to cope with blackouts.

Farhangi criticizes missing alignment of technological evolution and legal regulations in smart grids and presents a general road map for smart grid development in (Farhangi, 2014). The Holon approach requires both new technologies and new regulations, e.g., the permission to operate local energy producers during a blackout. In terms of technology, many challenges are to be solved, for example, operating multiple power producers concurrently requires them to synchronize their frequencies during a bootstrap phase.

The German Association of Energy and Water Industries BDEW proposes a so-called “Traffic Light Concept” for the operation of smart grids (BDEW, 2014). The traffic light concept classifies smart grid operation into three phases:

- During the **green phase**, the smart grid is fully functional and stable. Market mechanisms, like the ones proposed by Saad et al. (Saad et al., 2011), are in control of production, consumption, and prices.
- When the smart grid is in danger to become unstable (**amber phase**), the network operators together with the market participants enforce stability rules (BDEW, 2015).
- In the **red phase**, in the event of imminent risk of failure, the smart grid is solely managed and controlled by the network operators. Market mechanisms are suspended in order to restore a stable energy grid.

The Holon model comes into play during the amber and red phases of the traffic light concept.

In (Bessler et al., 2015), it is explained in detail how demand side flexibilities can be used to optimize city networks. Similar to flexibilities, in (Kausika et al., 2015) the authors investigate the distribution and potentials of PV systems. This is done in order to achieve optimal saturation of renewable energy sources within city networks.

2.2 Micro Grids

Micro grids, often also referred to as “cellular grids”, are very similar to our Holon approach. By isolating predefined areas of energy grids, these areas become able to harvest energy from local energy producers inside the micro grids. The size of micro grid cells varies on the given scenario. Sometimes, a micro grid cell might only be one building, e.g., a hospital with backup batteries, while in other scenarios, a cell can be a whole city network, as shown in figure 3.

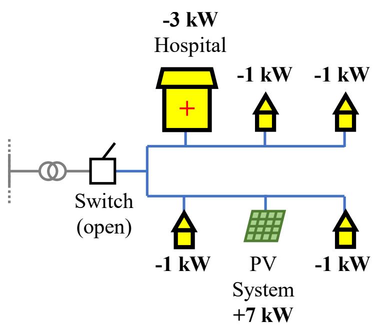

Figure 3: A micro grid in islanded operation.

The German cities of Mannheim and Dresden practically evaluated the concept of micro grids by rolling out such an energy grid for 1,000 households (MVV Energie AG, 2012). The main difference of micro grids and Holons is that micro grids are predefined areas that can be physically separated from their surroundings. Holons are virtual micro grids inside city networks that do not require physical separation and, thus, allow dynamic service composition based on communication infrastructure.

In Schiffer’s PhD thesis (Schiffer, 2015), he investigates practical constraints like frequency stability and voltage stability that are introduced by operating energy producers inside city networks. Schiffer proposes multiple control concepts to cope with these constraints. All these constraints also apply to Holons.

Operating micro grids in islanded mode, i.e., operating them independently from a distribution network, is discussed in (Kroposki et al., 2008) as well as in (Shafiee et al., 2014). While this paper at hand focuses on operating Holons in islanded mode, a mixed operational setting for Holons that are connected to the distribution network is planned for the future.

Schiller and Fassmann describe IT challenges for network operators introduced by micro grids (Schiller and Fassmann, 2010). As Holons depend on control and communication infrastructures just as micro grids do, the challenges discussed by Schiller and Fassmann apply to Holons as well.

In (Ramesh et al., 2015), the authors present a micro grid architecture that allows to identify line faults and to isolate affected areas. They claim that their approach is able to localize a fault in less than two seconds. As Holons do not require physical separation, an isolated segment of a micro grid could continue its operation as a Holon.

3 HOLON MODEL

In this section, we contribute a formalized Holon model. The term holon was first described by Arthur Koestler (Koestler, 1967) as a modeling scheme for autonomous entities that can consist of other, smaller autonomous entities. Our model represents autonomous sets of energy producers and consumers inside city networks. The overall goal is to evolve smart grids into more resilient energy grids by overcoming the limitation of only having predefined micro grids. Hereby, our understanding of resilience is aimed at a system which provides a high degree of service availability. Blackout scenarios result into isolated city networks with specific energy production and consumption configurations. Such a "snapshot" of a city network is represented by one energy grid instance as defined below.

3.1 Formal Model

We model an energy grid as graph $G = (N, E)$ of nodes N with edges $E \subseteq N \times N$. The whole energy grid builds one *connected component*. A node $n \in N$ can be classified into one of the following sets: *Producers* $P = \{p_i \mid p_i \in N\}$ that produce energy in the grid, *Consumers* $C = \{c_i \mid c_i \in N\}$ that consume energy in the grid, or *Junctions* $J = \{j_i \mid j_i \in N\}$ that split power cables if necessary, e.g., at crossroads.

For simplicity we define $P \cap C = P \cap J = C \cap J = \emptyset$. Any object that has to be covered by more than one class can be (virtually) split into subnodes, so that the subnodes can be correctly classified as either producers, consumers or junctions.

The function

$$power : N \to \mathbb{R} : n \to \begin{cases} \mathbb{R}^+ & \text{if } n \in P \\ 0 & \text{if } n \in J \\ \mathbb{R}^- & \text{if } n \in C \end{cases}$$

returns the production or consumption of a node in an energy grid. While the producers supply energy to the grid and have a positive power value, the consumers draw energy from the grid and have a negative power value. A junction does not change the overall energy and therefore, it has a power value of 0.

The function

$$cap : E \to \mathbb{N}_0^+ : e \to cap(e)$$

returns the capacity of a power cable for transmitting energy. Thereby, the capacity is defined by the breaking capacity of the respective fuse that protects the power cable.

A Holon is a connected subgraph $H = (N_H, E_H)$ with $N_H \subseteq N$ and $E_H = \{(n1, n2) \in E : n1, n2 \in N_H\}$ and can be thought of as kind of Peer-to-Peer–Overlay that does not alter edges. In order to transmit energy, the Holon has to be connected, i.e., the Holon has to form a single connected component.

Additionally, the available energy within a Holon must be transmittable from producers to the respective consumers by the existing power cables, leading to a *valid* Holon.

3.2 Valid Holons

A holon has to fulfill few prerequisites to be able to supply consumers with energy in a distributed way.

- The first important requirement is the connectivity. As stated before, connectedness is only a necessary but not a sufficient condition for a Holon.
- Moreover, the sum of produced and consumed energy has to be in balance:

$$\sum_{p_i \in P} power(p_i) = \sum_{c_i \in C} power(c_i)$$

- A third requirement is the sufficient capacity of power cables. At no time shall an energy flow surpass the maximum capacity of any edge in a Holon. Therfore, $\forall e \in E_H : flow(e) \leq cap(e)$ has to hold. This requirement can be reduced to a max-flow problem (Schroeder et al., 2004).

Max-flow problems can be solved with the Dinic algorithm (Dinic, 1970) or the Ford-Fulkerson (Ford and Fulkerson, 1956) algorithm. In order to be able to compute these algorithms, an additional source as well as an additional sink are introduced into the graph. The source is connected to all producers by edges with their weights equaling the capacities of the respective producers. Similar, all consumers are connected to the sink by edges with their respective consumption values.

4 EVALUATION

In order to evaluate the effects of applying our Holon approach to city networks, we conducted a large-scale simulation based on randomly generated city networks.

These city networks are generated based on parameters we obtained from measurements and experiences of a German network operator. The city networks consist of different energy producers, consumers, and power cables, each with specific capabilities.

Our aim is to gather information on how the Holon approach performs in comparison with predefined, fixed micro grids. Especially, we are interested in specifics that distinguish Holons from static micro grids.

4.1 Real-world Test Site

The Holon approach will be evaluated in the context of a publicly funded research project PolyEnergyNet in a real-world test site. The test environment which served as basis for evaluation is based on the city network of a real-world, medium sized German city with an industrial quarter with PV systems and consumers.

The setup of the following simulation is based on time-snapshot measurements taken in the test site and on know-how of the local network operator.

Consumer households usually draw 2–3 kW from the city network. PV systems within city networks generate 5 kW up to 60 kW under optimal conditions. The two cable types typically used for wiring are protected by fuses that allow 150 kW or 185 kW to pass the network. These values are used to generate random city networks and to evaluate our approach.

4.2 Simulation Setup

As stated before, our simulation generates random city networks based on parameters obtained from measurements in a real-world test site and on know-how of a network operator. All parameters are shown in Table 1.

Table 1: Parameter values used for the generation of random city networks.

Parameter	Value
Network Size	10–25 nodes
Producers	10%
Consumers	80%
Junctions	10%
Production Values	$\{5, 20, 30, 40, 60\}$ kW
Consumption Values	$\{10, 15, 20, 30\}$ kW
Cable Capacities	$\{150, 185\}$ kW

4.2.1 Network Size

Every city network was chosen to have about 10–25 nodes in total. Thereby, every consumer node represents 5–10 single households sharing one power cable.

4.2.2 Node Class Probabilities

Based on our observations, we modeled the city networks to consist of 80% consumers, 10% producers, and 10% junctions.

4.2.3 Consumption and Production Values

The network operator describes a consumption of 2–3 kW as typical value for a household. Thus, consumer nodes with 5–10 households consume either 10, 15, 20, or 30 kW. The production values for producer nodes are chosen in the same fashion.

4.3 Research Questions

The simulation is used to investigate the following research questions:

1. How many of the generated city networks can operate in complete as micro grids?
2. How many non-functional micro grids can operate in parts as Holons?
3. How much of a city network can covered by Holons?
4. How does the size of city networks influence the amount of nodes covered by Holons?

Figure 4 shows a city network consisting of seven nodes and one additional junction. As can be seen, there are three valid holons in the network:

- *Producer 1*, *Consumer 3*
- *Producer 3*, *Consumer 2*, and *Consumer 3*
- *Producer 2*, *Consumer 1*

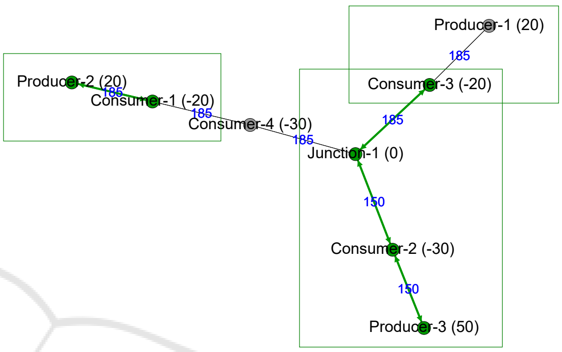

Figure 4: An exemplary city network with three Holons and 71.4% coverage.

Because of the overlap of the first two holons, namely in *Consumer 3*, the maximum coverage of this city network with Holons is given by the five green nodes in Figure 4. A fixed micro grid would not be able to operate in islanded operation, while the Holon approach would power 71.4% of the city grid.

5 RESULTS

The following results are based on 10,000 randomly generated and evaluated city networks. Each city network was generated according to the parameters in Table 1.

5.1 Comparison with Micro Grids

Out of the 10,000 generated city networks, only 25 (0.25%) expose valid micro grids. Thus, these 25 city networks also form Holons, which include all nodes from the generated city network.

6,139 (61.39%) city networks contain valid Holons, that is, at least one valid Holon configuration is present. The number of Holons within a city network increases with the size of the city networks. In larger city networks, more producers and junctions will appear, thus enabling more valid combinations according to our model. On average, 2.46

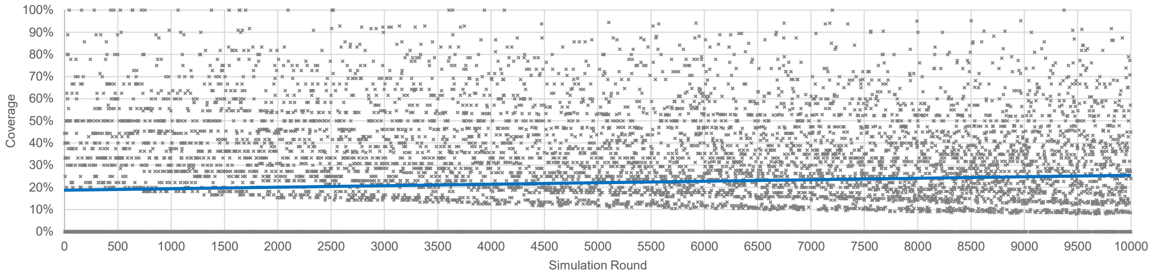

Figure 5: Distribution of city network supply coverage. The rounds on the x-axis are sorted ascendingly with respect to the city network size. This result shows higher ratios of coverage with growing network sizes on average, as more nodes contribute to a more coarse-grained distribution and promote the chances of valid Holon setups.

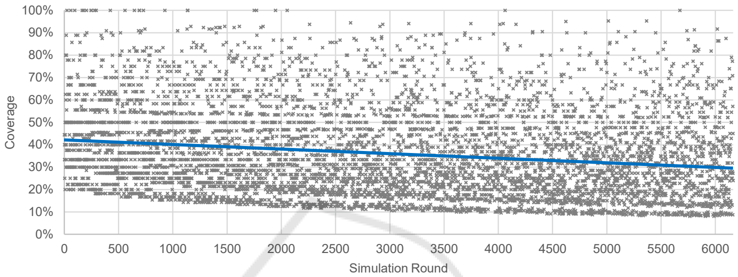

Figure 6: Distribution of city network coverage, omitting city networks without valid Holons altogether. The rounds on the x-axis are sorted ascendingly with respect to the city network size. The reverse trend can be explained by higher average coverage values due to not considering solutions with 0 solutions.

valid holons exist in every city network. 22.08% of all buildings can be supplied on average by the largest possible combination of Holons within the same city network.

5.2 Influence of City Networks Without Holons

Substantial differences can be observed when distinguishing on the analysis of gathered data from city networks with at least Holon present and complementary data from city networks allowing also 0-Holon configurations. In cases where there is at least one valid Holon, there are three further Holons to find. This means, that usually you will find on average 4 Holons per network if you neglect networks which do not meet the Holon criteria at all. The average supply coverage also increases from 22.08% to 35.73% in these networks.

Table 2 summarizes the number of found holons and the supply coverage ordered by the city network size for all investigated city networks. Table 3 presents the same data for city networks with at least one valid Holon present.

The histogram in Figure 7 shows how city networks without valid Holons are distributed over city network size. As can be seen, with an increasing number of nodes, the amount of city networks without

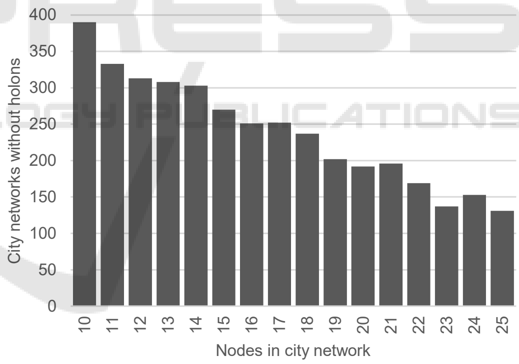

Figure 7: Distribution of cells without any solution in relation to cell size.

valid Holons decreases. This observation may contribute to the difference between the results shown in Tables 2 and 3.

5.3 Coverage Distribution

A look at the distribution of the overall supply coverage (cf. Figures 5 and 6) yields three observations:

- There appears to be a correlation between small city network sizes and the probability of finding either a Holon that covers the whole city network or finding no Holon at all. However, it is much

Table 2: Evaluation results for all city networks, including those without valid Holons.

Network	Holons Found		Supply Coverage	
Size	avg.	med.	avg.	med.
10	0.70	0	17.62%	0.00%
11	0.78	0	18.17%	0.00%
12	1.06	0	20.70%	0.00%
13	1.07	1	20.19%	15.38%
14	1.37	1	21.11%	15.38%
15	1.64	1	22.02%	15.38%
16	1.87	1	22.76%	18.75%
17	1.93	1	20.43%	17.65%
18	2.23	1	21.74%	17.65%
19	2.94	1	24.76%	21.05%
20	2.80	2	23.23%	20.00%
21	3.30	2	23.64%	21.05%
22	3.42	2	22.69%	19.05%
23	3.96	2	24.22%	22.22%
24	4.71	2	24.34%	21.05%
25	5.75	2	25.52%	20.83%

Table 3: Evaluation results for city networks that include at least one valid Holon.

Network	Holons Found		Supply Coverage	
Size	avg.	med.	avg.	med.
10	1.79	2	45.06%	42.86%
11	1.85	1	43.28%	40.00%
12	2.20	2	42.90%	36.36%
13	2.13	2	40.11%	38.46%
14	2.52	2	38.79%	33.33%
15	2.83	2	38.00%	30.77%
16	3.17	2	38.64%	35.71%
17	3.21	2	34.02%	28.57%
18	3.54	2	34.52%	29.41%
19	4.25	2.5	35.78%	31.25%
20	4.03	3	33.38%	27.78%
21	4.69	3	33.63%	30.00%
22	4.74	3	31.46%	26.32%
23	5.10	3	31.19%	27.27%
24	6.23	3	32.20%	28.57%
25	7.33	3	32.53%	28.00%

more likely to find no Holons in such a setting.

- When including all city networks, the overall coverage by Holons increases with the city network size (cf. trend line in Figure 5). However, leaving out those city networks without any Holons, the overall coverage decreases (cf. trend line in Figure 6).
- Holons always have a natural number of nodes. Thus, the coverage values for small city networks are more coarse-grained.

6 CONCLUSION AND FUTURE WORK

In this paper, we investigated the adopted concept of Holons in city energy networks. Holons are regarded as enablers for decentralized energy producers inside city networks to supply power to consumers independently from external energy sources, like, power plants connected via the transmission network.

We conducted a large-scale simulation with random city networks based on experiences from a real-world test site to analyze the performance of the Holon approach. As the evaluation results show, Holons can power parts of city networks, even when they are disconnected from the transmission and distribution network during a blackout.

Our results show that the Holon concept is able to supply 22.08% of a city network on average. This coverage raises with increasing city network size while the probability of total blackouts drops.

We see this increase of coverage as an effect of higher flexibility when more producers and consumers are available inside the city network. Our future work will investigate how the flexibility in city networks can be increased. We will investigate how influencing the consumption of energy (and, likewise, the production of energy) by introducing lower and upper bounds for energy consumption relates to flexibility. We hope that increased flexibility enables higher coverage of city networks. Moreover, our investigation will include prioritization of specific consumers in order to favor critical infrastructures, like, hospitals, over other consumers in case of energy scarcity.

ACKNOWLEDGEMENTS

The work in this paper was performed in the context of the PolyEnergyNet project and partially funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) under grant no. “0325737E”. Additionally, this work has been co-funded by the DFG as part of project B.2 within the RTG 2050 “Privacy and Trust for Mobile Users”. The authors assume responsibility for the content.

REFERENCES

Amin, S. and Wollenberg, B. (2005). Toward a smart grid: power delivery for the 21st century. *IEEE Power and Energy Magazine*, 3(5):34–41.

BDEW (2014). Smart Grids Traffic Light Concept. Functional Interaction between the Market and the Regulated Sphere (Interim Report). Technical report, BDEW.

BDEW (2015). Smart Grids Traffic Light Concept. Design of the amber phase (Discussion paper). Technical report, BDEW.

Bessler, S., Drenjanac, D., Hasenleithner, E., Ahmed-Khan, S., and Silva, N. (2015). Using flexibility information for energy demand optimization in the low voltage grid. In *2015 International Conference on Smart Cities and Green ICT Systems (SMARTGREENS)*, pages 1–9.

Dinic, E. A. (1970). Algorithm for Solution of a Problem of Maximum Flow in a Network with Power Estimation. *Soviet Math Doklady*, 11:1277–1280.

Fang, X., Misra, S., Xue, G., and Yang, D. (2012). Smart grid – the new and improved power grid: A survey. *IEEE Communications Surveys Tutorials*, 14(4):944–980.

Farhangi, H. (2014). A road map to integration: Perspectives on smart grid development. *IEEE Power and Energy Magazine*, 12(3):52–66.

Ford, L. R. and Fulkerson, D. R. (1956). Maximal Flow through a Network. *Canadian Journal of Mathematics*, 8:399–404.

Guérard, G., Ben Amor, S., and Bui, A. (2015). A context-free smart grid model using pretopologic structure. In *2015 International Conference on Smart Cities and Green ICT Systems (SMARTGREENS)*, pages 1–7.

Hashmi, M., Hanninen, S., and Maki, K. (2011). Survey of smart grid concepts, architectures, and technological demonstrations worldwide. In *2011 IEEE PES Conference on Innovative Smart Grid Technologies (ISGT Latin America)*, pages 1–7.

Kausika, B., Dolla, O., Folkerts, W., Siebenga, B., Hermans, P., and van Sark, W. (2015). Bottom-up analysis of the solar photovoltaic potential for a city in the netherlands: A working model for calculating the potential using high resolution lidar data. In *2015 International Conference on Smart Cities and Green ICT Systems (SMARTGREENS)*, pages 1–7.

Koestler, A. (1967). *The ghost in the machine*. Hutchinson London.

Kroposki, B., Lasseter, R., Ise, T., Morozumi, S., Papatlianassiou, S., and Hatziargyriou, N. (2008). Making microgrids work. *IEEE Power and Energy Magazine*, 6(3):40–53.

MVV Energie AG (2012). Model City Mannheim. http://www.modellstadt-mannheim.de/.

Ramesh, M. V., Mohan, N., and Devidas, A. R. (2015). Micro grid architecture for line fault detection and isolation. In *2015 International Conference on Smart Cities and Green ICT Systems (SMARTGREENS)*, pages 1–6.

Saad, W., Han, Z., and Poor, H. (2011). Coalitional game theory for cooperative micro-grid distribution networks. In *2011 IEEE International Conference on Communications Workshops (ICC)*, pages 1–5.

Schiffer, J. (2015). *Stability and power sharing in microgrids*. PhD thesis, Technische Universität Berlin.

Schiller, C. A. and Fassmann, S. (2010). The Smart Micro Grid: IT challenges for energy distribution grid operators. Technical report, IBM.

Schroeder, J., Guedes, A., and Duarte Jr, E. P. (2004). Computing the minimum cut and maximum flow of undirected graphs. Technical report, Federal University of Paraná.

Shafiee, Q., Guerrero, J., and Vasquez, J. (2014). Distributed secondary control for islanded microgrids – a novel approach. *IEEE Transactions on Power Electronics*, 29(2):1018–1031.