ENERGY 2017

The Seventh International Conference on Smart Grids, Green Communications and IT Energy-aware Technologies

ISBN: 978-1-61208-556-2

May 21 - 25, 2017

Barcelona, Spain

ENERGY 2017 Editors

Steffen Fries, Siemens, Germany

Mark Apperley, University of Waikato, New Zealand

ENERGY 2017

Foreword

The Seventh International Conference on Smart Grids, Green Communications and IT Energy-aware Technologies (ENERGY 2017), held between May 21 - 25, 2017 - Barcelona, Spain, continued the event considering Green approaches for Smart Grids and IT-aware technologies. It addressed fundamentals, technologies, hardware and software needed support, and applications and challenges.

There is a perceived need for a fundamental transformation in IP communications, energy-aware technologies and the way all energy sources are integrated. This is accelerated by the complexity of smart devices, the need for special interfaces for an easy and remote access, and the new achievements in energy production. Smart Grid technologies promote ways to enhance efficiency and reliability of the electric grid, while addressing increasing demand and incorporating more renewable and distributed electricity generation. The adoption of data centers, penetration of new energy resources, large dissemination of smart sensing and control devices, including smart home, and new vehicular energy approaches demand a new position for distributed communications, energy storage, and integration of various sources of energy.

We take here the opportunity to warmly thank all the members of the ENERGY 2017 Technical Program Committee, as well as the numerous reviewers. The creation of such a high quality conference program would not have been possible without their involvement. We also kindly thank all the authors who dedicated much of their time and efforts to contribute to ENERGY 2017. We truly believe that, thanks to all these efforts, the final conference program consisted of top quality contributions.

Also, this event could not have been a reality without the support of many individuals, organizations, and sponsors. We are grateful to the members of the ENERGY 2017 organizing committee for their help in handling the logistics and for their work to make this professional meeting a success.

We hope that ENERGY 2017 was a successful international forum for the exchange of ideas and results between academia and industry and for the promotion of progress in the fields of smart grids, green communications and IT energy-aware technologies.

We are convinced that the participants found the event useful and communications very open. We also hope that Barcelona provided a pleasant environment during the conference and everyone saved some time for exploring this beautiful city.

ENERGY 2017 Chairs:

Steffen Fries, Siemens, Germany
Akhtar Kalam, Victoria University, Australia
Vincenzo Gulisano, Chalmers University of Technology, Sweden
Marco Lützenberger, Technische Universität Berlin, Germany
Evangelos Pournaras, ETH Zurich, Switzerland
Angela Russo, Politecnico di Torino, Italy
Chun-Hsi Huang, University of Connecticut, USA
Mark Apperley, University of Waikato, New Zealand
Magnus Almgren, Chalmers University of Technology, Sweden

ENERGY Industry/Research Advisory Committee
Hongbo Sun, Mitsubishi Electric Research Laboratories, USA

Daisuke Mashima, Advanced Digital Sciences Center, Singapore
Sambaran Bandyopadhyay, IBM Research, India
Eric MSP Veith, TU Bergakademie Freiberg, Germany
Dragan Obradovic, Siemens - Corporate Technology, Munich, Germany
Chresten Træholt, Center for Electric Power and Energy - CEE | Technical University of Denmark - DTU, Denmark

ENERGY 2017

Committee

ENERGY Steering Committee

Steffen Fries, Siemens, Germany
Akhtar Kalam, Victoria University, Australia
Vincenzo Gulisano, Chalmers University of Technology, Sweden
Marco Lützenberger, Technische Universität Berlin, Germany
Evangelos Pournaras, ETH Zurich, Switzerland
Angela Russo, Politecnico di Torino, Italy
Chun-Hsi Huang, University of Connecticut, USA
Mark Apperley, University of Waikato, New Zealand
Magnus Almgren, Chalmers University of Technology, Sweden

ENERGY Industry/Research Advisory Committee

Hongbo Sun, Mitsubishi Electric Research Laboratories, USA
Daisuke Mashima, Advanced Digital Sciences Center, Singapore
Sambaran Bandyopadhyay, IBM Research, India
Eric MSP Veith, TU Bergakademie Freiberg, Germany
Dragan Obradovic, Siemens - Corporate Technology, Munich, Germany
Chresten Træholt, Center for Electric Power and Energy - CEE | Technical University of Denmark - DTU, Denmark

ENERGY 2017 Technical Program Committee

Ahmed Al-Salaymeh, University of Jordan, Jordan
Magnus Almgren, Chalmers University of Technology, Sweden
Mark Apperley, University of Waikato, New Zealand
Sambaran Bandyopadhyay, IBM Research, India
Chakib Bekara, University of Tlemcen, Algeria
Rachid Benchrifa, Mohammed V University, Morocco
Erik Buchmann, Hochschule für Telekommunikation Leipzig (University of Applied Sciences) Leipzig, Germany
Davide Careglio, Universitat Politècnica de Catalunya, Spain
Hsi-Ya Chang, National Center for High-performance Computing, Taiwan
Antonin Chazalet, Orange, France
Margot Deruyck, iMinds - Ghent University - INTEC - WAVES, Belgium
Rekioua Djamila, University of Bejaia, Algeria
Essam E. Khalil, Cairo University, Egypt
Khaled Elbassioni, Masdar Institute of Science and Technology, Abu Dhabi, UAE
Tullio Facchinetti, University of Pavia, Italy
Steffen Fries, Siemens, Germany
Vincenzo Gulisano, Chalmers University of Technology, Sweden
Patrick Heinrich, Fraunhofer Institute for Embedded Systems and Communication Technologies ESK,

Table of Contents

Implementing Load Management in Manufacturing Companies: A Feasible Approach

Jan Hicking, Steffen Nienke, Günther Schuh
Institute for Industrial Management
at RWTH Aachen University (FIR)
Aachen, Germany
E-mail: Jan.Hicking@fir.rwth-aachen.de

***Abstract*—In order to introduce load management in the manufacturing industry, some obstacles need to be pointed out. This paper presents a feasible approach on how to implement load management measures in companies. To do so, load management and energy management are explained and distinguished in a first step. Subsequently, the implementation method is introduced. Therefore, by using this paper, companies will be enabled to use load management measure and reduce their energy costs significantly.**

Keywords - Load management; Energy management; Energy Monitoring; Manufacturing industry; Renewable energies.

I. INTRODUCTION

In a continuously changing production environment, the ability to stay competitive depends for the majority of companies on the production price of a product [1]–[3]. The ability to produce a product at lower costs can lead to a significant market advantage. Therefore, the ideal adjustments of essential target values like occupancy, timelines, or process costs are crucial for a company's success [2]. However, the costs for resource, energy and production utility raised in the last decades dramatically [4].

In particular, the price for electrical energy in Germany has risen severely over recent years. This development refers to the increasing expansion of renewable energy [1]. Within the implementation of the priority access of renewable energy the prices for electrical energy raised [5]. This development refers to the fact, that the EEG-allocation (EEG: German Renewable Energy Sources Act, legislation to foster the use and invest in renewable energies) in Germany increases in the amount of expanding renewable energies [6]. As a result of the expansion of renewable energy the grid stability is endangered [7]. The priority access of volatile renewable energy leads to an unsecure supply reliability, which is one of the most important location factors for the German manufacturing industry [8].

Raising energy prices promotes a significant competitive disadvantage for the manufacturing industry shown in Figure 1 [5]. Moreover, growing scarcity of resources pushes energy prices [1]. Especially the scarcity of resources in the past increased environmental awareness in society and industry [2][9].

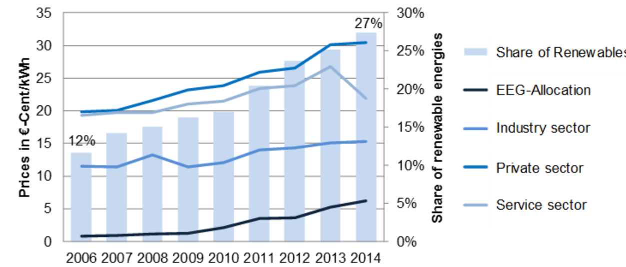


Figure 1. Development of energy prices [10]

In order to guarantee the grid security and create a greater environmental compatibility, Germany published a target to develop the most energy efficient and environmental friendliest economy in the world [11]. The focus of this program is the expansion of renewable energy. To compensate the incoming side effects like increasing energy prices flexibility mechanisms are even more relevant. The management of loads in the electrical grid can be realised by using flexibility potentials in manufacturing industry. The identification of those potentials is very important. Hence the survey of process-specific energy data in the manufacturing industry is necessary to point out any potential [12]–[14]. In this context, information gathering can be done by continuous energy monitoring of manufacturing companies [2]. Many companies are struggling to identify which information is necessary for load management and how the information can be collected. Consequently, there is a lack of a structured approach on how to create the information base to archive the energy transparency as a first step to load management. The presented approach focusses on the manufacturing industry, as literature research confirms, that this area has the greatest potential for load management. However, the concept can easily be adopted to other application areas (e.g. Office buildings).

In Section 2, this paper describes fundamentals of load management concepts. In Section 3 it then focusses on the implement of load management in the manufacturing industry. Considering, among other things, organisational requirements as well as the necessary transparency of the energy system, this paper develops a general approach to introduce load management in manufacturing companies.

 ISBN: 978-1-61208-556-2

II. DEFINITIONS AND FUNDAMENTALS

Describing basic concepts and distinguishing several terms within the field of energy management, load management and energy efficiency is essential to get a common understanding of the presented work. In contrast to base loads that is covered by conventional power plants like lignite-fired power plants or nuclear power plants, the sustainable generation in renewable energy plants usually cannot be controlled. These circumstances lead to a discrepancy between feed-in time and amount of fed-in power of some renewable energy technologies like wind and solar systems [7][15][16]. To get deeper understanding of this, Figure 2 visualises a comparison of installed and given power of renewable energy technologies. The figure displays the discrepancy of installed and given power of renewable energy technologies in January, May and June. Biomass and hydropower are not volatile. Therefore, the loads are nearly constant or were reduced by demand management. The behaviors of Solar and Wind plants are quite different. The strong volatility of solar can be seen in the difference between January and May. Wind, on the other hand, covers 70% of the installed load in January, but drops the production close to zero in June.

German electricity transmission system operators compensate the incoming volatility by using control energy. Within this concept manageable power plants like gas turbine plants or pumped-storage power plants are usually used [17]. The control energy concept leads to dealing with peak loads or loss loads properly [18]. In Summary it can be said, that through expanding renewable energy in the electrical grids the supply reliability cannot be guaranteed. Dealing with the volatility of renewables refers to the priority access of those ones legitimated by EEG-allocation. Control energy uses load flexibilities to secure supply reliability. This is necessary to ensure the critical success factor like low energy prices for a society with a manufacturing industry as leading edge. However, energy prices are rising. Therefore, load management is one possible opportunity to compensate increasing energy prices.

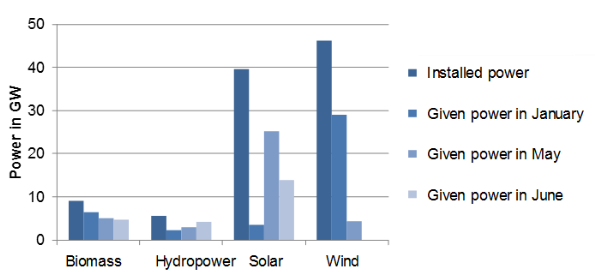


Figure 2. Renewable energy volatility [19]

A. Definition of Energy

Energy is a fundamental factor. Several types of energy can be transformed into each other, but neither be created nor exterminated [7][14][20]. Energy is used to heat buildings or to warm up process fluids to a high temperature (space or process heat). Besides that, energy is used to drive engines within machines or vehicles. In this context, energy is called mechanical energy or electrical energy.

B. Definition of Energy efficiency

The term “efficiency” follows its Latin origin “efficientia” which means efficacy [21]. Energy efficiency is the relation between benefit and initial energy input [22]. Energy efficiency also describes an intelligent usage of the initial input aiming to use the available energy as efficient as possible [13]. Following this definition, energy efficiency is increased by reducing energy consumption while (simultaneously) keeping the energy benefit constant [23].

C. Definition of energy management

The introduction of energy management in the manufacturing industry will have an impact on increasing sustainability, receiving environment and lowering energy costs [9][24]–[26]. Energy management is defined as an instrument of coordination aiming an ecological and economical satisfaction of energy requirements in companies. This goal is realized by a predictive, organised and systematic approach of energy production, procurement, storage, distribution and usage [27][28].

Energy management can be considered from two perspectives. There is a technical perspective dealing with energy monitoring, analysing the energy data and deriving plans of action to achieve defined goals. Furthermore, there is an organisational perspective which follows a holistic view of energy consumption and usage in processes, proceedings and procedures in the manufacturing industry [9]. To achieve goals, such as raising energy efficiency or reducing energy costs, energy management uses approaches like investing in new technologies, changing behaviours and identifying energy saving opportunities [29]. Referring to the identified approaches and goals of energy management, load management describes one aspect of energy management.

D. Definition of load management

First, load management must be distinguished from demand side management (DSM), since both terms are easily mixed up. Demand Side Management is a generic term for different approaches of systematically switching loads. It contains load management, energy saving approaches, fuel substitution and load optimisation [30]–[32]. Load management, however, describes the way to achieve the goal of changing the point of time and amount of load that is required [31]. Hence, load management describes the temporal relocation of energy consumption [12]. In addition to that definition load management is defined as switching loads on and off [13]. Therefore, load management focuses on internal processes, to reduce load peaks and thus reduce energy costs [33]. Examples of load management are described in the following chapter.

 ISBN: 978-1-61208-556-2

E. Measures of load management

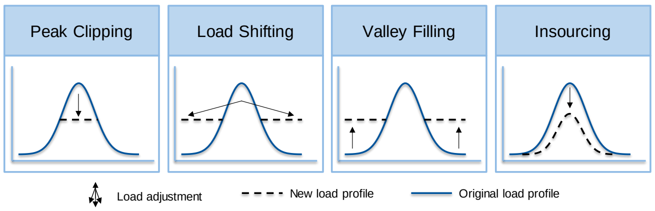


Figure 3. Load management measures

To avoid energy costs due to load peaks, load management focuses four different types of measures as shown in Figure 3 [30]–[32][34]. In the following, the different types are explained. "Peak Clipping" describes the immediate handling of peak loads. Thereby peak loads are reduced by a specific amount which reduces the energy costs significantly [30]–[32]. It is achieved by ejecting loads to prevent a significant peak load [35][36]. Using energy storage technologies are another opportunity to prevent peak loads by feeding-in energy at the point a peak load would occur [37].

"Load Shifting" also describes the immediate handling of peak loads. However, in this case, technologies are introduced to reduce peak loads. Energy storage technologies enable companies to temporary switch production processes. The change of organisational or production processes leads to a reduction of peak loads. Although energy is not saved, energy costs are significantly reduced. The energy consumption of several production procedures is not saved but switched to a point of time in there is no risk of peak load [30]–[32].

"Valley Filling" describes a load management measure, which lifts the base load of a company to cut the average electricity price. This measure accompanies with a change of energy contract of the energy supplier. Because the total energy consumption is increased, the load profile is polished. Any energy supplier prefers a polished load profile and will remunerate those profiles. Another use case is a loading of electric cars in the night. The raised load in off-peak times polishes the whole load profile.

The last measure of load management is named "Insourcing". It describes the reduction of energy purchase. Unlike "peak clipping", "insourcing" reduces the load profile holistically. There is no need for a specific peak load analysis. Companies reduce the energy purchase by producing a specific energy amount themselves. Achieving this goal, companies need new energy production technologies like cogeneration units or PV-plants in combination with an energy storage.

In order to summarise and classify these findings, the following Figure 4 explains in several layers how terms like energy and load management relate. The top layer represents the concept layer. As described earlier, operational energy management is the primary term. Energy management comprises several goals and measures.

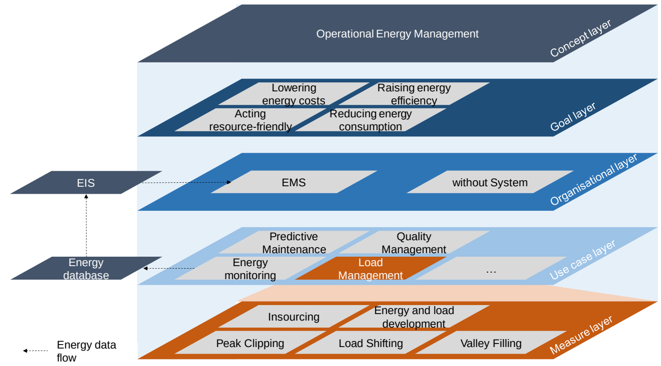


Figure 4. Content of operational energy management

Hereafter follows the goal layer. In this layer, all goals of energy management are summed up. It starts with lowering energy costs, raising energy efficiency, acting resource-friendly and finishes with reducing energy consumption. These goals which have their origin in the operational energy management, can be achieved be various actions. The organisational layer describes two typical types how energy management topics can be addressed. On the one hand, companies can implement a holistic energy management system (EMS) that is standardized by a German, European or international institutions. On the other hand, a not standardized solution to achieve the formulated goals can be realised without using such a system. In this case, the organisation of the individual solution falls in the responsibility of the company. For an appropriate usage of an energy management system, the information flow must be organised properly. Therefore, an energy database for continuous memorizing energy data would be crucial. Thus, the measured data is always ready for a delivery on demand. For a company, it is important to receive data and information to the exact right point of time, spot and quality. Therefore, the introduction of an energy information system (EIS) is necessary. The combination of an energy management system, energy information system and energy database is the best way to deliver information and data to the type of quality as further up explained. The use caser layer describes different applications within the energy management context. The focus of this paper is on the field of load management, but it is worth mentioning, that use cases like predictive maintenance, quality management and energy monitoring can also achieve energy management goals. All aspects have in common that they collect data which must be memorized for later using.

The last layer is the measure layer. This layer contains all load management approaches. In principle, all terms of the layer above have their own measures on the layer below. Hence, this figure represents one expression from a concept to certain measure in energy management context and load management application.

 ISBN: 978-1-61208-556-2

III. IMPLEMENTATION OF LOAD MANAGEMENT IN THE MANUFACTURING INDUSTRY

Companies should be supported by the following approach to introduce load management. It should give answers to questions such as: how can load management implemented holistically? Where are the benefits?

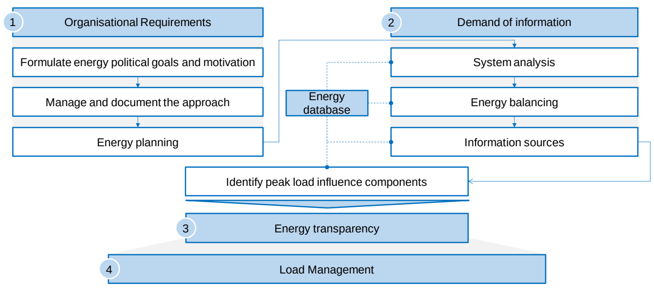


Figure 5. Load management introducing approach

The approach in Figure 5 contains four essential steps. First, companies must meet the organisational requirements. Second, companies must fulfil the demand of information. Third, when the demand of information is accomplished, the required energy generation/consumption transparency can be achieved. Fourth, once all required foundations are provided the load management can be introduced by implementing load management measures.

A. Organisational requirements

The reduction of energy consumption is a long term process. Therefore, it is recommended that the introduction of load management must be well organised and controlled. The organisational requirements are basically described by the DIN EN ISO 50001:2011. But not all requirements to introduce load management are addressed in this standard. First, it is important that companies create an energy policy. A policy in this context must contain energy long-term goals. Furthermore, it must contain a motivation that is communicated within the company, because the employees shall live and realise those policies. The policy must be formulated close to reality, comprehensible and goal-orientated. Moreover, a company must implement a process of documentation. Besides that, a company must develop an energy plan to summarise all goals, approaches and review processes. Within an energy plan, a company decides which energy data must be collected, how data can be collected, how does a data working process looks like and how a company would work with the information flows. Those steps are important to build a fundament for the introduction of load management.

B. Demand of information

Every measure within the context of load management works with real time data. Collecting those data is therefore a necessary requirement. To acquire the required information in a continuously changing environment, data must be collected in various dimensions of the company, e.g., company's location, buildings, rooms, production processes and energy sources. This kind of consideration is called system analysis. The objective is to create a holistic flow sheet of all forms of energy and its use locations. Assuming an overall system, to achieve a holistic flow sheet, it has to be broken down to its source elements.

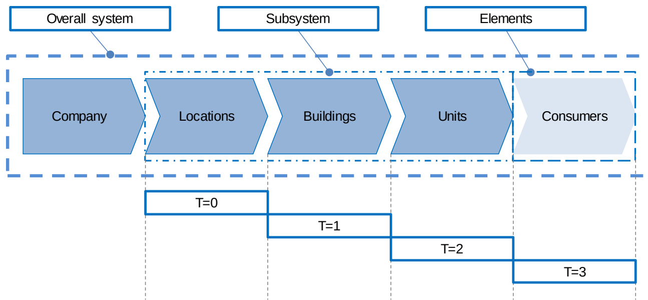


Figure 6. System analysis [22]

Figure 6 represents a typical construct of a company in the manufacturing industry. Dividing this construct in three types of system elements, it is shown that there are different degrees of depth. Starting with the overall system, which contains all given components, a company has its locations (T=0). The location level is the first layer. Diving in the subsystem, a location contains at least one building (T=1). The building level is the second layer. Each building contains at least one unit of its company for example production, supply, quality management or services (T=2). The unit level is the third layer. The deepest layer are the energy consumers (T=3). For example, there are machine tools, cooling energy generation or printers. The consumer level is the last layer. In order to achieve energy transparency in a company, a system analysis is fundamental. Close to a system analysis is the balancing. The goal of both concepts is to disperse the areal boundaries of energy consumers in a company for transparent visible consumer structure.

Once all energy consumers in a company have been identified, the next step would be to determine where they are located, what form of energy they are using and when they are consuming how much energy. Consequently, an energy monitoring system must be implemented to collect the real-time consumption data. The collected real-time data must be memorized in a database. But there are circumstances, for example financial barriers, which inhibit a company to implement an energy monitoring system. In this case, there are different options to collect data. Literature has shown that there are just few energy consumers in the manufacturing industry with high impact on peak loads. By comparing the main energy consumers and the main energy conserve potentials in the manufacturing industry, a measurement priority listing can be determined:

1. Compressed air generation
2. Energy generation for cooling purposes
3. Ventilation system
4. Machine tools
5. Electrical system
6. Pumps

Influences to peak loads due to illumination or information and communication technologies are usually neither significant nor manageable. The list above shows, which consumers in the manufacturing industry must be prioritised when collecting real-time data.

C. Energy transparency

Collecting real-time data is a fundamental component to achieve energy transparency in a company. Real-time data is required to implement an autonomous load management in the future. The needed data acquisition is a separate challenge, which is discussed in other publications. In addition, the issue of IT security must be considered. The acquired data is now used to identify specific components of the maximum load peak of a company's load profile. Figure 7 presents an activity diagram which contains an approach to identify specifics peak load components.

Deriving essential elements of the diagram, it is noted that load profiles of energy consumers and the main load profile of a company are required. Furthermore, the specific consumer load profiles must be inspected for load peaks to the point of time when the main peak load occurs. After this step, all specific loads are summarized and compared with the amount of the main peak load. If there is a difference (<<if(n)>>) it must be ensured, that the data set is complete as possible. If there is no difference (<<if(y)>>) a visualisation of the result should be created. The next question asked is whether the result is detailed enough or not. To answer this question, a company's layer must be determined. As explained before, a company has several layers. Load management requires information about the peak load components in sufficiently detailed depth. The ideal case would be at plant level (T=3). Including these last steps, energy transparency is guaranteed. The described steps enable companies to get a detailed view over their energy consumption and which kind of consumer has the highest impact on the total consumption. Another advantage of implementing the whole energy monitoring process is that the result can be used to identify energy wastage.

This procedure was validated at a company. The energy transparency was established and it was shown that the energy generation for cooling purposes had a peak load share of 20%. This transparency allowed counter-measures to be implemented.

IV. CONCLUSION AND OUTLOOK

Load management leads to lower energy costs in companies working in the manufacturing industry. This paper described the requirements that needs to be fulfilled to implement a load management. With the presented approach, companies are enabled to collect these data and information in a well-structured development. Starting with fundamentals like formulating a company's energy strategy and an energy plan. Furthermore, the company is advised to motivate their employees and document the whole introduction process.

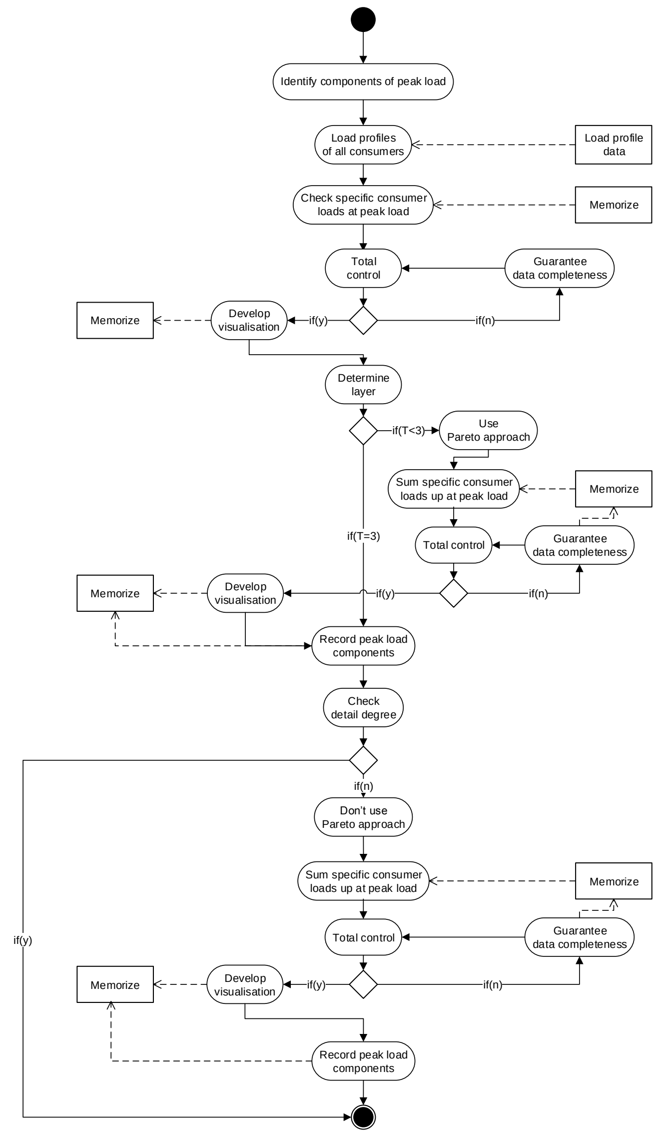


Figure 7. Identification of peak load components

Besides that, a company must start with a system analysis in order to create a transparent list of all energy consumers. Furthermore, a company must start with measurements in an early stage, to collect necessary data. Energy monitoring system assists companies in collecting important data and information regarding the energy consumption of machines, etc. Possible circumstances force companies to reject energy monitoring systems. In this case, the measurement of the energy consumption of prioritised consumers is recommended. This paper presented relevant consumers which have a high impact on the main peak load in the manufacturing industry. Using these fundamentals and the memorized data and information, energy transparency can be achieved by analysing collected and memorized data. Therefore, load profiles on all layers, such as buildings, units or consumers must be analysed following the presented approach. The result of this approach is detailed knowledge about every component of the main peak load. In the end, load management can be used to reduce energy cost in a company.

ACKNOWLEDGMENT

This article arose during the work of the authors, within the context of the research project FlAixEnergy (project number: 0325819A) funded by the Federal Ministry for Economic Affairs and Energy in Germany. The authors want to thank all donors, supporter and critics.

REFERENCES

[1] M. Schenk and M. Schumann, “Einleitung - Herausforderungen für die Produktion mit Zukunft,” in Produktion und Logistik mit Zukunft: Digital engineering and operation, M. Schenk, Ed., Berlin: Springer Vieweg, 2015, pp. 1–48.

[2] G. Schuh, Produktionsmanagement: Handbuch Produktion und Management 5, 2nd ed. Berlin: Springer Vieweg, 2014.

[3] G. Schuh and V. Stich, Eds., Grundlagen der PPS, 4th ed. Berlin: Springer Vieweg, 2012.

[4] T. Bauernhansl, Energieeffizienz in Deutschland - eine Metastudie: Analyse und Empfehlungen, 2014th ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2014.

[5] J. Gochermann, Expedition Energiewende, 1st ed. Wiesbaden: Springer Fachmedien Wiesbaden, 2016.

[6] S. Döring, Energieerzeugung nach Novellierung des EEG: Konsequenzen für regenerative und nicht regenerative Energieerzeugungsanlagen. Berlin: Springer Vieweg, 2015.

[7] H. Niederhausen and A. Burkert, Elektrischer Strom: Gestehung, Übertragung, Verteilung, Speicherung und Nutzung elektrischer Energie im Kontext der Energiewende. Wiesbaden: Springer Vieweg, 2014.

[8] BMWi - Bundesministerium für Wirtschaft und Energie, Ein Strommarkt für die Energiewende: Ergebnispapier des Bundesministeriums für Wirtschaft und Energie (Weißbuch). Berlin: Bundesministerium für Wirtschaft und Energie (BMWi), 2015.

[9] M. Geilhausen, J. Bränzel, D. Engelmann, and O. Schulze, Energiemanagement: Für Fachkräfte, Beauftragte und Manager. Wiesbaden: Springer Vieweg, 2015.

[10] BMWi - Bundesministerium für Wirtschaft und Energie, “Energiedaten: Gesamtausgabe: Stand: Januar 2016,” Jan. 2016.

[11] Deutsche Bundesregierung, “Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorung,” Berlin, Sep. 2010.

[12] M. Roscher, C. Maasem, and R. Martynski, “Intelligentes Energiemanagement in der Produktion: Effiziente Energienutzung in der Fertigung durch Energiemonitoren und Lastmanagement,” UdZ - Unternehmen der Zukunft, 2014, pp. 20–22, 2014.

[13] H. Seidl, C. Schenuit, and M. Teichmann, “Roadmap Demand Side Management. Industrielles Lastmanagement für ein zukunftsfähiges Energiesystem: Schlussfolgerung aus dem Pilotprojekt DSM Bayern,” Berlin, Jun. 2016.

[14] F. Wosnitza and H. G. Hilgers, Energieeffizienz und Energiemanagement: Ein Überblick heutiger Möglichkeiten und Notwendigkeiten. Wiesbaden: Vieweg+Teubner Verlag, 2012.

[15] P. Kurzweil and O. K. Dietlmeier, Elektrochemische Speicher: Superkondensatoren, Batterien, Elektrolyse-Wasserstoff, Rechtliche Grundlagen, 1st ed. Wiesbaden: Springer Vieweg, 2015.

[16] C. Köpp, H.-J. von Mettenheim, and M. H. Breitner, “Lastmanagement in Stromnetzen,” Wirtschaftsinf, vol. 55, no. 1, pp. 39–49, 2013.

[17] S. Lehnhoff, Dezentrales vernetztes Energiemanagement: Ein Ansatz auf Basis eines verteilten adaptiven Realzeit-Multiagentensystems. Wiesbaden: Vieweg+Teubner Verlag / GWV Fachverlage GmbH Wiesbaden, 2010.

[18] H. Voss, Modellierung des regionalen Erzeugungsangebots auf dem Elektrizitätsmarkt der Europäischen Union. Berlin: Lit, 2012.

[19] Fraunhofer ISE, Energy Charts. [Online] Available: https://www.energy-charts.de/contact_de.htm. Accessed on: Jun. 16 2016.

[20] B. Diekmann and E. Rosenthal, Energie: Physikalische Grundlagen ihrer Erzeugung, Umwandlung und Nutzung, 3rd ed. Wiesbaden: Springer Spektrum, 2014.

[21] J. Hesselbach, Energie- und klimaeffiziente Produktion: Grundlagen, Leitlinien und Praxisbeispiele, 1st ed. s.l.: Vieweg+Teubner (GWV), 2012.

[22] E. Müller, J. Engelmann, T. Löffler, and J. Strauch, Energieeffiziente Fabriken planen und betreiben, 1st ed. Berlin: Springer Berlin, 2009.

[23] W. Irrek and S. Thomas, “Definition Energieeffizienz,” Wuppertal, Jul. 2008.

[24] H. Wannenwetsch, Integrierte Materialwirtschaft, Logistik und Beschaffung, 5th ed. Berlin: Springer Vieweg, 2014.

[25] M. Schenk, S. Wirth, and E. Müller, Fabrikplanung und Fabrikbetrieb: Methoden für die wandlungsfähige, vernetzte und ressourceneffiziente Fabrik, 2nd ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2014.

[26] S. Hirzel, “Betriebliches Energiemanagement in der industriellen Produktion,” Karlsruhe, Sep. 2011.

[27] Energiemanagement - Begriffe, 4602-1, 2016.

[28] J. Kals and K. Würtenberger, “IT-gestütztes Energiemanagement,” HMD, vol. 49, no. 3, pp. 73–81, 2012.

[29] Manufacturing Execution Systems (MES) – Kennzahlen für Energiemanagement, 66412-4, 2015.

[30] CRA, “Primer on Demand-Side Management: With an emphasis on price-responsive programs,” Oakland, USA, Feb. 2005.

[31] S. C. Bhattacharyya, Energy economics: Concepts, issues, markets and governance. London: Springer, 2011.

[32] Arnusorn Saengprajak, “Efficiency of demand side management measures in small village electrification systems,” Dissertation, Universität Kassel, Kassel, 2006.

[33] M. Kruppa, “Lastmanagement im Unternehmen: Grundlagen,” 2015.

[34] Z. Hu, D. Maskovitz, and J. Zhao, “Demand-Side Management in China's Restructured Power Industry: How Regulation and Policy Can Deliver Demand-Side Management Benefits to a Growing Economy and a Changing Power System,” Washington, D.C., USA, Dec. 2015.

[35] Z. Hu, Integrated resource strategic planning and power demand-side management. Heidelberg, S.l.: Springer; China Electric Power Press, 2013.

[36] D. Y. Goswami and F. Kreith, Energy efficiency and renewable energy handbook. Boca Raton: CRC Press, Taylor & Francis Group, 2015.

[37] M. Kleber, “Leitfaden Lastgangmessung: für das Projekt Teilenergiekennwerte, gefördert durch das BMWi, erstellt durch das Fachgebiet Bauphysik & Technischer Ausbau (fbta),” Karlsruhe, 2010.

SEAM: Swarm Algorithms for Energy Allocation in Microgrids

Erik Buchmann and Jens Wagner
Hochschule für Telekommunikation Leipzig, Germany
Email: {buchmann|wagner}@hft-leipzig.de

***Abstract*—Microgrids are local energy distribution cells that include energy consumers and energy generators and may or may not be connected to wide-area transmission grids. By balancing consumption and supply locally, microgrids foster the transition to renewable energy sources that are less predictable than carbon-based ones. In this context, an important issue is to develop scheduling approaches for energy appliances that can be scaled to numerous independent, small energy consumers and generators. We propose SEAM, our approach for Swarm-based Energy Allocation in Microgrids. SEAM allows supply- and demand-side management based on a price signal that reflects over- or undersupply of energy. Together, all individual energy appliances that participate with SEAM form a swarm, which balances generation and consumption of energy. Thus, SEAM provides a distributed platform for transactive energy management with low entry barriers for participants and without a third party learning personal details from consumption data. To acknowledge that SEAM works as intended, we provide a formal framework that allows us to derive important properties regarding grid stability. Furthermore, we describe a model prototype using SEAM. Our prototype shows that SEAM can be realized easily and copes very well with fluctuating energy sources, as predicted by our framework.**

Keywords–Smart Grid; Demand Response, Swarm Approaches

I. INTRODUCTION

Right now, the number of renewable sources that feed energy into local energy grids (”Microgrids” [1], [2]) is growing worldwide, at an amazing pace. However, this comes with a number of open issues. First, existing power grids have not been designed to cope with numerous small energy sources that feed energy at variable rates. With classical energy grids, such fluctuating energy generators increase the need for spinning reserve energy. Second, most existing smart grid technologies that are available on the market yet focus on large installations, such as megawatt-sized power plants and industrial consumers in the same range. However, such technologies are by far too complex and too expensive to be deployed to many small, independent energy generators and consumers, e.g., roof-top photovoltaic (PV) installations or cold warehouses. Third, existing storage approaches, be it power-to-gas, compressed-air storage or battery banks, are unlikely to be deployed at a sufficiently large scale to keep pace with the installation of renewables in the near future.

In Germany, the highest peak in power consumption is at noon when the electrical ovens are turned on (e.g., see [3]). This fits with the peak generation of PV power plants. However, other countries face different problems when integrating renewables [4]. Furthermore, it can be regularly observed [5] that the price on the spot market for energy drops below 0 ct or that renewable energy sources are regulated down in favor of less adjustable traditional power sources [6]. In consequence,

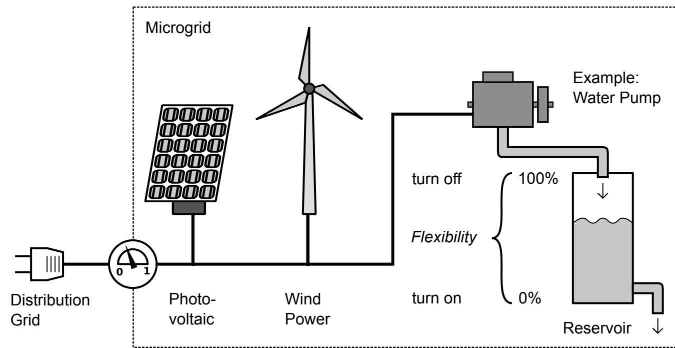


Figure 1. Basis scenario

there is a clear demand [4] for smart grid approaches that focus on the prosumer market (cf. Figure 1). Prosumers generate and/or consume energy at a small scale and may or may not have some flexibility to shift the energy supply and demand in time.

For example, prosumers might be the members of a rural cooperative that wants to use wind- and biogas-power plants to operate agricultural machines, drainage pumps and cold warehouses as much as possible from renewable energies that are locally available at little costs. Prosumers also could be the co-tenants of a sustainable city quarter, wanting to fuel thermal heat pumps, air conditioning, hot-water boilers etc. from roof-top PV installations and a combined heat-and-power-plant. A third example are islands, which want to shift from diesel-generated electrical power to renewable energies without having to install expensive battery banks.

With our approach, the energy-consuming or generating prosumers can alleviate the impact of fluctuating energy sources. For example, one prosumer might operate a raw-water reservoir for flushing the toilet while another one provides a roof-top PV installation. If both prosumers synchronize so that the raw-water pump starts if (a) the sun shines and the reservoir is not filled entirely, or (b) the reservoir is empty and must be filled immediately, the total demand for the spinning reserve of the grid operator decreases. A smart grid approach for such a scenario must fulfil a number of specific requirements:

R1: Balance Energy Consumption and Generation The smart grid approach must be able to tell each prosumer in real-time if it is cost-efficient to start or stop energy generators or consumers.

R2: Clear Benefit The installation of such technologies must pay for itself, beginning from the first energy appliance to be installed and within a reasonable period of time.

R3: Interoperability It must be possible to mix appliances

 ISBN: 978-1-61208-556-2

under control of a smart grid approach with energy appliances and infrastructures that already exist.

R4: Low Complexity Adding or removing smart grid appliances must be possible without having to inform or reconfigure other appliances. There should be no need for elaborate communication protocols.

R5: Robustness The approach should come with no single point of failures and must remain operative even if, say, the communication has been interrupted.

R6: Understandability The actions of each appliance under control of the smart grid approach must be directly comprehensible for the prosumer.

R7: Data Privacy The approach must do without any external instances that might learn in detail the energy appliances, preferences and habits of each prosumer.

In this paper, we propose SEAM, our approach for Swarm-based Energy Allocation in Microgrids on the prosumer level. We strive for a simple approach that can be installed on inexpensive off-the-shelf hardware and allows generation-side management and demand-side management for prosumers. That is, we assume that a grid operator exists, which balances over- and undersupply of energy, if this is beyond the capacities of the prosumers.

Our approach considers each energy appliance under control of SEAM as a swarm member. Thus, we want to obtain an emergent, complex swarm behavior as a result of the actions of many independent, distributed swarm members following simple rules without a central coordinator. In our case, each swarm member decides individually, based on a price signal and local information, if it should start or stop operating. The sum of the decisions of all swarm members converges to an emergent state where generation and consumption of energy is balanced as good as possible, which reduces the need for the spinning reserve at the site of the grid operator. From a business perspective, SEAM creates a distributed, privacy-aware platform for transactive energy management with low entry barriers for participants. In particular, we make the following contributions:

1) We describe the intuition behind SEAM, our approach for Swarm-based Energy Allocation in Microgrids.
2) We provide a formal framework for SEAM, which allows to assess its applicability to a given scenario, such as an insular grid or a urban microgrid.
3) We formally show under which conditions SEAM converges to a global state where energy consumption and generation is balanced.
4) We provide a description of a model prototype using SEAM.

Our prototype shows that the behavior of SEAM is in line with the properties derived from our formal framework. Furthermore, SEAM copes very well with fluctuating energy sources and unpredictable energy consumers.

Paper structure: The next section reviews related work. In Sections III and IV, we provide an intuitive and a formal description of SEAM. Section V analyzes the stability of SEAM, followed by a description of our prototype in Section VI. Section VII concludes.

II. Related Work

In this section we outline and compare general strategies for energy allocation in smart microgrids.

A. Smart Microgrids

Microgrids [1] are collections of energy consumers, energy sources and perhaps facilities for energy storage, functioning as a single system. A microgrid can be connected to a wide-area transmission grid. It also can be an autonomous system, using its own resources for energy generation and grid stabilization. Microgrids show their strengths in areas with heterogeneous loads, varying energy sources and long distances/few options to store energy locally [2]. One of the core objectives of today's microgrids and the focus of this work is to balance supply and demand in order to foster the integration of renewable energy sources. For this purpose, a number of alternatives exist:

Centralized forecasting approaches let a centralized coordinator compute a forecast of energy consumption and supply, based on a wide range of information. A typical example is a microgrid in Chile [7], which uses a neuronal network to continuously calculate a two-day forecast. The microgrid uses a rolling-horizon strategy to control battery banks, diesel generators and loads like water pumps. Another typical example [8] uses a genetic algorithm for forecasting. A characteristic feature of this example is that it uses not only weather information and load profiles, but also economic models and the energy price to produce an optimal schedule for all connected appliances. A novel high-frequency microgrid is shown in [9]. The advantage of high-frequency (500Hz) is the reduction of the transformation and transportation costs at smaller networks. The system works also with a two day forecast, optimization of loads like water pumps and optimization of storage systems like battery banks.

Multiagent systems allow to build decentralized microgrid coordinators. Each agent is free to implement its own scheduling strategy to, e.g., build a smart city grid [10], charge electrical vehicles [11] or route energy between grid segments [12]. Since the agents are autonomous to some extent, this approach allows flexible microgrids with low entry barriers that do not need to transfer sensitive personal information to a third party. As a disadvantage, the agent run-time environment is a critical infrastructure.

Hybrid approaches combine two or more different energy sources, such as PV and Diesel generators [13], Wind-PV-Diesel [14] or solar thermal-geothermal power [15] into an integrated energy appliance. The appliance uses a controllable energy source when a flexible one cannot meet the energy demand. Because the vendor ensures that both energy sources complement each other, this approach allows to build low-complexity microgrids. However, this approach does not support the integration of other prosumers.

Transactive energy focuses on the active participation of prosumers via market mechanisms [16]. That is, the grid operator calculates a net-metering price for energy at real-time, which includes the costs of consuming and generating energy as well as the costs of stabilizing the grid. Each prosumer can decide individually if he is willing to generate or consume energy to the given price. As experience shows [17], the technology works as intended, but the calculation of a good net-metering price heavily depends on big-data analytics, including weather forecasts, marginal costs at different generation plants, congestion data of the transmission grid and various factors related to grid stabilization.

Energy auction approaches transform supply and demand of energy into bids that are placed on a centralized auction platform. This platform performs double-sided continuous auc-

 ISBN: 978-1-61208-556-2

tions to obtain the optimal market price and energy allocation for any point in time. PowerMatcher [18] is a well-known implementation of such an auction platform. Similarly to multiagent systems, each participant is free to implement its own scheduling strategy. Extensions of PowerMatcher even have been developed to run hybrid systems [19]. However, it is difficult to derive reasonable bids [20], e.g., for renewables that generate energy nearly without marginal costs, or for heating systems where the user does not want to gamble a convenient temperature. Thus, the complexity of the system is high for prosumers that do possess detailed background knowledge. Furthermore, the bids reveal many personal details.

B. Swarm Approaches

Our approach has been inspired by collective swarm intelligence, as seen by ants, bees or birds. The common factor of collective intelligence is that a complex, ”smart” swarm behavior emerges from individuals who compete for resources based on straightforward rules and local ad-hoc information. Note that other definitions of swarm behavior additionally require interactions between neighboring swarm members. In our case, the resource is the price signal and the rules consider the valuation for energy. It is appealing to apply swarm concepts to microgrids. For instance, particle swarm algorithms (running on a central instance) can be used to optimize microgrid parameters [21], [22]. However, existing swarm algorithms (cf. [23], [24]) are difficult to distribute over a microgrid. One approach [25] allows a distributed architecture by modeling energy generation and consumption as a system of coupled oscillators. Since this model comes with a high complexity and binds the prosumers to a predefined scheduling strategy, this approach does not meet our requirements. Furthermore, some enterprises, e.g., Encycle, Easy Smart Grid, LichtBlick, GridSense and Siemens, are developing swarm approaches, with different directions of impact. Finally, a preliminary simulation study of our approach can be found at [26].

III. SEAM

Without loss of generality, assume a scenario as shown in Figure 1: A microgrid contains a PV site and a wind power plant, which feed energy into the microgrid at variable and less predictable rates. The major energy consumer in the microgrid is a raw-water pump, which fills a water reservoir. The pump has some demand-side flexibility: If the reservoir is full, the pump must be turned off. If the reservoir is empty, the pump must be turned on. In between, the pump may or may not be activated. The microgrid is connected with a distribution grid. The grid operator (a) provides energy if the local renewables do not provide enough energy to match the demand and (b) connects to spinning-, non-spinning- and frequency-response reserve power to ensure grid stability. In comparison to the normal energy supply, using reserve power is more expensive by some orders of magnitude. Furthermore, the transmission grid comes with transmission losses. Thus, the most efficient mode of operation is to consume the energy provided in the microgrid locally, i.e., to minimize the energy flow to and from the grid operator.

Now assume four pumps and an amount of energy provided over time as shown in the graph in Figure 2. Intuitively, an *optimal schedule* as shown in the figure would activate pumps in a way that their reservoirs never run empty. Furthermore, the schedule would activate many pumps in parallel if there

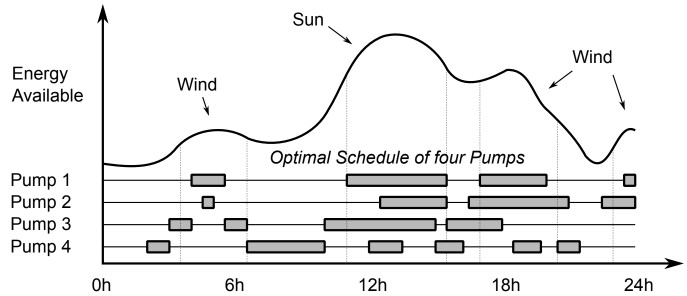


Figure 2. Example schedule

is a surplus of energy and deactivates pumps in case of an undersupply. Note that we do not make any restrictive assumptions on the kind of flexibility of the energy appliances. For example, an owner of an electrical vehicle might want to charge the battery to 30% immediately after coming home for spontaneous drivings. He might be willing to deliver energy to the microgrid if the battery is charged above 80%, and he might want the car to be charged to at least 60% at 7am each week day for commuting.

A. Scheduling Energy Appliances

Obviously, in reality an optimal schedule is impossible for supply- and demand-side management, since it would require a perfect forecast of the states of any energy appliance in the microgrid at any time in the future. With large grid installations, the law of large numbers mitigates the effect of local fluctuations in the energy supply and demand. In a microgrid, several alternatives already exist to obtain a *reasonable schedule*:

- A straightforward way would be to use a *timer switch*. The timer can be programmed so that the activity times of the pumps correspond with the typical hours of sunlight and wind. The effectivity of such a schedule is limited, but this approach is feasible for each prosumer without invoking third parties or installing sophisticated hardware.
- A *central coordinator* can do forecasting or implement an environment for a multi-agent system, as described in Section II. However, the coordinator puts the privacy of the prosumers at risk, comes with high total costs of ownership and requires a high overhead for installation, maintenance, configuration and communication.
- The third option is to implement a real-time market for energy, e.g., with transactive energy approaches or by using energy auctions. While such an approach comes with much lesser entry barriers for prosumers than a global coordinator, it still requires a trusted third party knowing personal details regarding the energy consumption of the prosumers. Furthermore, it known from economics that the efficiency of markets depend on perfect information.

B. The SEAM Approach

We have developed SEAM, a different approach based on swarm mechanics, as shown in Figure 3: An energy meter measures the amount of energy that is imported from the distribution grid into the microgrid. Based on this information, the energy meter calculates a price signal. The more energy is imported, the higher the price to consume energy and vice versa (left side of Figure 4). With SEAM, the price signal helps to shepherd the swarm of energy appliances similarly to pheromone trails of ant colonies. Thus, the semantics of the price signal differs from net metering prices as used with transactive energy approaches or energy auctions.

Our price signal is broadcasted periodically to a number of smart controllers. A smart controller can be a standalone device, but it can also be implemented in the firmware of any device containing a micro-controller. Each smart controller is responsible for controlling an individual energy appliance, i.e., an energy storage, a consumer or a generator. In particular, the smart controller uses the price signal and local information about the flexibility of the appliance. Such local information can be the allowed tolerance for the temperature of a cooling house, it can be the charging status and desired charge of a electrical vehicle or it can be the heating demand of a combined-heat-and-power plant. If the flexibility is high, e.g., if there is plenty of time until a water pump must be activated to ensure that the reservoir does not run empty, the controller is unwilling to pay much for activating the pump. On the other hand, if the reservoir is about to drain, the controller must accept any price for energy.

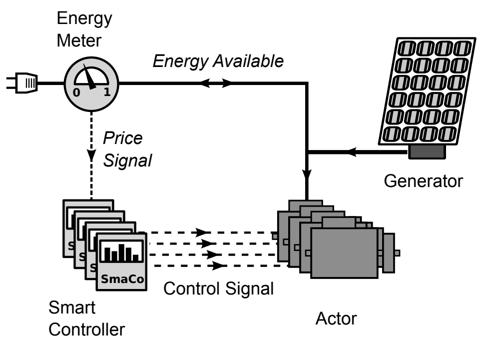


Figure 3. SEAM swarm

A straightforward approach to implement such a strategy would be a linear regression model. In this case, a straight function describes the relationship between the flexibility and the price signal (right side of Figure 4). Thus, each controller would implement the following swarm algorithm, which is continuously evaluated:

Switch on if: *The device is off, local properties allow that it can be switched on, and the local flexibility results in a valuation of energy that is higher than the price signal.*

Switch off if: *The device is on, local properties allow that it can be switched off, and the local flexibility results in a valuation of energy that is lower than the price signal.*

A more sophisticated strategy could solve an optimization problem on a forecast of the energy price (see Section IV).

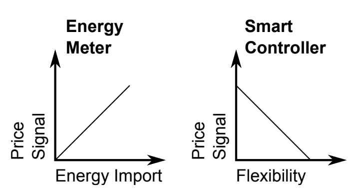


Figure 4. Balancing supply and demand

The decision about turning an energy appliance on or off is based solely on the broadcasted price signal and local data, i.e., there is no global optimizer and no communication with other controllers involved. The decisions of the swarm of smart controllers have an effect on the energy generated and consumed. This is measured by the energy meter and transformed into a new price signal, which is broadcasted again. Thus, a closed-loop feedback control circuit is established with the energy consumption as a feedback channel. If one appliance has an urgent need for energy and turns on, others might decide that the price is too high and switch off. Similarly, if the PV power plant delivers more energy, some appliances might decide that the energy now is inexpensive enough to be used even if, say, the tolerance limit of a cooling warehouse is not reached yet.

Because the price signal is obtained by measuring the available energy, it is possible operate SEAM-controlled appliances together with existing ones, and controllers can enter and leave the swarm at any time without having to reconfigure any grid component. Since there is no outgoing communication, the privacy of the prosumers is not an issue. It is simple to understand the decisions of the smart controller by observing the local demand and the price signal. Finally, if the broadcasted price signal fails, the energy appliances can simply return to a mode of operations that is identical to a non-smart grid. Thus, SEAM fulfils the Requirements R3–R7 named in Section I.

Observe that the price signal is just a representation of the balance between supply and demand. Thus, it is possible to realize SEAM without modifying business cases of the grid operator – instead of a price, a normalized factor in the interval $(0, 1)$ would serve the same purpose. Furthermore, the price signal contains the marginal fee for energy. In other words, it is the price of consuming an infinitesimally small amount of energy at a certain time. Thus, the price signal represents the balance between demand and supply of energy, which allows us to develop swarm algorithms that allocate energy, but it cannot be directly used for net metering.

IV. A Formal Framework for SEAM

In order to show that SEAM converges to a state where energy consumption and energy generation is in balance (Requirement R1), we now describe a formal framework that describes the optimal point in time to turn on or off a device, given the local information and a time series of past energy prices in the possession of each smart controller. To ease our presentation, we model consumers as loads that are active for a predefined time interval, once they have been turned on. Our framework can be extended to more elaborate models easily.

A. Basic Properties

Without loss of generality, assume an electrical device $d \in D$ must be active for a certain time Δt^d within a time interval ΔT^d. This is typical for many devices, e.g., anything that operates cold or heat and fills or drains a reservoir that is continuously in use.

$d \in D$	Electrical device with flexibility
ΔT^d	Flexibility to shift the consumption of d
Δt^d	Minimal time span d must be running in ΔT^d
s^d	Start time of d
l^d	Electrical load of d
p_i	Price signal at time i
c_i	Forecast of the price at time i

TABLE I. Important symbols

Assume a cold warehouse must hold a temperature between 4 and 6°C. The cooler consumes $l = 800$ Watt. The warehouse warms up in 20 Minutes from 4 to 6°C, and it cools down from 6 to 4°C within two minutes. Thus, $\Delta t = 2$ min. To ensure a temperature below 6°C, the last point in time s' the cooler must start for $\Delta T = 22$ min is after 20 minutes. Thus, $0 < s' < (\Delta T - \Delta t)$. Table I lists the most important symbols used. Our model comes with three assumptions:

Assumption 1. *$|D|$ is large, i.e., there are many individual devices.*

Assumption 2. *The distribution of the loads l_d of any device $d \in D$ follows a Gauss Distribution, i.e., there are few devices with a very high energy consumption and a long tail of devices with a small consumption. This models a difficult case: Our framework will show that the energy allocation is easier if all devices have the same load l.*

Assumption 3. *The inaccuracy of the forecast c_i for the price signal at time i increases with increasing i. Let $\Delta c_i = c_i - p_i$ the difference between the exact price and its forecast at time i: For any two points in time $\forall i, j \in \Delta T$ with $i < j$, $|c_i - p_i| \leq |c_j - p_j|$. Thus, Δc_i increases with i: $|c_i - p_i| \sim i$*

This is natural. At the current point in time the price is exactly known. It might be possible to guess the energy supply and demand in a local microgrid for some minutes in the future with high accuracy. But it is hard to tell the weather and the devices that are active for some hours or days in the future.

Obviously, it is impossible to shift the starting time s^d of a device d into the past. If a smart controller thinks there will be a better price in the future and the demand can be shifted to the end of the flexibility interval, but the price is higher then, the device must be activated anyway.

Proposition 1. *The valuation for energy z^d increases with decreasing flexibility. If the flexibility in time is large, i.e., there are many options to turn on the device at a later point in time without violating the user's settings, the controller will accept low energy prices only. In contrast, if the time is near when the device must be turned on, the smart controller is willing to pay a higher fee. Thus, $z^d \sim i$.*

B. Optimal time for turning on the device

After having shown the assumptions and basic properties of our model, we now describe how each controller might identify the optimal point in time to activate its electrical device.

Proposition 2. *All smart controllers try to minimize the total costs for consuming energy. To this end, the controllers compute a forecast c_i for the price in the future at time i. Thus, for each device d there is a smart controller solving at any point in time i an optimization problem: Find a starting time s_d so that the costs for consuming l^d over the time Δt^d will be minimal.*

$$\underset{0 \leq s^d \leq \Delta T^d - \Delta t^d}{\arg\min} \int_{s^d}^{s^d + \Delta t^d} c_i \cdot l^d \quad di \tag{1}$$

A simple forecasting approach would be to interpolate the current price to the future. Another simple approach might use the time series of the prices from the day before. Our prototype (see Section VI) shows that even simple approaches work well. However, the price k^d paid by any device d is not the forecast, but the price that is valid at the respective time, i.e.,

$$k^d = \int_{s^d}^{s^d + \Delta t^d} p_i \cdot l^d \quad di \tag{2}$$

Recall that the smart controllers rely on local information and do not communicate with each other. Each controller derives the optimal starting point in isolation. Furthermore, it can be assumed that the energy prognosis is similar on each controller. Proposition 1 tells us that controllers with a high flexibility use their forecast to avoid high prices and favor low prices in the future. However, if many controllers turn on their devices at the same time, the price will increase and vice versa. This multiplicates the effect of Assumption 3, i.e., the inaccuracy of the forecast increases with the increasing forecasting time.

Proposition 3. *From Assumption 3 it follows that the optimal starting point must be closer to the present time than obtained by Equation 1. Otherwise, the increasing risk for an inaccurate prognosis would result in a suboptimal starting point.*

We model the optimal point in time for switching on by considering a risk premium for the optimization problem in Equation 1.

Proposition 4. *The risk premium is the sum of the entry probability multiplied with the costs. With SEAM, the costs are the differences between prognosis and real price $(p_i - c_i)$ paid at time i. The entry probability can be described as a probability density function. Without loss of generality, we denote the risk premium at time i as r_i. Our optimization problem to find the optimal point in time to turn on a device now is as follows:*

$$\underset{0 \leq s^d \leq \Delta T^d - \Delta t^d}{\arg\min} \int_{s^d}^{s^d + \Delta t^d} c_i \cdot l^d \cdot r_i \quad di \tag{3}$$

The choice of the probability density function allows to model participants that might be risk-averse, risk-neutral or risk-aware. Another option would be to learn the probability density by observing the difference between price and forecast.

Considering a risk premium results in a swarm behavior where the participants consume energy if the price is "good enough" instead of hoping for a better price in the future by risking inaccurate forecasts. Thus, for a sufficient number of swarm participants (cf. Assumption 1), Requirement R1 is fulfilled. Observe that we can say that without specifying an algorithm to compute the forecast or the probability density function. With our preliminary tests, using a time series of the price signal from the past as a forecast and a linear regression as probability density function turned out to perform well. Thus, our approach comes with a low complexity (Requirement R4).

V. On Swarm Stability

At the first glance, SEAM could produce an oscillating behavior: All or a large share of the devices turn on. Thus, the energy consumption increases and the price signal rises as well. The next time the devices receive the price signal, all or a large share of the energy consumers are unwilling to accept a high price for energy and turn off. In consequence, the consumption and the price signal decreases. The next time the price signal

 ISBN: 978-1-61208-556-2

is received, all devices are turned on again and the procedure is repeated indefinitely. To ensure that this behavior does not materialize in a real installation, two research questions must be considered:

1) Under which conditions is it possible to provoke an oscillating behavior of a large share of all swarm members?
2) How must the swarm be constructed to ensure that oscillations do not occur normally and oscillations provoked by external events fade away?

Assume a subset $M \subseteq D$ of the set of all devices D. All devices $m \in M$ switch on and off at the same time, i.e., all smart controllers responsible for those devices solve the optimization problem from Proposition 4 with the result that the optimal point in time to start consuming energy is the current point in time. For example, such an behavior could be provoked by a very high risk premium or by having many identical devices. Formally,

$$\forall m \in M : s^m = 0 \tag{4}$$

Equation 4 allows us to derive three of properties that must be fulfilled altogether to obtain an oscillating swarm behavior.

Proposition 5. *The sum of the energy consumptions of all devices in M must be larger than the sum of the energy consumptions of all other devices that are able to counteract the sudden increase in the total energy consumption by turning off.*

$$\sum_{m \in M} l^m > \sum_{d \in (D \setminus M)} l^m \tag{5}$$

Assumption 2 allows to derive for any real setting the share of devices that must be in M.

Proposition 6. *The run-times Δt^m of all devices in M must have a common divider. Otherwise, there would be no stable oscillation.*

$$\forall p, q \in M : \frac{\Delta t^p}{x} = a \wedge \frac{\Delta t^q}{x} = b \text{ with } a, b, x \in \mathbb{Z} \tag{6}$$

Proposition 7. *All devices in M must be turned on before an update of the price signal arrives that tells them to re-evaluate the optimization problem in Equation 3. I.e., the system must have some delay δ between two consecutive updates of the price signal:*

$$\delta = |i_1 - i_0| \tag{7}$$

From Proposition 5 to Proposition 7 it follows that it must be simple to design a microgrid based on SEAM, which cannot produce oscillations, either by ensuring a heterogeneous set of devices, well-distributed loads and/or updating the price signal with a low or random delay. If this is not possible, another feasible strategy would be to allow an operator to manually override the switching decisions of the largest loads in the microgrid.

VI. Prototype

We have build a prototype (see Figure 5) to confirm that SEAM operates on inexpensive off-the-shelf hardware (see Requirement R2), and that our formal framework as well as our assumptions can be applied to real settings.

From the algorithmic perspective, it does not make a difference if we connect real energy consumers with SEAM or a model. For practical reasons, we have decided for components from educational experimentation boxes (Franzis "'50 Experimente mit erneuerbaren Energien"' and Franzis "'Solarenergie"'). Our prototype provides two low-current LEDs and two motors as energy consumers (f). A lamp (a) shines on two PV modules (b) to provide renewable energy sources. A battery and two 1000μF capacitors (g) mimic a grid operator who provides a conventional energy source and grid stabilization. A display unit (e) allows us to monitor the state of the microgrid, the energy intake from the energy sources and the activities of the energy consumers. We have implemented SEAM in Java on a Raspberry Pi Model B+ in a DIN-Rail housing (c), which operates the energy consumers via a multi-channel potential free actor relais (d). Both the display unit and the energy meter makes use of MCP3426 16-bit multichannel $\Delta\Sigma$ analog-to-digital converters with I^{2}C interface and onboard reference. Observe that this setting stresses the Assumptions 1 and 2 requiring many devices with different loads.

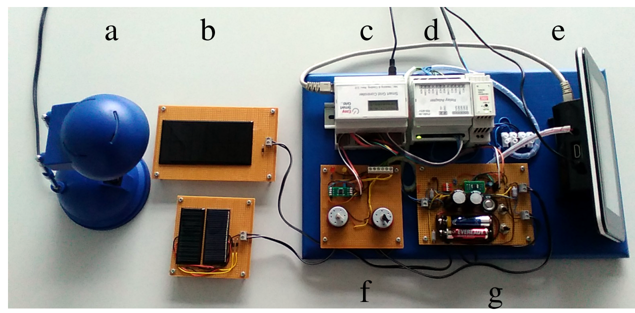


Figure 5. SEAM Prototype

The computational resources of the Raspberry PI model B+ are sufficient to run the energy meter service and four instances of a smart controller in parallel. Thus, the price signal can be transferred via inter-process communication. With our model prototype, we have defined a voltage between 2.7V and 3.3V as normal, i.e., below 2.7V, our conventional energy source steps in, and above 3.3V a Z diode has to consume surplus energy. In order to balance supply and demand, we have implemented the straightforward strategy denoted in Figure 4: Our forecast is an interpolation of the current price signal. The price signal is 1 at 2.7V and 0 at 3.3V. Any smart controller accepts a price of 0 if the flexibility (i.e., the time remaining until the the device must be turned on) is maximal, and a price of 1 if the flexibility is 0. The prototype allows us to configure a wide range of different flexibilities. Furthermore, by moving the lamp we can vary the generation of renewable energies easily. Switches allow us to manually activate and deactivate the conventional energy source and grid stabilization.

Our prototype provides a challenging scenario for SEAM: The energy consumption of a motor exceeds the consumption of a LED by an order of magnitude, we have only four energy consumers in total, and only one source of renewable energies. Furthermore, the energy sources are not under control of SEAM, and SEAM uses a straightforward approach to balance supply and demand.

Nevertheless, our prototype confirms that SEAM works well even in extreme situations. We have ran a number of experiments with two settings: (A) all devices are operated without SEAM, i.e., the devices are turned on if the flexibility is 0 and turned off after Δt. (B) SEAM controls the devices as described. With our experiments, we have moved the lamp in different positions and we have measured the energy drawn from the battery. Our experiments with setting B show that typically, our independent smart controllers organize themselves into a regular swarm behavior where one energy consumer is turned on after another one has been switched off. With this switching pattern, the energy produced by renewable sources is optimally consumed. If the pattern is disturbed, e.g., by moving the lamp, the controllers quickly find to another pattern. In comparison to setting (A), setting (B) typically consumes 30% less conventional energy. If the flexibilities are sufficient to compensate fluctuations in the generation of renewable energies, the conventional energy source can be removed.

We have tried to force our swarm of energy consumers into an oscillation where any device turns on and off periodically, as described in Section V. In fact, we can confirm Proposition 5 to Proposition 7: It needs a carefully designed artificial setup where the energy consumers are forced to start at the same time and must have identical run-times. Furthermore, we had to delay the update of the price signal. If we do not enforce this artificial setting, an oscillation will not materialize.

Finally, our prototype confirms that SEAM can be realized with inexpensive off-the-shelf components (Requirement R2). An industry-grade installation with a insulation level IP20 according DIN 40050 can be realized with modules that are readily available from manufacturers, such as Wago or Phoenix Contact. The computational resources needed to operate a smart controller can be provided even by a micro controller.

VII. SUMMARY

Microgrids are a promising approach to foster the transition to renewable energy sources by balancing energy consumption and supply locally. However, existing approaches to schedule energy appliances cannot be readily applied to small-scale producers and consumers of energy, for various reasons.

In this paper, we have proposed SEAM, a distributed approach for Swarm-based Energy Allocation in Microgrids. SEAM makes use of swarm intelligence to let energy producers and consumers adapt to the availability of energy. SEAM maps the availability of energy to a price signal, which is broadcasted to all swarm members in real-time. We have shown that the individual decisions of all swarm members let the microgrid converge to a state where renewable energy sources are utilized as good as possible, given the individual flexibility of the energy appliances. We have described both a formal framework and a model prototype for SEAM, showing that the formally derived properties of SEAM can be observed in a real system. Given that SEAM does not rely on complex infrastructures, expensive hardware components or elaborate algorithms, it copes very well with fluctuating energy sources. As part of our future work, we will focus on the response times, i.e., we strive to provide optimizations and guarantees for the time the SEAM swarm needs to adapt to fluctuations in the energy generation or consumption.

REFERENCES

[1] R. H. Lasseter and P. Paigi, “Microgrid: A Conceptual Solution,” in 35th IEEE Power Electronics Specialists Conference (PESC’04), vol. 6, 2004.

[2] M. Mahmoud, Microgrid: Advanced Control Methods and Renewable Energy System Integration. Elsevier Science, 2016.

[3] ED Netze, “Lastprofile der ED Netze GmbH,” (in German), https://www.ednetze.de/kunde/lieferanten/lastprofile-temperaturtabellen/, retrieved: March, 2017.

[4] Ea Energy Analyses, “The Danish Experience with Integrating Variable Renewable Energy,” Study on behalf of Agora Energiewende., 2015.

[5] European Energy Exchange AG, “EEX Transparency Platform,” https://www.eex-transparency.com, retrieved: March, 2017.

[6] H.-M. Henning and A. Palzer, “100% Ernerbare Energien für Strom und Wärme in Deutschland (in German),” Fraunhofer-Institut für Solare Energiesysteme ISE, Tech. Rep., 2012.

[7] R. Palma-Behnke, C. Benavides, F. Lanas, B. Severino, L. Reyes, J. Llanos, and D. Sáez, “A microgrid energy management system based on the rolling horizon strategy,” IEEE Transactions on Smart Grid, vol. 4, no. 2, 2013, pp. 996–1006.

[8] C. Chen, S. Duan, T. Cai, B. Liu, and G. Hu, “Smart energy management system for optimal microgrid economic operation,” IET renewable power generation, vol. 5, no. 3, 2011, pp. 258–267.

[9] S. Chakraborty, M. D. Weiss, and M. G. Simoes, “Distributed intelligent energy management system for a single-phase high-frequency ac microgrid,” IEEE Transactions on Industrial electronics, vol. 54, no. 1, 2007, pp. 97–109.

[10] S. Karnouskos and T. N. De Holanda, “Simulation of a smart grid city with software agents,” in Computer Modeling and Simulation, 2009. EMS’09. Third UKSim European Symposium on. IEEE, 2009, pp. 424–429.

[11] S. Vandael, N. Boucké, T. Holvoet, K. De Craemer, and G. Deconinck, “Decentralized coordination of plug-in hybrid vehicles for imbalance reduction in a smart grid,” in The 10th International Conference on Autonomous Agents and Multiagent Systems-Volume 2. International Foundation for Autonomous Agents and Multiagent Systems, 2011, pp. 803–810.

[12] P. H. Nguyen, W. L. Kling, and P. F. Ribeiro, “Smart power router: A flexible agent-based converter interface in active distribution networks,” IEEE Transactions on Smart Grid, vol. 2, no. 3, 2011, pp. 487–495.

[13] A. Roy and G. N. Kulkarni, “Analysis on the feasibility of a pv-diesel generator hybrid system without energy storage,” Clean Technologies and Environmental Policy, 2016, pp. 2541–2553.

[14] S. Rehman, M. M. Alam, J. Meyer, and L. M. Al-Hadhrami, “”feasibility study of a wind-pv-diesel hybrid power system for a village”,” Renewable Energy, vol. 38, no. 1, 2012, pp. 258–268.

[15] SkyFuel, Inc., “A Solar Thermal Geothermal Hybrid,” Available at http://www.skyfuel.com/whitepapers.shtml, retrieved: March, 2017.

[16] F. A. Rahimi and A. Ipakchi, “Transactive energy techniques: Closing the gap between wholesale and retail markets,” The Electricity Journal, vol. 25, no. 8, 2012, pp. 29–35.

[17] J. St. John, “Results from the world’s biggest transactive energy test,” in gtm: Greentech Media, Sep 2015.

[18] K. Kok, “The powermatcher: Smart coordination for the smart electricity grid,” Ph.D. dissertation, Technical University of Denmark, 2013.

[19] D. Geysen, P. Booij, and C. Warmer, “A framework for simulation and control of hybrid energy networks,” in Energy Conference (ENERGYCON), 2014 IEEE International. IEEE, 2014, pp. 989–995.

[20] A. van der Veen, “Connecting PowerMatcher to the electricity markets: an analysis of a Smart Grid application,” M.Sc. Thesis, Rijksuniversiteit Groningen, Nederlands, 2015.

[21] M. A. Hassan and M. A. Abido, “Optimal design of microgrids in autonomous and grid-connected modes using particle swarm optimization,” IEEE Transactions on Power Electronics, vol. 26, no. 3, 2011, pp. 755–769.

[22] W. Al-Saedi, S. W. Lachowicz, D. Habibi, and O. Bass, “Voltage and frequency regulation based {DG} unit in an autonomous microgrid operation using particle swarm optimization,” International Journal of Electrical Power & Energy Systems, vol. 53, 2013, pp. 742–751.

[23] A. P. Engelbrecht, Fundamentals of Computational Swarm Intelligence. John Wiley & Sons, 2006.

[24] J. Kennedy, “Particle swarm optimization,” in Encyclopedia of Machine Learning. Springer, 2010.

[25] M. C. Cagigal, “A Swarm Intelligence Approach Based on Coupled Oscillators: An Application in Demand Side Management with Photovoltaic Distributed Generation,” Ph.D. Thesis, Universidad Politcnica de Madrid, Spain, 2014.

[26] P. Bozsoky, “Transactive Energy in Inselnetzen,” B.Sc. Thesis (in German), Karlsruhe Institute of Technology, Germany, 2015.

Multilayer Fuzzy System Applied to Locate Faults in Distribution Systems Using Only Voltage Measurements

Marcel Ayres Araújo; Rogério Andrade Flauzino; Lucas Assis de Moraes; Oureste Elias Batista
Department of Electrical and Computing Engineering
University of São Paulo – USP
São Carlos, Brazil
e-mail: marcel.araujo@usp.br; raflauzino@sc.usp.br; lucas.moraes@usp.br; oureste.batista@usp.br

***Abstract*—Smart grids are a more and more present concept in electrical systems. In the context of smart grids, alike in the present topology of electrical systems, it is necessary to guarantee quality and reliability of energy provision. Thus, this work has the objective to locate faults ins energy distribution systems using only post-fault voltage data. This data will be collected on the medium voltage side of distribution transformers, a likely place for installation of concentrating devices of smart grids, and will be applied to a multilayer fuzzy inference system. The scenario studied is a feeder of an actual distribution system, with 1600 buses and 505 transformers. The obtained results are still very imprecise to faults too close or too far from the measurement point, but they are satisfactory for a specific range of fault distances. Improvements are going to be made to obtain more accurate results.**

Keywords-Distribution system; Fault location; Fuzzy inference systems.

I. Introduction

Electrical power systems have been facing different technical, economic and environmental changes, mainly in response to the increasing energy demand, the efforts to incorporate renewable generation sources and the intensification of reliability of energy supply. A feasible way to alleviate the problems caused by such changes is the use of Distributed Generation (DG) [1][2].

DG is defined as small generating units installed in distribution systems near load centers. Its main advantages are: reduction of losses in the system, improvement of voltage profile and power quality indices, increase of energy supply trustworthiness, reduction of operating and environmental costs (less penalties for emission of pollutants, because of the use of a renewable source) and market opening [1][3].

The energy generated with DG can be used to feed the energy needs of the producer, but it also can be sold to the grid when convenient. However, for the implantation of DG to be allowed, there is a set of rules that must be followed by the producer. One of them says that when an abnormal condition is verified, the DG must be disconnected from the grid [3][4].

A fault in the system is an abnormal condition, since it is a sudden voltage sag which leads to high currents. Faults are events that happen randomly, and are very prejudicial to the grid, especially due to these overcurrents. To save the system from potential damage, the protection system must work correctly and must isolate the fault from the grid [5][6].

However, isolating the faulty point is not the solution to the problem. Some faults must be located and repaired before reconnecting that point to the grid. This is where the objective of this paper lies. This paper aims to develop a multilayer Fuzzy Inference System (FIS) to locate faults in distribution systems using only voltage measurements. It is expected that the FIS can estimate the fault location no matter the distance to a reference point, which in this paper is any transformer in a simulated distribution system identical to a real one.

This paper is organized as follows: Section II contains the state-of-the-art regarding fault locations in distributions systems and the original contribution of this paper. Section III describes the multilayer FIS used. Section IV exposes the methodology used to obtain the results, which are in Section V. Finally, Section VI contains the conclusions of this paper.

II. State of the Art and Original Contribution

Currently, there are several methodologies for locating faults in electrical systems to reduce the reestablishment time of electrical energy in the region where the fault occurred, and each of these techniques has advantages, disadvantages and particularities [7][8]. These methods can be divided into three main categories: based on apparent impedance, based on traveling waves, and methods using artificial intelligence.

Apparent impedance-based methods consider that the distance between a given measuring point, usually the substation, and the fault point is proportional to the apparent impedance seen from the measurement point, calculated at the time of the fault, as explained in [9]-[13]. An advantage of this method is that it does not require a geo-referencing system with synchronized measurements to detect the point of the fault, since the measurement of parameters in one grid terminal is sufficient, but in contrast its disadvantage is the estimation of multiple possible points of fault, due to the branching of the radial distribution systems [7][8]. Other important aspects are that the fault impedance and the fault current impact the calculation of the apparent impedance.

 ISBN: 978-1-61208-556-2

The fault impedance is always unknown and the fault current is influenced by several factors of the system, such as the load and the presence of distributed generation [14].

The methods based on traveling waves rely on the analysis of the waveform of the voltage that travels to both sides of the grid, being reflected and refracted in its discontinuities while its amplitude is attenuated. The method consists in measuring the time between the first and the second incidence of the wave originated with the fault, which travels back and forth from the fault point to the terminal, as presented in [15]-[21].

One of the main difficulties in applying this method comes from the branching of the distribution systems, since each connection of the system is a point of discontinuity where the traveling wave will be reflected and refracted [7][8]. In this case, a possible approach is the use of the wavelet transform, which can detail the characteristics of traveling waves in the time and in the frequency domains in order to determine at what moment of time a high frequency transient, i.e., a fault, happens [18][20]. The main advantage of this methodology, compared to the method based on the apparent impedance, is that the multiple estimation does not occur, instead a single location of the fault point is found [22]. At the same time, there are the disadvantages of this second method, which are the need for syncing the measurements in two terminals, or alternatively, using a high frequency of data acquisition [20].

Intelligent systems used in fault location can profit from the advantages and avoid the disadvantages of both preview methods by using known historical data to be trained, as explained in [23]-[27]. In [28], for example, the fault distance is calculated through the apparent impedance method, which leads to multiple possible fault points. After that, an Artificial Neural Network (ANN) is trained to recognize patterns using voltage sag data in the moment of the fault so the correct fault point among all can be determined.

In [29] the authors use as inputs of an ANN the parameters of the wavelet transformation applied to the line currents of the 34-bus IEEE feeder. Likewise, in [30], a neuro-fuzzy system receives wavelet parameters of voltage and current, obtaining 80% accuracy index when DG is present in the distribution system, and 90% accuracy index when DG is absent.

When analyzing the most recent researches related to fault location in distribution systems it is noticed that their indexes of accuracy are quite satisfactory. The most used methodology consists of intelligent systems whose inputs are post-fault, voltage and/or current wavelet parameters [29][31]. An important detail is that in most of recent works the current measurement is considered as something essential for the correct and precise location of the fault [7][8].

The original contribution of this work comes from the fact that only voltage data is used to locate the fault in a distribution system. This consideration is important because of the following reason: in Brazil, the National Agency of Electrical Energy (ANEEL) considered as minimum requirements to a smart meter to acquire voltage, active power and reactive power data [32]. Current measurements are not included in the minimum requirements of smart meters, thus not using them in fault location methods increase the applicability of this work in a future Brazilian smart grid scenario.

III. Multilayer Fuzzy Inference System

The FIS may be treated as systems that use the concepts and operations defined by the fuzzy set theory and by the fuzzy reasoning methods, since they use the fuzzy inference process to perform their operational functions. Basically, these operational functions include the inputs fuzzification of the system, the inference rules associated to it, the aggregation of rules and the later defuzzification of the aggregation results, which represent the outputs of the FIS [33].

Considering the operational functions performed by the FIS, it is convenient to represent them by a three-layer model. Thus, a FIS may be given by the sequential composition of an input layer, an inference layer and an output layer.

A. Input Layer

The system inputs fuzzification has the purpose of determining the membership degree of each input related to the fuzzy sets associated to each input variable. To each input variable, as many fuzzy sets as necessary can be associated. This way, given a FIS with only one input, to which there are N fuzzy sets defining it associated, then the output of the first layer is a column vector with N elements, which are representing the membership degrees of this input in relation to those fuzzy sets.

If we define the input of this FIS with one only input x, then the input layer output of the FIS is the vector I_1, that is

$$I_1 = (\mu_{A_1}(x) \;\; \mu_{A_2}(x) \;\; \cdots \;\; \mu_{A_N}(x))^T \tag{1}$$

where $\mu_{Ak}(\cdot)$ is the membership function defined to x input, which is referring to the k-th fuzzy set associated to this input.

The generalization of the input layer concept for a FIS having p input variables can be achieved if we consider each input of this FIS being modeled as a sub-layer of the input layer. Considering this, the output vector of the input layer $I(x)$ is then defined by

$$I(x) = (I_1(x_1)^T \;\; I_2(x_2)^T \;\; \cdots \;\; I_P(x_P)^T)^T \tag{2}$$

where x_i is the i-th input of the FIS and $I_k(\cdot)$ is the k-th vector of membership functions associated to the x_k input.

B. Inference Layer

The set of rules has fundamental importance to the correct functioning of the FIS. There are several methods for the extraction of fuzzy rules from the tuning set.

In this paper, the FIS has initially all the possible inferred rules. Therefore, the tuning algorithm has the task of weighting the inference rules. The weighting of the inference rules is an adequate way to represent the most important rules in the FIS, or even to allow that conflicting rules are related to each other without any verbal completeness loss.

 ISBN: 978-1-61208-556-2

Thus, it is possible to express the i-th fuzzy rule as (3), where $R_i(\cdot)$ is the function representing the fuzzy weight value of the i-th fuzzy rule, w_i is its weight factor and $r_i(\cdot)$ represents its fuzzy value.

$$R_i(I(x)) = w_i \ r_i \ I(x) \tag{3}$$

C. Output Layer

The output layer of the FIS aims to aggregate the inference rules, as well as the defuzzification of the fuzzy set generated by the aggregation of inference rules.

In the FIS design, the choice of not only the aggregation method but also the defuzzification method constitutes a very important decision. The aggregation method of the fuzzy inference rules must be in such a way that the fuzzy set resulting from aggregation is capable of adequately representing the knowledge contained in this set of fuzzy rules. By analogy, the method chosen for the defuzzification must express, in a crisp value, the fuzzy set resulting from the fuzzy aggregation.

D. Adjustment of the Fuzzy Inference System

To summarize what was exposed until now in this Section, Figure 1 illustrates how the layers are disposed. In this example, two inputs were provided and three rules activated.

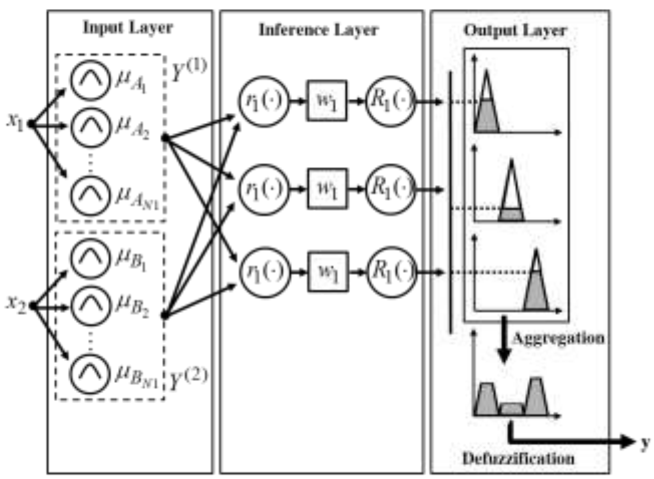


Figure 1. Multilayer fuzzy inference system [33].

The formalization of a FIS in the form of a multilayer system can be justified not only by the different operational division of each one of these layers, but also by the presence in each of them of different free parameters.

This way, the mapping f between the input space x and the output space y may be defined by (4), where mf_{1n}, w and mf_{out} respectively represent the vectors of the input membership functions parameters, the weight of the inference rules and the output membership functions parameters.

$$y = f(x, \ mf_{1n}, \ w, \ mf_{out}) \tag{4}$$

Therefore, mf_{1n}, w and mf_{out} represent the free parameters of the FIS and for this reason it is more suitable to rewrite (4) as presented in

$$y = f(x, \ \theta) \tag{5}$$

where θ is the vector resulting from concatenation of the free parameters involved to system, that is

$$\theta = \left(mf_{1n}{}^T \ w^T \ mf_{out}{}^T \right) \tag{6}$$

The definition of the energy function to be minimized remains in function of the fuzzy mapping. Considering that the tuning set $\{x,y\}$ is fixed during the whole adjustment process, it may be written as (7), where ξ represents the energy function associated to the FIS f.

$$\xi_{(x,y)} = \xi_{(x,y)}(\theta) \tag{7}$$

In problems like this, involving the minimization of energy functions, it is desired that, after any iteration, the energy function value is lower than that value obtained in the previous iteration. There are several techniques used to solve unconstrained optimization problems. A detailed description of the unconstrained optimization techniques may be found in [34]. The choice of the most adequate technique to be used is conditioned to the form by which the energy function is defined. For example, the Gauss-Newton method for the unconstrained optimization may be more applicable in problems where the energy function is defined as (8), where $e(i)$ is the absolute error of the i-th tuning pattern.

$$\xi(\theta) = \frac{1}{2} \sum_{i=1}^{m} e^2(i) \tag{8}$$

In this paper, a derivation of the Gauss-Newton method is used for the FIS. The Gauss-Newton expression to update the vector $\boldsymbol{\theta}$ is defined by (9), where g is the gradient of ξ expressed in (7) and J is the Jacobian matrix of e presented in (8).

$$\theta_{next} = \theta_{now} - \frac{1}{2} \left(J^T J \right)^{-1} g \tag{9}$$

The optimization algorithm used was the Levenberg-Marquardt method [35]. The Levenberg-Marquardt method can handle well ill-conditioned matrices $J^T J$ by altering (9) to

$$\theta_{next} = \theta_{now} - \frac{1}{2} \left(J^T J + \lambda I \right)^{-1} g \tag{10}$$

The calculation of the matrices J and the vectors g were performed through the finite differences method.

IV. Methodology

Aiming to locate faults in a distribution system, this paper uses simulations of faults in a real system, which is in Biritiba-Mirim (Brazil). This distribution system contains 505 transformers and 1600 buses. Each simulation consisted in applying a fault to one bus and measuring the medium-side voltages in each transformer, in addition to zero and positive impedances between each transformer and the fault. This way, more than 800,000 sets of data were gathered. All the voltage data collected are: module, real part and imaginary part of phase, line and sequence voltages. Since phase A is the reference, its imaginary part is zero and the real part is equal to the module. This way, there are 25 different vectors of voltage data that will be the inputs of the FIS.

The medium voltage side of transformers was chosen as the points to collect data because of two main reasons. First, the transformers are a likely spot to place the data concentrators of a smart grid [36]. Second, the work presented in [37] develops and designs a Phasor Measurement Unit (PMU) that fits perfectly for data acquisition in the purpose of this paper. Although it is placed in the low voltage side of transformers (220 V), it can collect all 25 different voltages used in the magnitude of 13.8 kV by considering the transformer model.

The outputs of the FIS are the modules of the zero and positive impedances in fault condition. These variables are used to calculate the apparent impedance, which is directly proportional to the fault distance between a transformer (measurement point) and the fault point. The equations below shows these relations between the distance D, the apparent impedance Z_{ap}, the zero and positive sequence impedances Z_0 and Z_1, the fault voltage V_A and current I_a and the zero sequence current i_0 [38].

$$D \ \alpha \ Z_{ap} = \frac{V_A}{I_a + \left(\frac{Z_0 - Z_1}{Z_1}\right) i_0} \tag{11}$$

$$D \ \alpha \ \frac{Z_1}{Z_0 - Z_1} \tag{12}$$

Some considerations were made in this study. It was considered that the system is balanced, equilibrated and symmetric before the fault. The fault is phase-A-to-ground with no resistance. The system is unloaded.

V. RESULTS

The results were obtained by training and testing the FIS with 5 inputs and 12 rules, once for calculating Z_0 and another for calculating Z_1. These 5 inputs were selected among all the 25 measured voltages by the method developed in [39].

For Z_0, the voltages selected as inputs of the FIS were V_A, V_{1i}, V_{0r}, V_{Br} e V_{1r}. The rules and membership functions are in Figure 2, while the estimation result is in Figure 3. For estimating Z_1, the inputs were V_A, V_{1i}, V_{BCr}, V_{2i} e V_{0r}. The results are in Figure 4 while the FIS configuration is in Figure 5.

Figures 2 and 5 show 6 columns (5 inputs and 1 output) and 12 rows (rules). In each but the last column there is a red line which represents the value of each input. This value can vary from 0 to 1 individually, since all data is in pu, but they are all assumed 0.5 here as an example. In each row, there are all the membership functions that are activated by the values of the inputs in the corresponding rule. The yellow region in each membership function is the pertinence of that function. In the last row and column, there is a thick red line that represents the value of the output after the aggregation of all membership functions of the output. This value is the impedance in pu.

Figures 3 and 4 show how many estimations exist by interval of impedance. By analyzing them, it is possible to see that the FIS was not able at all to estimate impedances in the intervals [0.0 0.1] pu and [0.6 1.0] pu. Instead, the FIS placed them in the ranges of impedances [0.1 0.2] pu and [0.3 0.6] pu, making their estimation not as correct as they should be. The only interval were the estimations matched reasonably the real impedances is the [0.2 0.3] pu interval in both cases.

With these estimation data, the distance between the fault and the measurement point can be calculated, using (12). Then, they are compared to the real distance of the fault. This comparison is showed in Figure 6, which can be analyzed similarly to Figures 3 and 4, and in in Figure 7, which is the histogram of the error, indicating the number of estimations that provided similar intervals of errors (in km).

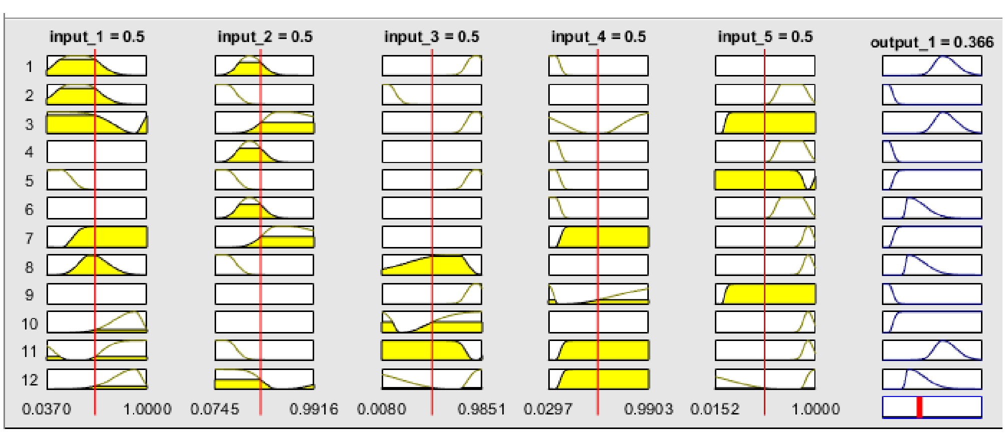


Figure 2. FIS configuration for estimating Z_0.

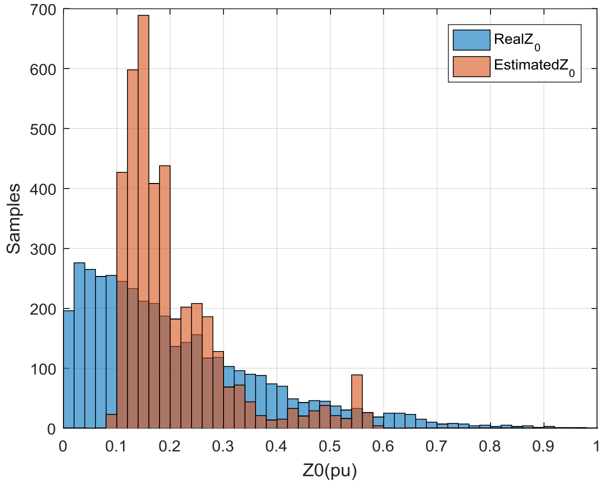


Figure 3. Z_0 estimatiom.

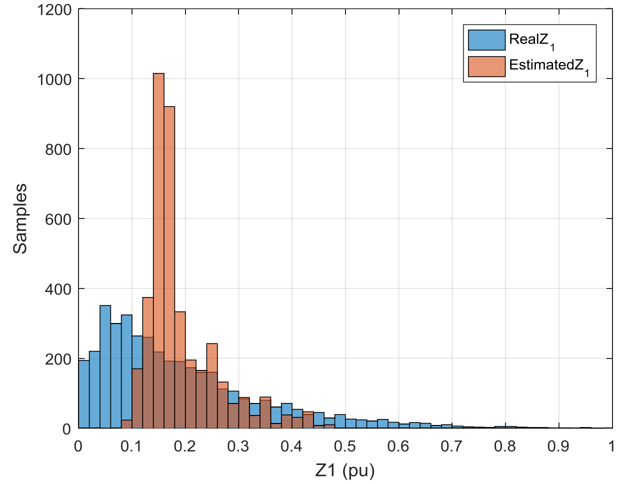


Figure 4. Z_1 estimation.

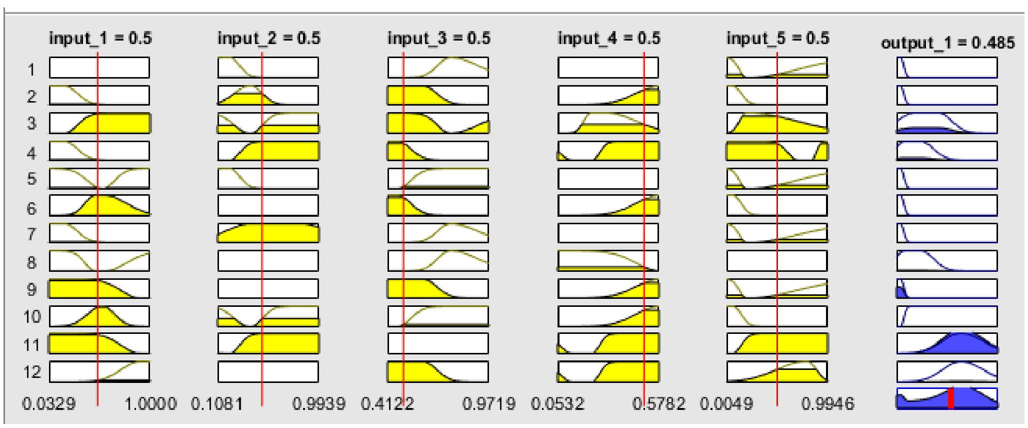


Figure 5. FIS configuration for estimating Z_1.

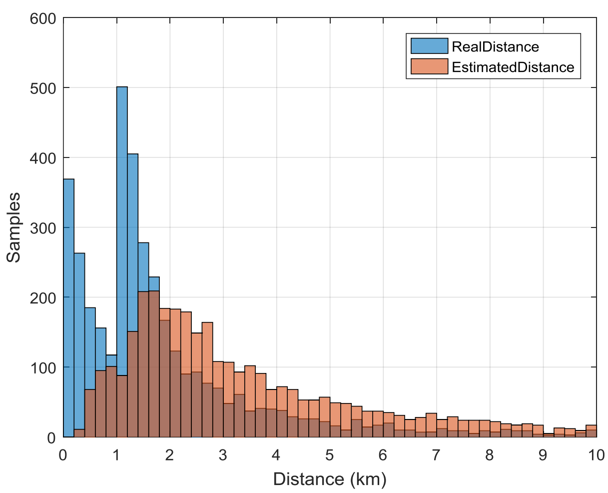


Figure 6. Comparison between estimated and real fault distances.

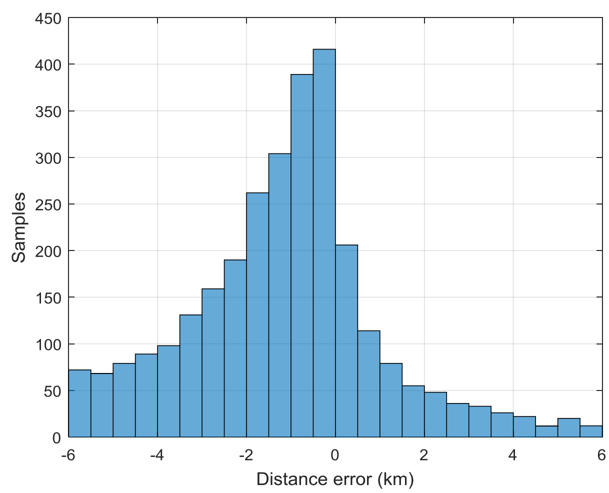


Figure 7. Histogram of distance estimation error.

 ISBN: 978-1-61208-556-2

Circa 400 samples (10% of the training data) resulted in errors close to zero, approximately the same amount of samples whose estimated distance is between 1.6 km and 2.0 km, that is the interval of distances with the smallest estimation error.

VI. CONCLUSION

This paper developed a fault location method in distribution systems using only voltage measurements. A Fuzzy Inference System was trained with these voltage data and provided as outputs the zero and positive impedances, which were used to calculate the distance from each transformer of the grid to the fault point.

In a first glance at Figure 6, the results look far from being satisfactory to completely fulfill the objective of this work. Yet, this work has some good results, as explained below.

Taking a closer look on Figure 6, there is a range of distances, [1.6 2.0] km, where the estimation has little error. This is the only acceptable range because the FIS could only estimate the zero and positive impedances more accurately in the narrow interval associated with this distance range, that is the [0.2 0.3] pu impedances interval. Knowing this, after a fault happens, when calculating the distance from every transformer to the fault, most of them will locate the fault incorrectly. Transformers closer than 1.6 km from the fault will accuse that the fault is even closer, and transformers further from 2.0 km will indicate an even longer distance to the fault. Nevertheless, there is a circle of transformers with radius varying between 1.6 km and 2.0 km that will give a precise fault location, which is the center of this circle.

However, even after this analysis, there is more room for improving the results of this work in future ones. First, locating the fault using the thought exposed above is only conceivable if the correct number of measurement points is used. In this paper, 505 transformers were not enough to locate the fault regardless of its distance, but this number is fine to locate faults within the distance described above. Changing this number may improve the results, that is, may widen the range of precise distance estimations.

Second, the FIS must be restructured. Changing the number of transformers implies in a different set of data used to train the Fuzzy Inference System, making it necessary to alter the number of rules, membership functions, inputs and epochs of training for optimizing the results.

The third possible improvement regards the distribution system, that is rather simplified. It is convenient to add more characteristics of the system, such as unbalanced voltages, fault impedance and presence of loads to obtain a more applicable result in a real distribution system.

Additionally, there is still an important factor of this present work to investigate. Very low or very high impedances could not be estimated by the FIS, and the reasons for this are unknown. A hypothesis is that the distribution system is too complex for a fault to be located without clustering this system to be trained by different FIS. Making the FIS capable of accurately estimating these extreme impedances will certainly grant a more precise fault location.

ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of all the professionals in the Department of Electrical and Computing Engineering for all the help and support provided. This paper was supported by the University of São Paulo under CNPq, CAPES and FAPESP Research Grants.

REFERENCES

[1] C. Santos, C. R. Rio, D. B. Diez, and E. C. Fernández, “Distributed generation: A review of factors that can contribute most to achieve a scenario of DG units embedded in the new distribution networks,” Renewable and Sustainable Energy Reviews, vol. 59, pp. 1130-1148, 2016.

[2] R. Jordehi, “Allocation of distributed generation units in electric power systems: A review,” Renewable and Sustainable Energy Reviews, vol. 56, pp. 893-905, 2016.

[3] J. C. Gomez, J. Vaschetti, C. Coyos, and C. Ibarlucea, “Distributed Generation: impact on Protections and Power Quality,” IEEE Latin America Transactions, vol. 11, nº 1, pp. 460-465, 2013.

[4] Y. Ates, M. Uzunoglu, A. Karakas, A. R. Boynuegri, A. Nadar, and B. Dag, “Implementation of adaptive relay coordination in distribution systems including distributed generation,” Journal of Cleaner Production, vol. 112, part 4, pp. 2697-2705, 2016.

[5] P. M. Anderson, Analysis of Faulted Power Systems. IEEE Press Power Systems Engineering Series, 1973.

[6] M. M. Saha, J. J. Izykowski, and E. Rosolowski, Fault location on power networks. Springer Science & Business Media, 2009.

[7] M. Mirzaei, M. Z. A. A. Kadir, E. Moazami, and H. Hizam, “Review of Fault Location Methods for Distribution Power System,” Australian Journal of Basic and Applied Sciences, vol. 3, nº 3, pp. 2670-2676, 2009.

[8] K. Chen, C. Huang, and J. He, “Fault detection, classification and location for transmission lines and distribution systems: a review on the methods,” High Voltage, vol. 1, nº 1, pp. 25-33, 2016.

[9] Y. Gong and A. Guzmán, “Integrated Fault Location System for Power Distribution Feeders,” IEEE Transactions on Industry Applications, vol. 49, nº 3, pp. 1071-1078, 2013.

[10] D. S. Gazzana, G. D. Ferreira, A. S. Bretas, A. L. Bettiol, A. Carniato, L. F. N. Passos, A. H. Ferreira, and J. E. M. Silva, “An integrated technique for fault location and section identification in distribution systems,” Electric Power Systems Research, vol. 115, pp. 65–73, 2014.

[11] C. Grajales-Espinal, J. Mora-Flórez, and S. Pérez-Londoño, “Advanced fault location strategy for modern power distribution systems based on phase and sequence components and the minimum fault reactance concept,” Electric Power Systems Research, vol. 140, pp. 933–941, 2016.

[12] S. A. Hosseini, J. Sadeh, and B. Mozafari, “Robust wide-area impedance-based fault location method utilising LAV estimator,” IET Generation, Transmission & Distribution, vol. 10, nº 10, pp. 2475-2485, 2016.

[13] M. A. Gabr, D. K. Ibrahim, E. S. Ahmed, and M. I. Gilany, “A new impedance-based fault location scheme for overhead unbalanced radial distribution networks,” Electric Power Systems Research, vol. 142, pp. 153–162, 2017.

[14] S. S. Gururajapathy, H. Mokhlis, and H. A. Illias, “Fault location and detection techniques in power distribution systems with distributed generation: A review,” Renewable and Sustainable Energy Reviews, vol. 74, pp. 949–958, 2017.

[15] S. Lin, Z.Y. He, X. P. Li, and Q. Q. Qian, “Travelling wave time-frequency characteristic-based fault location method for transmission lines,” IET Generation, Transmission & Distribution, vol. 6, nº 8, pp. 764-772, 2012.

[16] S. Azizi, M. S. Pasand, M. Abedini, and A. Hasani, “A Traveling-Wave-Based Methodology for Wide-Area Fault Location in

Multiterminal DC Systems," IEEE Transactions on Power Delivery, vol. 29, nº 6, pp. 2552- 2560, 2014.

[17] F. Xu, X. Dong, B. Wang, and S. Shi, "Self-adapted single-ended travelling wave fault location algorithm considering transfer characteristics of the secondary circuit," IET Generation, Transmission & Distribution, vol. 9, nº 14, pp. 1913-1921, 2015.

[18] P. E. Argyropoulos and H. Lev-Ari, "Wavelet Customization for Improved Fault-Location Quality in Power Networks," IEEE Transactions on Power Delivery, vol. 30, nº 5, pp. 2215-2223, 2015.

[19] F. V. Lopes, K. M. Silva, F. B. Costa, W. L. A. Neves, and D. Fernandes, "Real-Time Traveling-Wave-Based Fault Location Using Two-Terminal Unsynchronized Data," IEEE Transactions on Power Delivery, vol. 30, nº 3, pp. 1067-1076, 2015.

[20] R. Liang, F. Wang, G. Fu, X. Xue, and R. Zhou, "A general fault location method in complex power grid based on wide-area traveling wave data acquisition," International Journal of Electrical Power & Energy Systems, vol. 83, pp. 213–218, 2016.

[21] M. Abad, M. G. Gracia, N. E. Halabi, and D. L. Andía, "Network impulse response based-on fault location method for fault location in power distribution systems," IET Generation, Transmission & Distribution, vol. 10, nº 15, pp. 3962-3970, 2016.

[22] J. Sadeh, E. Bakhshizadeh, and R. Kazemzadeh, "A New Fault Location Algorithm for Radial Distribution Systems using Modal Analysis," Electrical Power and Energy Systems, vol. 45, nº 1, pp. 271-278, 2012.

[23] M. J. B. Reddy, D. V. Rajesh, P. Gopakumar, and D. K. Mohanta, "Smart Fault Location for Smart Grid Operation Using RTUs and Computational Intelligence Techniques," IEEE Systems Journal, vol. 8, nº 4, pp. 1260-1271, 2014.

[24] H. Jiang, J. J. Zhang, W. Gao, and Z. Wu, "Fault Detection, Identification, and Location in Smart Grid Based on Data-Driven Computational Methods," IEEE Transactions on Smart Grid, vol. 5, nº 6, pp. 2947-2956, 2014.

[25] Q. Yang, J. Li, S. Le Blond, and C. Wang, "Artificial Neural Network Based Fault Detection and Fault Location in the DC Microgrid," Energy Procedia, vol. 103, pp. 129-134, 2016.

[26] P. E. Farias, A. P. Morais, G. C. Junior, and J. P. Rossini, "Fault location in distribution systems: A Method Considering the Parameter Estimation Using a RNA Online," IEEE Latin America Transactions, vol. 14, nº 12, pp. 4741–4749, 2016.

[27] O. E. Batista, R. A. Flauzino, I. N. Silva, L. A. Moraes, and M. A. Araujo, "Methodology for information extraction from oscillograms and its application for high-impedance faults analysis." International Journal of Electrical Power & Energy Systems, v. 76, p. 23-34, 2016.

[28] M. Daisy and R. Dashti, "Single Phase Fault Location in Electrical Distribution Feeder using Hybrid Method." Energy, vol. 103, pp. 356-368, 2016.

[29] A. C. Adewole, R. Tzoneva, and S. Behardien, "Distribution Network Fault Section Identification and Fault Location using Wavelet Entropy and Neural Networks," Applied Soft Computing, vol. 46, pp. 296-306, 2016.

[30] A. A. P. Bíscaro, R. A. F. Pereira, M. Kezunovic, and J. R. S. Mantovani, "Integrated Fault Location and Power-Quality Analysis in Electric Power Distribution Systems," IEEE Transactions on Power Delivery, vol. 31, nº 2, pp. 428-436, 2016.

[31] A. Rafinia and J. Moshtagh, "A new approach to fault location in three-phase underground distribution system using combination of wavelet analysis with ANN and FLS," International Journal of Electrical Power & Energy Systems, vol. 55, pp. 261–274, 2014.

[32] National Agency of Electrical Energy (ANEEL). Normative Resolution 43 of 2010. [Online]. Available from: http://www2.aneel.gov.br/aplicacoes/audiencia/arquivo/2010/043/documento/resolucao_medicao_-_ap_43_2010.pdf. 2017.04.03.

[33] R. A. Flauzino, "Identification and Location of High-Impedance Faults in Power Distribution Systems Based on Orthogonal Component Decomposition and Fuzzy Inference" (Identificação e Localização de Faltas de Alta Impedância em Sistemas de Distribuição Baseadas em Decomposição por Componentes Ortogonais e Inferência Fuzzy). Ph.D. Thesis, University of São Paulo, São Carlos, Brazil, 2007.

[34] G. C. Onwubolu and B. V. Babu, New Optimization Techniques in Engineering. Series: Studies in Fuzziness and Soft Computing (Book 141), Springer, 2013.

[35] D. Marquardt, "An Algorithm for Least Squares Estimation of Nonlinear Parameters," Journal of the Society for Industrial and Applied Mathematics, pp. 431-441, 1963.

[36] Workgroup on Smart Grids – Ministry of Mines and Energy, "Report: Smart Grids", April 15th 2010. (Grupo de Trabalho de Redes Elétricas Inteligentes - Ministério de Minas e Energia, "Relatório: Smart Grids,"). [Online]. Available from: http://www.mme.gov.br/documents/10584/1256641/Relatxrio_GT_Smart_Grid_Portaria_440-2010.pdf/3661c46c-5f86-4274-b8d7-72d72e7e1157. 2017.04.03.

[37] A. S. F. Sobrinho, "Developing of an Optimized Phasor Measurement Unit for Power Distribution Systems" (Desenvolvimento de uma Unidade de Medição Fasorial Otimizada para Sistemas de Distribuição), Ph.D. Thesis, University of São Paulo, São Carlos, Brazil, 2014.

[38] D. V. Coury, M. Oleskovicz, and R. Giovanini, "Digital Protection of Electrical Power Systems" (Proteção Digital de Sistemas Elétricos de Potência), University of São Paulo, 2007.

[39] Moraes, L. A. "Development of a fuzzy approach for power demand forecast in an electrical energy distribution system" (Desenvolvimento de uma abordagem fuzzy para estimação de demanda de potência em um sistema de distribuição de energia elétrica), Master Degree Essay, University of São Paulo, São Carlos, Brazil, 2014.

Electric Vehicles Charging Infrastructure Integration Into The Electric Grid Considering The Net Benefits To Consumers

Vivian Sultan, Hind Bitar, Ahmed Alzahrani, and Brian Hilton
Claremont Graduate University CISAT
Claremont, USA
e-mail: Vivian.Sultan@cgu.edu

***Abstract*—The Electric Vehicle (EV) market is one of the most rapidly changing and fastest growing high-tech sectors in the United States. The relatively small number of large-scale public vehicle-charging stations makes recharging electric vehicles problematic, if not impossible at times. This study aims at addressing "How to properly integrate EV charging infrastructure into the electricity system and deliver net benefits to the consumers?" To answer the research question, we have built a prototype of Geographic Decision Support Systems (GDSS), which is an elegant, interesting, and novel solution, to demonstrate how an interactive, computer-based system can assist in decision-making considering the net benefits to consumers and the potential benefits to the grid. The proposed solution provides evidence that GIS can play an integral role in the problem domain.**

Keywords-dispatchable grid resource; battery range; V2G technology

I. Introduction

The Electric Vehicle (EV) market is one of the most rapidly changing and fastest growing high-tech sectors in the United States. According to some recent estimates from the United States Department of Energy's Clean Cities program [1], the U.S. has approximately 482,000 EVs, 14,000 public charging stations, and 36,000 charging outlets. The U.S. market currently has over 20 electric vehicle models from 12 manufacturers. To increase the adoption and use of plug-in electric vehicles, President Obama announced the "EV Everywhere Challenge" in 2012 as a part of the Energy Department's Clean Energy Grand Challenges. It aims "to make electric vehicles more affordable and convenient to own and drive than today's gasoline-powered vehicles within the next 10 years." [2]. Similarly, a Bloomberg New Energy Finance report [3] suggests that the sale of electric vehicles will hit almost 90 times the equivalent figure for 2015 by 2040. The report also highlights that, by year 2022, electric vehicles will cost the same as their gasoline-driven equivalents, the point from where the sale of EVs will takeoff. California's target is to have 1.5 million EVs on the road by 2025, which is more than 600% increase over the roughly 200,000 EVs it has today [4]. According to Trabish [5], EV sales have already outperformed infrastructure growth, which is a problem that is expected to increase with the skyward trend of the EV sales.

The relatively small number of large-scale public vehicle-charging stations makes recharging electric vehicles problematic, if not impossible at times. Supporting California's target to have 1.5 million EVs on the road by 2025, a rapid expansion of charging infrastructure (between 150,000 and 750,000 non-home charging stations) is needed [6]. Faster adoption of EVs will require flexibility in charging. Various analyses suggest that more charging stations are necessary to accommodate consumer demand for convenient electric vehicle recharging but the question is where these charging stations should be located. Decisions on making more charging stations are not as simple as simply opening more stations. The reason is that an electric charge depends on and impacts the overall electric grid in a region. Charging an electric vehicle is, in some instances, the equivalent of adding three houses to the grid and the electric grid is not ready for these stratospheric spikes in power demand [7]. Utilities need to keep a close eye on the grid constraints as they plan EV charging stations infrastructure in order to avoid grid reliability problems, power outages, and other unplanned costs that might occur due to peak demand influences and the grid overload. According to SDG&E calculations, if California's targets by 2025 (1.5 million EVs) are all gotten charged during peak times, it could add almost 10,000 MW of new peak load to the existing 64,000 MW load on California's grid [6].

An additional point is that deploying networks of EV charging stations can stabilize and bring benefits to the grid in locations where there is excess power. Looking at possible benefits and the new electricity grid of the future, EV charging can absorb mid-day solar over-generation and alleviate wind curtailment at night. Charging EVs when non-dispatchable assets like solar and wind generators are producing more energy than the electricity system can help flatten out the duck curve of demand and reduce the extent to which supply suddenly escalates. All of these characteristics reduce system costs, benefit ratepayers, and improve the profitability of generators [6].

Considering the grid capacity constraints, implications of EV charging if it is not appropriately incorporated into the electricity system, and the potential benefits of infrastructure planning, this paper addresses the research question: "How to properly integrate EV charging infrastructure into the electricity system and deliver net benefits to the consumers?" Previous literature showed insufficient attempts by researchers to provide solutions that can assist in decision-making with respect to this research question. The existing research was developed bearing in mind only the net benefits to EV owners while neglecting the electric circuit capacity constraints and the impact of the EV charging infrastructure on the electric grid.

The objective of this research is to build a Geographic Decision Support Systems (GDSS) prototype, which is an elegant, interesting, and novel solution to assist in the placement of electric vehicles charging stations. The goal is to demonstrate an interactive, computer-based system to assist in decision-making considering the net benefits to consumers and the potential benefits to the grid.

This research paper is based on the process steps in Takeda, et. al.'s design cycle to create the artifact/solution [8]. This cycle has five main steps, which are the awareness of the problem, suggestion, development, evaluation, and conclusion. The awareness of the problem phase has been indicated as mentioned above in the introduction and problem definition section. The suggestion phase is the decisions that have been made to develop the prototype to assist in the placement of electric vehicles public charging stations. In Section 2, we indicated the steps taken to develop and create the prototype considering some factors that will impact decision-making; in Section 3, we analyzed the prototype and wrote our findings; in Section 4, we explained the evaluation section of the paper; in Section 5 and 6, we highlighted the limitations, future work, and conclusion.

II. Artifact: GDSS Prototype

This study proposes a GDSS solution to assist in the placement of EV public charging stations as shown in Figure 1. A GDSS model can aid in EV charging stations location choices and provide actionable information for utilities, state-level decision-makers, and other stakeholders who are concerned about the EV integration as a dispatchable grid resource (a resource for which its power output can be adjusted, turned on or off at the request of the power grid operators). Though a GDSS can provide a solution to address the placement of all types (levels) of EV public charging infrastructure, we chose to only focus on level 2 EV public charging stations as we are building the prototype for illustration purposes.

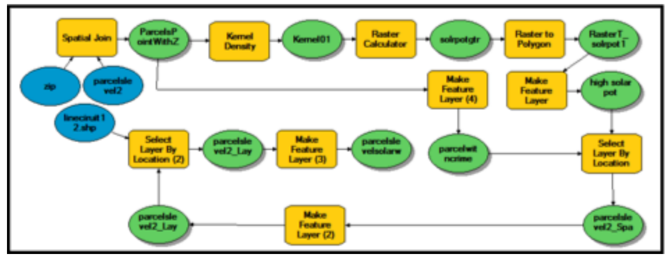


Figure 1. GDSS Prototype For Placement Of Electric Vehicle Charging Stations

The factors that we have considered and used are safety, number of EV in the area, exploiting excess power, grid capacity, convenience, and accessibility. We identified these factors as follows:

1) Security: safety assessment based crime rate [9].
2) Number of EV in the area: total count of vehicles that can be plugged into an electric power source to charge the battery, which is the sum of battery electric vehicles (BEVs) and Plug-In Hybrid electric vehicles (PHEVs) [10].
3) Exploiting excess power: locations with potential excess solar and/or wind generation [11]).
4) Grid capacity: Load capacity of electric circuits determined by the maximum load a circuit can handle safely without overheating. The minimum requirement of Load capacity is 12 kilovolts modern circuit ([11]; [12]).
5) Convenience: Anything that saves or simplifies work, adds to one's ease or comfort, which is short distance and comfortable place to spend time. For example, destination location for work and/or home ([13]; [14]).
6) Accessibility: the maximum and the minimum distance that EV owners are willing to walk from and to charging station. The maximum walk is 0.5 mile [9].

A. Data Selection and Acquisition

1) Crime Index Data: LA County Portal is the data source for the 2016 crime index data. The LA County crime index database is available at [15].
2) Parking Lot boundaries Data: LA County GIS Data Portal is the data source for 2014 dataset which contains the boundaries of the parking lots in the County of LA 5000 square feet and larger for commercial, industrial, and government properties. The database is available at [16].
3) Southern California Edison (SCE)'s Distributed Energy Resources interconnection Map (DERiM) Capacity Analysis Data: SCE's DERiM includes power electric lines and the capacity analysis in

kilowatts by circuit line. The data is retrieved from DERiM web map at [17].

4) Solar Parcel Data: LA County is the data source for the solar parcel data. The link to LA County solar parcel database is available at [18]. LA County solar map provides key data elements such as: total roof area and area suitable for solar, potential solar system size, solar potential annual output, and potential cost savings.

B. Data Preparation Steps

1) Data was extracted and loaded into ArcMap to show four map layers. The first layer showed LA county solar data by parcel while the other layers showed the crime index, SCE electric circuit capacity by circuit line and the targeted parking lots.
2) The targeted parking lot types were suggested by researchers as shown in Table 1 to meet the specification of the convenience factor for level 2 EV public charging stations. Similarly, walking distance from the potential targeted locations were set to 500 feet to meet the requirement of the accessibility factor.
3) According to Sultan et al. [19], the solar rooftop's potential electricity output was calculated for each parcel by multiplying the rooftop's solar panel area, the solar panel yield, the annual average solar radiation on tilted panels (constant for LA county, equal to 2018.45), and the solar system's performance ratio which is the coefficient for losses (used default value = 0.75). Two fields were added in ArcMap attribute table to perform these calculations. Considering the V2G technology/exploiting excess power factor, these calculations are required to predict areas with potential solar excess generation assuming maximum adoption of solar rooftops in LA County.
4) Considering the Grid Capacity requirement, locations not meeting the 12 kilovolts minimum circuit capacity constraints were excluded.
5) Using ArcMap model builder tool, a model was constructed to spatially join all map layers and provide an output map layer showing the potential locations for level 2 EV public charging stations.

TABLE 1. LA COUNTY TARGETED PARKING LOTS FOR LEVEL 2 EV PUBLIC CHARGING STATIONS

Use Description	Count
Athletic & Amusement Facilities	247
Colleges, Universities (Private)	170
Commercial	4970
Department Stores	298
Golf Courses	153
Government Parcel	7551
Hospitals	460
Hotel & Motels	1317
Industrial	5698
Institutional	37
Office Buildings	7989
Parking Lots (Commercial Use Properties)	11598
Parking Lots (Industrial Use Properties)	1424
Professional Buildings	2895
Recreational	11
Restaurants, Cocktail Lounges	4238
Rivers & Lakes	6
Schools (Private)	1096
Shopping Centers (Neighborhood, community)	3110
Shopping Centers (Regional)	610
Supermarkets	566
Theaters	67

III. ANALYSIS AND FINDINGS

According to Esri [20], "the Kernel Density tool calculates a magnitude-per-unit area from point or polyline features using a kernel function to fit a smoothly tapered surface to each point or polyline." In this case, Kernel Density Estimation (KDE) is used to estimate the probability density function of solar excess generation. KDE statistics is given as:

$$\int_h^1 (x) = \frac{1}{n}\sum_{i=1}^{n} k_h\,(x - x_i) = \frac{1}{nh}\sum_{i=1}^{n} k\,\left(\frac{x - x_i}{h}\right)$$

Where (x1, x2… xn) is an independent and identically distributed sample drawn from some distribution with an unknown density f, K (•) is the kernel (a non-negative function that integrates to one and has mean zero) and h > 0 is a smoothing parameter called the bandwidth. KDE statistics estimates the shape of this function f.

Assuming the maximum adoption of solar rooftops in LA County, analysis indicates there are several dense areas

 ISBN: 978-1-61208-556-2

where solar excess generation is estimated as shown in Figure 2.

Figure 2. Areas With Projected Solar Excess Generation

The excess solar generation dense spots appeared, as shown in Figures 2 and 3, in areas such as Lawndale, Hawthorne, Inglewood, Gardena, Downey, Norwalk, Cerritos, and Paramount. It is important to note that the dense spots (red areas) imply higher statistically significant excess solar generation. In addition, Figure 4 shows locations with excess solar generation along with SCE DERiM circuits line and substations (blue squares).

Figure 3. Areas With Forecasted Solar Excess Generation

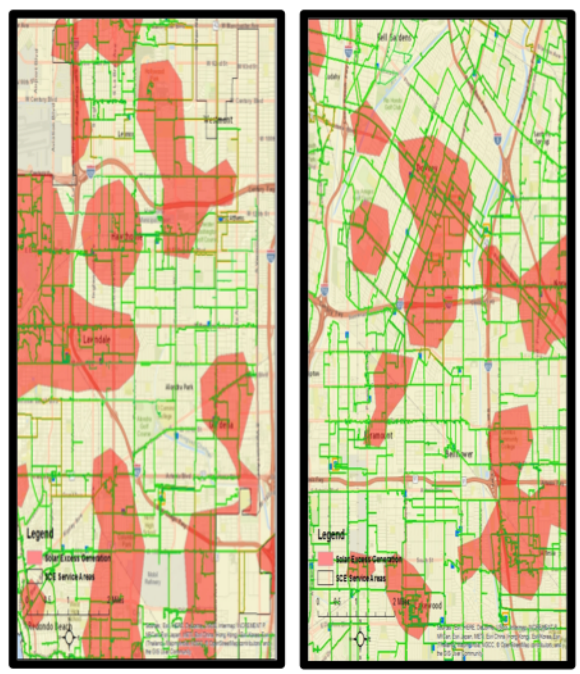


Figure 4. Locations Along With SCE DERiM Circuits Line and Substations

The crime Index layer was joined with the excess solar generation layer. Then, Select *Layer By Location* tool was used to intersect the two layers in order to show only safe zip codes areas with excess solar generation as shown in Figure 5. It is important to note that crime index for less than 93 per zip code were not considered safe area for level 2 EV stations installation. Considering the electric circuit current hosting capacity with 12 kilovolts as minimum circuit capacity constraints and the potential targeted areas yielded from the previous steps, locations where the level 2 charging stations might be installed were shown as in Figure 6.

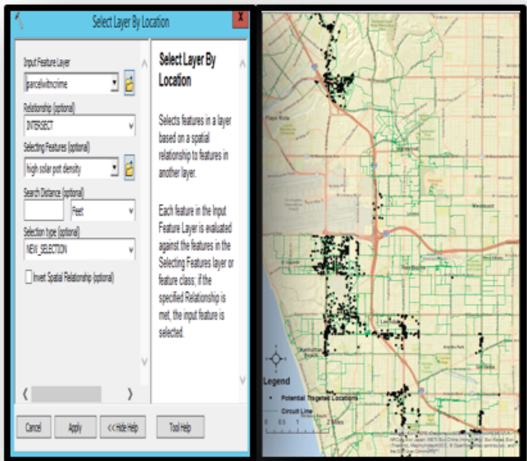


Figure 5. Safe Zip Codes Targeted Areas
With The 12 Kilovolts Minimum Circuit Capacity Constraints

Figure 6. Optimal Locations For Placement
Of Level 2 EV Public Charging Stations

IV. EVALUATION

The project team applied a qualitative interview method to evaluate the prototype using socio-technical technique to assess the following metrics: propriety and utility. The researchers evaluated the different values held by the different stakeholders by sending the following three interview questions via email: (1) Do you agree with the factors' definitions on page 2, please explain why? (2) Do you see the potential solution offered by the GDSS prototype (shown in Figure 7)? (3) What changes would you recommend for improvement? In this case, both EV drivers' and utility executives' perspectives were part of the evaluation process to ensure that their unique stances were understood.

Feedback was solicited from participants who were previously involved in the awareness of the problem phase and gathering the requirements. Two participants responded with positive feedback and they highlighted the potential offered by the proposed solution. According to Jim Horstman, a utility industry consultant, the artifact is useful and he agreed with the factors' definitions. However, Horstman pointed out that there is an overlap of some factors such as the accessibility and convenience. In spite of the factors' overlap, the actual analysis would not change.

V. LIMITATIONS AND FUTURE WORK

Public charging infrastructure can thus be prioritized in locations with sufficient circuit capacity, potential excess renewable power, low crime index, convenience and accessibility factors of the EV drivers/owners. However, a limitation of the GDSS prototype proposed in this paper is that it offers a solution to address the placement of level 2 stations only. Thus, a prototype to address the placement of level 3 stations is not offered in this case.

Due to time and data availability constraints, the prototype illustrated the optimal locations for placement of level 2 EV public charging stations considering the convenience, accessibility, security, V2G technology/exploiting excess power, and grid capacity factors. We did not address the travel time, battery range, and the number of EV factors of the decision-making framework.

Another limitation is in the evaluation phase. It is important to recognize that the time constraint imposed limitations on the evaluation and what these limitations are. The project team did not have the time to complete the evaluation phase and address the interviewees' comments after the solution delivery. The researchers did not have an opportunity to perform further iterations to improve the prototype. The project team need to get and address the interviewees' suggestions to move to the next phase of the research.

The utility and novelty of the solution is important to emphasize as the driving factors for this project. By developing a GDSS prototype for decision making that previously did not exist, a great amount of time is reduced for both the developers who are interested in finding the optimal locations and the utility companies who are interested in integrating the EV charging infrastructure into the electricity system in ways that deliver net benefits to utility customers, shareholders, vehicle owners, and society at large. It is important to realize that this prototype is only meant to serve as a good starting point for the illustration of

 ISBN: 978-1-61208-556-2

how EV charging demand can be managed geographically to minimize potential increases to overall electric system costs while still meeting customers' needs.

In future DSR cycles, the project team will address all of the suggestions from interviewees after they collect the remaining feedback from them. The project team will evaluate the GDSS prototype many times through multiple iterations to improve its utility. The next iteration will offer a custom tool for developers/utilities, so that they are better able to evaluate the results. The prototype will run on a public server to give the research participants access to the application.

Moreover, the project team will add quantitative methods in the evaluation such as System Usability Scale (SUS) and cognitive walkthrough. The usability of this prototype will increase since both methods measure the usability of any application. The SUS and cognitive walkthrough will be administered to all research participants. In this case, the evaluation will involve more participants who will be given access to the application to ensure the validity of the evaluation results.

As part of future work, multiple tools can be developed for the purpose of building an interactive, computer-based system where developers/utilities are allowed to configure their own criteria for decision-making.

VI. CONCLUSION

This study aimed at addressing "How to properly integrate EV charging infrastructure into the electricity system and deliver net benefits to the consumers?" To answer the research question, we have built a prototype of Geographic Decision Support Systems (GDSS). Our proposal was developed bearing in mind not only the net benefits to EV owners but also the electric circuit capacity constraints and the impact of the EV charging infrastructure on the electric grid.

From this research, we conclude that EV charging demand can be managed geographically to minimize potential increases to overall electric system costs while still meeting customers' needs. Our solution provides evidence that GIS can play an integral role in the problem resolution. If additional funds and data are made available, a custom GDSS solution can be developed to allow EV charging developers to configure their own criteria for decision-making.

REFERENCES

[1] United States Department of Energy's Clean Cities program (2015). Alternative Fuels Data Center: Electric Vehicle Charging Station Locations. [retrieved: October, 2016], from http://www.afdc.energy.gov/fuels/electricity_locations.html

[2] United States Department of Energy (2012). President Obama Launches EV-Everywhere Challenge as Part of Energy Department's Clean Energy Grand Challenges. [retrieved: October, 2016], from http://energy.gov/articles/president-obama-launches-ev-everywhere-challenge-part-energy- department-s-clean-energy

[3] California Public Utility Commission (2015a). Distribution Resources Plan, from Bloomberg New Energy Finance (2016). Electric vehicles to be 35% of global new car sales by 2040. [retrieved: October, 2016], from https://about.bnef.com/press-releases/electric-vehicles-to-be-35- of-global-new-car-sales-by-2040/

[4] Chris Nelder, James Newcomb, and Garrett Fitzgerald (2016). Electric Vehicles as Distributed Energy Resources | Rocky Mountain Institute. [retrieved: October, 2016], from http://www.rmi.org/pdf_evs_as_DERs

[5] H. Trabish, (2016). If you build it, will they charge? Utilities cautious in plans to spur electric vehicle adoption | Utility Dive. [retrieved: October, 2016], from http://www.utilitydive.com/news/if-you- build-it-will-they-charge-utilities-cautious-in-plans-to-spur-elec/423982/

[6] SDG&E (2015). Electric Vehicle Grid Integration. [retrieved: October, 2016], from http://www.westernlampac.org/2015 Spring Conference/Laura McDonald EVGI LAMPAC Presentation 042715.pdf

[7] K. Bullis, (2013). Could Electric Cars Threaten the Grid? | MIT Technology Review. [retrieved: October, 2016], from https://www.technologyreview.com/s/518066/could-electric-cars-threaten-the-grid/

[8] H. Takeda, P. Veerkamp, and H. Yoshikawa, "Modeling design process," AI magazine, vol. 11, no. 4, pp. 37-xx, 1990.

[9] J. Jin, (2016). "Installing Public Electric Vehicle Charging Stations: A Site Suitability Analysis in Los Angeles County, California," PhD dissertation, University of Southern California, 2016.

[10] M. Momtazpour, P. Butler, M. S. Hossain, M.C. Bozchalui, N. Ramakrishnan, and R. Sharma, "Coordinated clustering algorithms to support charging infrastructure design for electric vehicles," Proc. ACM SIGKDD International Workshop on Urban Computing, Aug. 2012, pp. 126-133.

[11] C. Nelder, J. Newcomb, and G. Fitzgerald, (2016). Electric Vehicles as Distributed Energy Resources | Rocky Mountain Institute. [retrieved: October, 2016], from http://www.rmi.org/pdf_evs_as_DERs

[12] J. Pyper, (2016). New Edison International CEO Pizarro Calls for Greater Grid Investment to Enable Change, [retrieved: October, 2016], from https://www.greentechmedia.com/articles/read/New-Edison-CEO-Pizarro-Calls-for-Greater-Grid-Investment-to-Enable-Change

[13] R. Walton, (2016). Location matters: Utilities focus on charger placement to drive electric vehicle adoption: Two EV pilot programs demonstrate that just building charging stations isn't enough. D Utility Dive. [retrieved: October, 2016], from http://www.utilitydive.com/news/location-matters-utilities-focus-on-charger-placement-to-drive-electric-ve/425276/

[14] B. Plumer, (2016). The rapid growth of electric cars worldwide, in 4 charts. Vox Technology. [retrieved: October, 2016], from http://www.vox.com/2016/6/6/11867894/electric-cars-global-sales

[15] Los Angeles County Sheriff's Department (2012). Crime Data. [retrieved: March, 2017], from http://shq.lasdnews.net/CrimeStats/CAASS/desc.html

[16] Los Angeles County GIS Data Portal (2014). Parking Lot Boundaries – Commercial, Industrial, Government. [retrieved: March, 2017], from http://egis3.lacounty.gov/dataportal/tag/parking-lots/

[17] Southern California Edison's Distributed Energy Resource Interconnection Map (2017). [retrieved: March, 2017], from https://www.arcgis.com/home/item.html?id=e62dfa24128b4329bfc8b27c4526f6b7

[18] LA County Solar Map and Green Planning Tool (2015). [retrieved: March, 2017], from http://solarmap.lacounty.gov/

[19] V. Sultan and H. Bitar, "Geographic Decision Support Systems To Optimize The Placement Of Distributed Energy Resources." International jurnal of smart grid and clean energy, pp. 201-211, 2016.

[20] Environmental Systems Research Institute (2014). ArcGIS Help 10.2 - Kernel Density (Spatial Analyst). [retrieved: Novamber, 2016], from http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/how-kernel-density-works.htm

Handling Role-based Access Control in the Digital Grid

Steffen Fries, Rainer Falk
Corporate Technology
Siemens AG
Munich, Germany
e-mail: {steffen.fries|rainer.falk}@siemens.com

Chaitanya Bisale
Energy Management
Siemens AG
Nuremberg, Germany
e-mail: {chaitanya.b}@siemens.com

Abstract*—The operation of the digital energy grid, as one of the critical infrastructures, has to cope with the need to control of increasingly fluctuating demand and generation of energy, and also to ensure the reliable transmission and distribution of centrally and decentrally generated energy. Control is accomplished by utilizing a communication infrastructure in parallel to the actual power system infrastructure with connections to the physical world by sensors and actuators. In the past, this control communication network was mostly isolated from other communication networks, but is connected more and more with external systems to support innovative cross-system services. Increasingly, this open connectivity exposes the digital grid to cyber attacks. Therefore, access to resources like the communication connections or communicated data needs to be protected to ensure a reliable operation. Legislation and operational best practice guidelines have taken this into account and provide the necessary framework for defining specific communication security requirements. From the technical perspective, different security counter measures exist to cope with the given requirements, but it has to be ensured that these technical means are not only provided technically, but are in fact applied correctly in operation. Usability of security is essential to support the correct application of technical security measures. This paper reviews the requirements for role-based access control (RBAC), as well as currently targeted technical approaches to achieve RBAC in the digital grid. The goal is to provide more insight into the existing application of RBAC mechanisms and to identify gaps for future enhancements. Proposals to address the identified gaps are described, which are intended to be brought to the International Electrotechnical Commission (IEC) to enhance the security standard IEC 62351 for power system automation.

Keywords–security; user and device authentication; role-based access control; substation automation; digital grid; cyber security; critical infrastructure; IEC 62351

I. INTRODUCTION

Critical Infrastructures (CI) are technical installations that are essential for the daily life of the society and the economy of a country, and also globally. Typical critical infrastructures in this context are the power grid, telecommunication, healthcare, transportation, water supply, just to state a few.

Digital Grids as one example of CI and especially their cyber security has gained more momentum over the last years. The increased threat level becomes visible, e.g., through reported attacks on critical infrastructure, but also through reactions in legislation, which explicitly require specific protection of critical infrastructures and reporting about serious attacks. There is a clear trend towards increased connectivity and tighter integration of systems from Information Technology (IT) in common enterprise environments with the Operation Technology (OT) part of the automation systems in the energy and industrial domains to provide enhanced services. This requires security measures to avoid negative effects of the formerly isolated OT. IT security in this context evolves to cyber security to underline the mutual relationship between the security and physical effects.

Cyber security measures typically comprise technical and organizational measures. Operators of CI need to maintain their systems by complying to an Information Security Management Framework while also coping with regulatory requirements. This requires technical support in the deployment environment. Such technical requirements relate to authentication and access control, or to secure and reliable communication for example. Within this paper, the focus is placed on access control, or more specifically on Role-based Access Control (RBAC).

RBAC is already a proven concept in IT systems. It is realized by many (operating) systems to control access to system resources. RBAC for the power automation environment is already considered in several requirements standards, guidelines, and also in regulatory requirements. Beside the requirements supporting this functionality, technical standards ensuring interoperability have been developed [5][8].

This paper targets the discussion of RBAC in general and focuses on the selected target scenario of the digital grid as depicted in Figure 1 below. Section II provides an overview of requirements from guidelines, standards, and regulations targeting access control specifically. Section III provides an overview of several state-of-the-art approaches for RBAC, while Section IV discusses the basic RBAC concept currently deployed in the digital grid. The identified shortcomings are addressed in Section V with first solution proposals that are intended to be brought to standardization. Section VI concludes the document.

Note that this paper addresses first ideas to tackle identified gaps in RBAC in the Digital Grid domain. Further investigation is necessary.

 ISBN: 978-1-61208-556-2

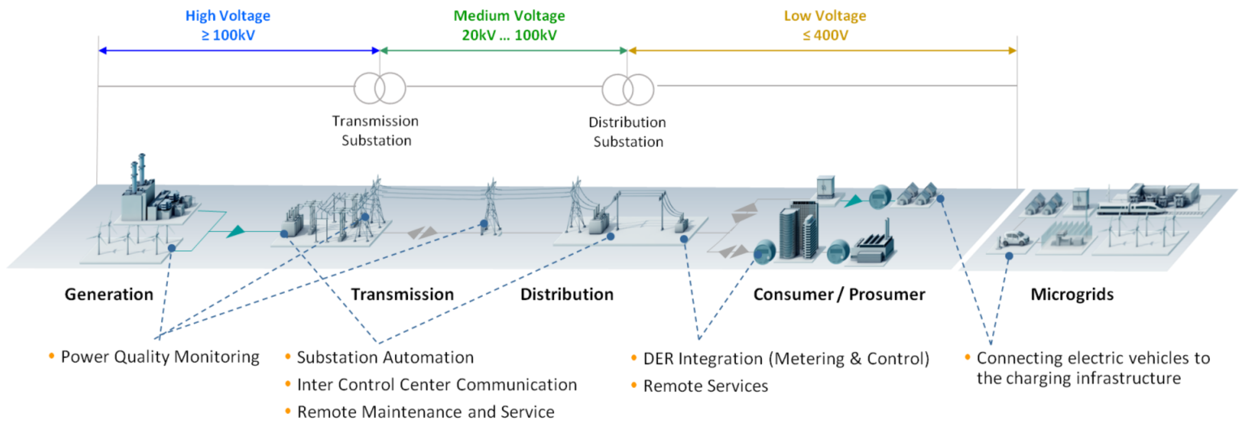


Figure 1. Overview Digital Energy Grid as Example for Critical Infrastructures

II. EXAMPLES OF DOMAIN-SPECIFIC GUIDELINES/STANDARDS/REGULATIONS

As outlined in [1] for secure communication, a variety of security requirements exist for digital grids. An overview of the most relevant standards, guidelines, and regulations is shown in Figure 2 below.

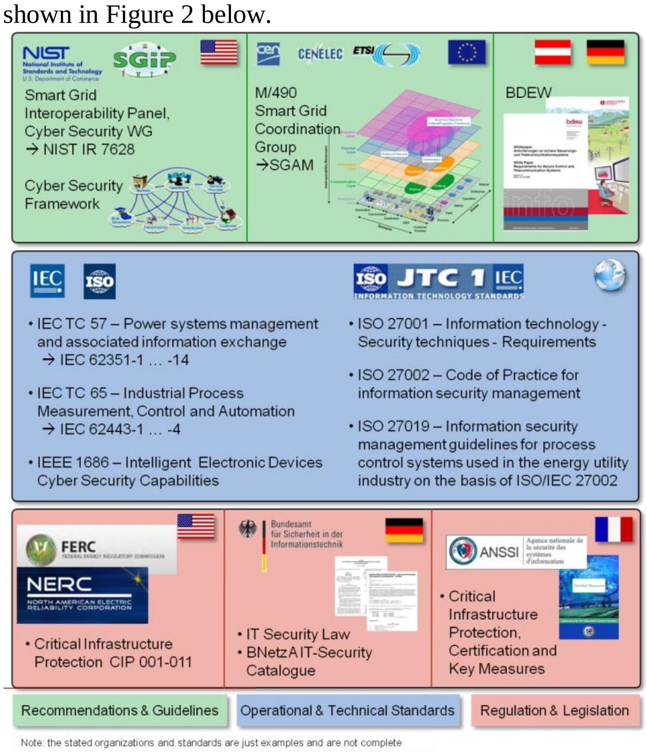


Figure 2. Examples for sources for security requirements for digital grid

Starting from the top in Figure 2, guidelines are available from the National Institute for Standards and Technology (NIST) of the U.S. through the “Guidelines for Smart Grid Cyber Security” in NIST IR 7628 [2] or the Report of the Smart Grid Coordination Group addressing the European Mandate M/490 [3], which explicitly recommend the support of RBAC in the context of system configuration, operation, and maintenance. Specifically for Germany and Austria, the BDEW White Paper [4] guideline has been published, addressing RBAC in the context of user management.

This white paper was one main source for developing ISO 27019:2013 [5] as a domain-specific profile of the Information Security Management System defined in ISO 27002 [6]. Both ISO documents address requirements for an operator regarding the handling of information security and require support for RBAC. Similar requirements can also be found in IEC 62443-2-1 for industrial environments. IEC 62443-3-3 [7] goes one step beyond by specifically defining, which foundational security requirements can be technically addressed with RBAC, without prescribing a specific technical solution. IEEE 1686 [8] is even more specific here, as it defines a minimum number of roles and also the associated rights. The last standard to be mentioned is IEC 62351-8 [9], providing specific technical means for binding RBAC information to entities in access tokens and to utilize them in communication. The latter can already be used to address some of the requirements stated before.

From a regulatory perspective, examples are provided through the American NERC-CIP [10], the German IT-Security Act [11], and the IT security catalogue of the German network regulator group BNetzA, and the French ANSSI [12]. They all require security measures to support reliable grid operations, which are mapped to processes and organizational means, but they also need the technical means to operate the infrastructure appropriately. The following section elaborates technical means to address these requirements.

III. STATE OF THE ART APPROACHES SUPPORTING RBAC

Security administration is simplified through the use of roles and constraints to organize subject access levels. RBAC in general can reduce costs within an organization, as it accepts that changes in roles and responsibilities of (especially) employees occur more frequently than the changes in the rights within roles. The basic idea of RBAC is to define roles according to responsibilities within the business organization. Permissions required to perform the duties of a role are assigned to the respective role. A subject, i.e., typically human user, is assigned roles according to his business responsibilities. This helps to achieve separation of duty by ensuring that a user is assigned only the roles according to his responsibilities, and possesses only the permissions required to fulfill his duties. Restrictions can be placed to prevent a single subject from being assigned to roles having a conflict of interest. RBAC also includes the concept of temporary roles to realize dynamic separation of duty: Over time, a subject may act in different roles. At any point in time, the subject only possesses the permissions of the currently active role or roles.

The general concept of RBAC is shown in Figure 3, which is the enhanced approach explained in [9]. As shown, the role separates the subject from the permissions. The permissions define certain rights on objects, like read or write operations on specific objects (e.g., files). The role itself bundles a set of permissions, which can be assigned to users. This subject assignment enables separation of duty, which is necessary to also support auditing of actions. Additionally, constraints may further be used to either restrict roles or to enable special handling in situations like emergency cases. Examples of constraints required in digital grids specifically are:

- *Area of Responsibility or scope* allows restricting the effectiveness of an issued RBAC token, e.g., to an organizational unit or a geographical location or area.
- *Operational constraints* allow a local augmentation of the associated rights if the (hosting) object detects or is informed about specific circumstances. As an example, an Engineer may not be allowed to perform certain actions, e.g., on a protection relay, in an emergency case.

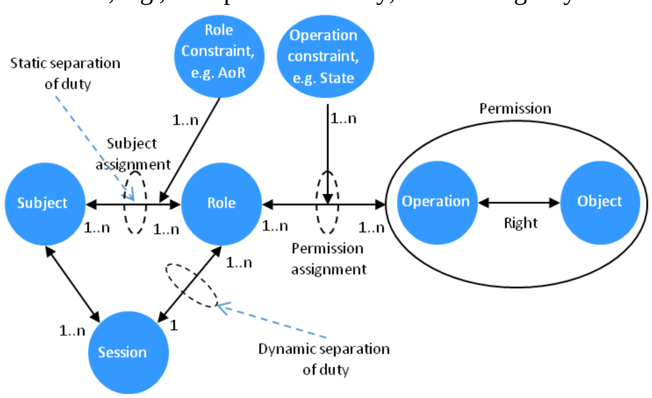


Figure 3. General concept for RBAC

The separation of the assignment of subjects-to-role and role-to-rights enables a flexible and centralized management of subject-to-role assignment that tends to be dynamic. At the same time, it can be combined with a well-defined role-to-permission-assignment that has more static character.

Figure 4 illustrates the concept of RBAC on a user base. In the upper part, the subject-role-right association is shown. Here "Tom" is assigned the role "Engineer". Acting in this role "Tom" is entitled to "view" and "control" objects. Objects may include status values or switching objects. It also shows the dynamic and static assignments between subjects, roles and rights. The example illustrates that granting the right "view" to "Mary" can be added by assigning the role "Engineer" to "Mary" without changing the associated rights on objects.

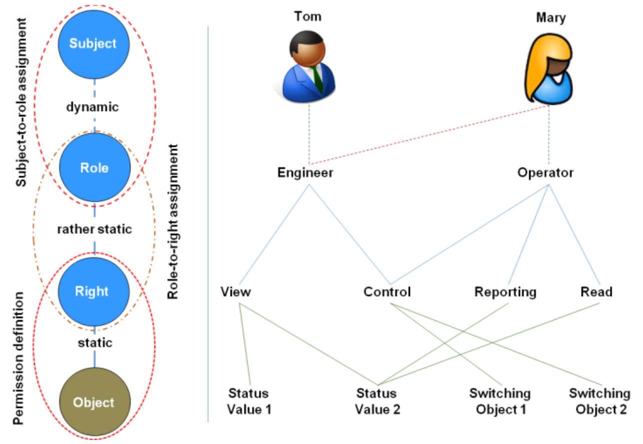


Figure 4. Basic RBAC concept applied in Digital Grids

To allow a subject to act in a distinct role, authentication is often a precondition, ensuring that the subject is who it claims to be and that it is entitled to act in this role. For this there already exist various solutions, often relying on a three-party-model, in which an identity and access server issues some form of security tokens or tickets to provide authorization information. Examples are Kerberos [13], the security assertion markup language (SAML) [14], OAuth 2.0 [15], and OpenID Connect [18]. Also domain specific approaches like X.509 certificate enhancements in IEC 62351-8 [9] for power automation have been standardized, which will be briefly introduced in the following. While they all rely on a security token mechanism, they differ, e.g., in the communication relations for the token exchange (protocols), the token format, the underlying cryptographic algorithms and the target application use cases.

A. *Kerberos*

Kerberos v5, specified in RFC 4120 [13], is a three-party system and protocol to be used for network authentication. In this system there exists a trusted third party, to which all participants authenticate as shown in Figure 5.

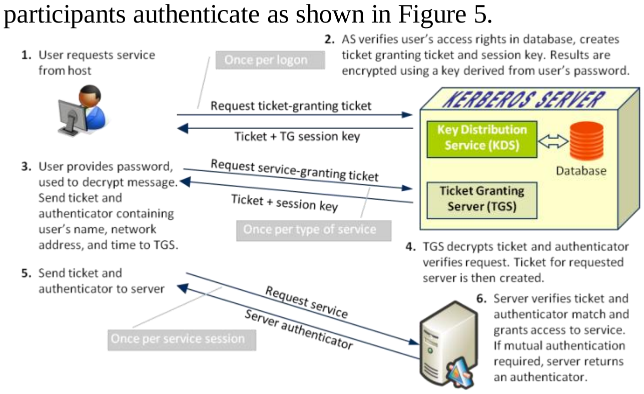


Figure 5. Kerberos authentication and authorization

This trusted third party grants tickets upon request to allow access to specific services or resources. Kerberos relies on symmetric cryptography for the authentication and also the ticket protection and binding and uses ASN.1 for the encoding. Kerberos is widely used and part of common operating system like Windows.

B. Security Assertion Markup Language (SAML)

SAML 2.0 was defined by OASIS in [14] and is an XML based protocol to exchange authentication and authorization information between a client, an identity provider (the SAML server) and the service provider. The SAML server uses so called SAML assertions to provide statements or claims about the client. Three types can be roughly distinguished: authentication, assertions, and authorization. Especially the latter allows realizing RBAC. SAML builds on assertions symmetric and asymmetric cryptography. Hence, SAML assertions are security tokens utilizing XML signatures and XML encryption to protect the contained information. For the authentication at the identity provider, SAML does not require a specific method and thus may be used with username/password combinations or X.509 certificate based authentication or others. SAML is often used in Single-Sign-On solutions and federation scenarios. It may be used also in open authorization (OAuth 2.0) for the token realization, as described in the following subsection.

C. Open Autorization (OAuth 2.0)

The OAuth 2.0 framework is specified in RFC 6749 [15] and defines an authorization method for accessing a resource. Since OAuth 2.0, this framework can be used with various applications and protocols, whereas the original OAuth was bound to the HTTP protocol. OAuth 2.0 also relies on tokens, which are requested by a user agent, issued by an authorization server and verified at the resource server. The tokens may be provided by reference or by value. OAuth 2.0 defines the handling of the security tokens (access token), as well as the format but allows for an own definition of the token content. Beside the pure request of access tokens, a client may request for a token for a specific scope. The supplied tokens are provided according to the bearer model or the proof-of-possession (PoP) or holder of key (HoK) model. Bearer token can be used to get access to an associated resource without demonstrating possession of a cryptographic key. In contrast, the PoP/HoK token model, requires the proof of possession of a corresponding cryptographic key in order to utilize the token, as defined in RFC 7800 [16]. Note that according to [17], plain OAuth 2.0 is intended for authorization. It may support authentication, e.g., in the combination with OpenID Connect (see next subsection). OAuth addresses typical Web-based access scenarios.

D. OpenID Connect

OpenID Connect is a security protocol to offload user authentication from a server hosting a resource to a trusted third party. It is defined by the OpenID Consortium. The core is specified in [18]. It utilizes the OAuth 2.0 protocol flows to obtain ID tokens, which are encoded as JSON web token (JWT, see also [19]). These ID tokens contain assertions about authenticated users from an authorization server. Optionally, access tokens as defined in OAuth 2.0 can be utilized to retrieve asserted user authorization information. OpenID Connect is used for web-based clients and also native clients in a variety of applications.

E. Digital Grid specific X.509 Certificate Enhancements

Another option to support RBAC has been taken in IEC 62351-8 [9] for power system automation. This standard relies on the authentication based on X.509 [20] certificates and corresponding private keys. In digital grids protocols like TLS are applied, which utilize X.509 key material.

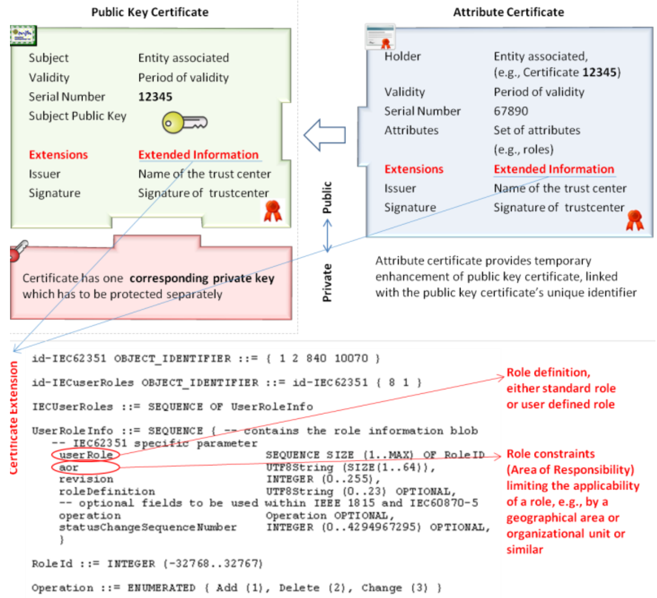


Figure 6. X.509 certificate enhancements (adopted from [9])

IEC 62351-8 leverages the option to enhance the ASN.1 structure of X.509 certificates with a specific extension. This extension carries information about the roles and constraints and can be added to X.509 public key certificates or X.509 attribute certificates as shown in Figure 6. The flexibility of attribute certificates can be leveraged in use cases, in which the user to role association is rather dynamic. User-bound public key certificates typically have a longer validity, while attribute certificates may have a much shorter validity and are only valid in conjunction with the associated public key certificate. Via the corresponding private key it can be proven, that a user may act in a certain role. As this approach is defined as an extension, protocols utilizing X.509 key material can directly leverage the approach. Note that for the token issuer, i.e., a certification authority, enhancements are likely to be necessary to support the RBAC extension.

IV. RBAC SPECIFICS IN THE DIGITAL GRID

As shown in Figure 6, for power systems supporting IEC 62351-8, an extension for carrying role information in X.509 certificates has been standardized, which may belong to a user, a device, or an application. This approach can be directly applied in use cases, in which protocols utilizing X.509 key material like Transport Layer Security (TLS, RFC 5246) are used. Moreover, this approach also supports application layer authentication and authorization, which can be required, if the communication link spans multiple hops. In both cases, beside the certificate validation it also involves the verification of the relying party that the applicant entity is entitled to utilize the X.509 certificate by checking the possession of a corresponding private key. This involves asymmetric cryptography for digital signature generation and verification. Compared to pure symmetric cryptography based approaches, this is costly. Hybrid methods addressing this establish a session, in which a X.509 certificate is involved in the negotiation of a symmetric session key, which is used in (different) security services to protect the session. The whole session is then executed in the context of a specific user, having an assigned role. As substation automation protocols like IEC 61850 utilize a session based approach for the transport or the application connection, this concept is immediately applicable. Note that for the generation of a digital signature, access to the private key is necessary. This private key needs to be protected accordingly, as it is necessary as proof, that the user is authorized to act in a certain role via the corresponding certificate. For devices or applications this protection may be achieved with secured memory or specific hardware modules that allow operation but not exporting of the private key. For a service technician, this protection will most likely be offered by a security token like a smart card or similar.

Current installations in digital grids often utilize a different concept by performing a local form of RBAC depending on the environment. Communication between entities in a control center for instance is performed based on either locally or centrally associated users to permission groups. This ensures that the local execution of commands can only be done if the appropriate permissions are granted, but does not necessarily provide a remote entity to verify who is going to perform a dedicated operation. This information may be necessary for audit purposes, and a complete audit trail would require having the complete chain from the remote point to the executing entity to comprehend the specific action. The approach described in IEC 62351-8 supports also a local audit trail through the capability to connect identity and access information in the access token. In substations, the local physical access may already be sufficient to get access to communicating entities.

While the approach utilizing X.509-based access tokens has its merits, it is not immediately applicable in all use cases. Also, one has to keep in mind that the infrastructure of the power grid has grown over many years and that the lifetime of installed devices is long, reaching 20-25 years. Two examples are used here to show potential shortcomings.

1. In substation automation, field devices often feature a local human-machine-interface (HMI) handled by a service technician. These field devices typically do not feature a local interface for a smart card, but only a small screen and a number keyboard pad allowing entering a personal identification number (PIN) or a passcode. Hence, RBAC information cannot be provided directly, but may be fetched by the field device..
2. As outlined in [21] web-based services based on XMPP are specified for the integration of decentralized energy resources (DER) into the digital energy grid. These services may leverage already existing technologies that support RBAC, such as OpenID Connect or OAuth 2.0 instead of building a parallel infrastructure for handling X.509 based RBAC.

Proposals are discussed in the next section for both examples.

V. Proposals for RBAC enhancements

In the following, solutions are proposed for handling RBAC in legacy devices and in upcoming web-based applications building on consistent RBAC information. The real-world applicability of these proposals has to be evaluated.

A. *Enabling RBAC on local HMI of legacy devices*

As noted, a variety of devices may not feature an appropriate interface to interact with a X.509 credential of a service technician. Despite the missing local interface, these devices may be enabled to work with the X.509 credentials. One approach to be used here is the fetching of the X.509 credential from a trusted third party utilizing the local login and password of the service technician. Once the service technician provides his login credentials, the field device may query a central repository for the corresponding X.509 certificate also providing the login credentials for verification. This X.509 certificate needs to be enhanced with the RBAC extension defined in IEC 62351-8 and can then be verified by the field device. The verification of the corresponding private key is neglected here, as the X.509 certificate is rather used as an assertion by the third party. By already relying on X.509 certificates with RBAC extensions, this approach may be used as a migration path without involving device local asymmetric cryptographic operations.

The central repository may generate the credentials on demand or they may be provisioned with the X.509 certificates. In either case, the certificates may have a rather short lifetime, which simplifies the revocation handling on the field device. This approach has been considered in IEC 62351-8 with the focus on Lightweight Directory Access Protocol (LDAP) [22]. While LDAP support is typically available in control centers, it is not too widespread in substations. Protocols like the Remote Authentication Dial In User Service (RADIUS) [23] are rather used.

If one would want to use RADIUS out-of-the-box, access information can be provided as RADIUS allows extensions using vendor specific attributes. The drawback is the limitation of this field to effectively 250 bytes. As X.509 certificates are typically larger (even if used with shorter ECDSA key instead of the larger RSA key), this field can only be used to transmit a subset of the RBAC information. A necessary subset is proposed as:

```
BEGIN-VENDOR IEC
  ATTRIBUTE RoleID          1  integer
  ATTRIBUTE roleDefinition  2  string
  ATTRIBUTE AoR             3  string
  ATTRIBUTE revision        4  integer
  ATTRIBUTE ValidFrom       5  string
  ATTRIBUTE ValidTo         6  string
END-VENDOR IEC
```

The semantic of the parameter would be the same as in IEC 62351-8 and would support also a later processing of other token formats containing the same information. As RADIUS has some shortcomings, like missing message integrity or confidentiality or the application of the weak

MD5 hash algorithm, it is recommended to use TLS according to [24] to protect the message exchange between field devices and the RADIUS server. As stated above, this approach is intended to support migration in restricted use cases without changes or enhancements to RADIUS itself.

B. Supporting RBAC in web service scenarios

Integration of DER into the digital grid will be supported with IEC 61850-8-2 [25]. Here XMPP is used to enable the connection of field devices (DER controller) to the control site using a publish-subscribe infrastructure. While in [25] the application of session-based end-to-end RBAC in conjunction with X.509 credentials is enabled, further services offered by the publish-subscribe infrastructure may utilize a message-based approach and may require an end-to-middle RBAC approach. Applications could be presence monitoring, notification, or discovery of resources, which may be utilized by a virtual power plant operator. Here the application of OpenID Connect is envisioned, which would need to map the existing access token information to the access token format in the OpenID Connect context.

VI. CONCLUSIONS AND OUTLOOK

This paper described the general concept of role-based access control and its usage within the digital energy grid. Ongoing standardization work for using RBAC for energy control networks has been described. This paper discussed role-based access control in the digital grid, starting from an analysis of requirements in regulation and standardization. It provided an overview about existing technical approaches from other domains and discusses the specifics of the digital grid, the target domain. Two exemplary gaps have been identified for the incorporation of legacy devices and for future DER devices for which first solution sketches have been provided. The feasibility of these proposals is to be investigated from a security assessment point of view, as well as from an implementation point of view. Hence, at the time of writing, a proof-of-concept implementation was not yet available, but is envisioned as the next consequent step.

REFERENCES

[1] S. Fries and R. Falk, “Ensuring Secure Communication in Critical Infrastructures,” Proceedings IARIA Energy 2016, June 2016, ISBN: 978-1-61208-484-8, page 15-20, https://thinkmind.org/download.php?articleid=energy_2016_1_30_30060, [retrieved: March. 2017].

[2] NIST IR 7628, “Guidelines for Smart Grid Cyber Security,” Sep. 2014, http://dx.doi.org/10.6028/NIST.IR.7628r1, [retrieved: March. 2017].

[3] SGIS “Smart Grid Information Security,” Dec. 2014, ftp://ftp.cencenelec.eu/EN/EuropeanStandardization/HotTopics/SmartGrids/SGCG_SGIS_Report.pdf, [retrieved: March. 2017].

[4] BDEW White paper “Requirements for Secure Control and Telecommunication Systems,” BDEW, Feb. 2015

[5] ISO TR 27019: Information security management guidelines for process control systems used in the energy utility industry on the basis of ISO/IEC 27002, March 2013

[6] ISO/IEC 27002:2005 Information technology – Security techniques – Code of practice for information security management, June 2005.

[7] IEC62443-3-3:2013, “Industrial communication networks – Network and system security – Part 3-3: System security requirements and security levels,” Edition 1.0, August 2013.

[8] IEEE 1686, “IEEE Standard for Intelligent Electronic Devices Cyber Security Capabilities,” Dec. 2013.

[9] ISO/IEC 62351-8, “Role-based access control for power system management,” June 2011.

[10] NERC, North American Reliability Corporation, http://www.nerc.com/pa/Stand/Pages/CIPStandards.aspx, [retrieved: March. 2017].

[11] German IT Security Law, July 2015, http://www.bgbl.de/xaver/bgbl/start.xav?startbk=Bundesanzeiger_BGBl&jumpTo=bgbl115s1324.pdf, (German), [retrieved: March. 2017].

[12] ANSSI Technical Note, Recommandations de sécurité concernant l’analyse des flux HTTPS, October 2015, http://www.ssi.gouv.fr/uploads/IMG/pdf/NP_TLS_NoteTech.pdf (French) [retrieved: March. 2017].

[13] C. Neuman, T. Yu, S. Hartman, and K. Raeborn, “The Kerberos Network Authentication Service (V5),” RFC 4120, July 2005, https://tools.ietf.org/html/rfc4120, [retrieved: March. 2017].

[14] S. Cantor, J. Kemp, R. Philpott, and E. Maier, “Assertions and Protocols for the OASIS Security Assertion Markup Language (SAML) V2.0,” March 2005, http://docs.oasis-open.org/security/saml/v2.0/saml-core-2.0-os.pdf, [retrieved: March. 2017].

[15] D. Hardt, “The OAuth 2.0 Authorization Framework,” RFC 6749, October 2012, https://tools.ietf.org/html/rfc6749, [retrieved: March. 2017].

[16] M. Jones, J. Bradley, H.Tschofenig., “Proof-of-Possession Key Semantics for JSON Web Tokens (JWTs),” RFC 7800, April 2016, https://tools.ietf.org/html/rfc7800, [retrieved: March. 2017].

[17] J. Richter, “User Authentication with OAuth 2.0,” https://oauth.net/articles/authentication/, [retrieved: March. 2017].

[18] J. Bradley et al., “OpenID Connect Core 1.0 incorporating errata set 1,” November 2014, http://openid.net/specs/openid-connect-core-1_0.html, [retrieved: March. 2017].

[19] M. Jones et al., “JSON Web Token (JWT) Profile for OAuth 2.0 Client Authentication and Authorization Grants,” May 2015, https://tools.ietf.org/html/rfc7523, [retrieved: March. 2017].

[20] D. Cooper et al., “Internet X.509 Public Key Infrastructure Certificate and Certificate Revocation List (CRL) Profile,” RFC 5280, May 2008, https://tools.ietf.org/html/rfc5280, [retrieved: March. 2017].

[21] S. Fries, R. Falk, H. Dawidczak, and T. Dufaure, “Decentralized Energy in the Smart Energy Grid and Smart Market – How to master reliable and secure control,” International Journal on Advances in Intelligent Systems, vol 9 no 1& 2, ISSN: 1942-2679, pg. 65-75, Sep. 2016.

[22] J. Sermersheim, “Lightweight Directory Access Protocol (LDAP): The Protocol,” RFC 4511, June 2006, https://tools.ietf.org/html/rfc4511, [retrieved: March. 2017].

[23] C. Rigney et. al., “Remote Authentication Dial In User Service (RADIUS),” RFC 2865, June 2000, https://tools.ietf.org/html/rfc2865, [retrieved: March. 2017].

[24] S. Winter et al, “Transport Layer Security (TLS) Encryption for RADIUS,” RFC 6614, May 2012, https://tools.ietf.org/html/rfc6614, [retrieved: March. 2017].

[25] ISO 61850-8-2: Communication networks and systems for power utility automation, Part 8-2: Specific Communication Service Mapping (SCSM) – Mapping to Extensible Messaging Presence Protocol (XMPP), Work in Progress

Mitigating Brown-Outs: Fair Distribution of Locally Sourced Energy in Smart Grids

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

***Abstract*—The introduction of more and more *local and distributed* energy resources (DER) into the current centralized electrical grid poses new challenges to energy distribution. DERs are significantly smaller in production capabilities than central power plants and their production is highly fluctuating. This means that their influence on the electrical grid is difficult to plan for, especially in brown-out situations, when there is not enough energy available to supply all consumers. This work focuses on the subproblem of fair electricity distribution in brown-out phases. Currently, network segments are switched on and off in a round-robin manner, regardless if there are local producers in these segments or not. However, enabling segments that include local producers more often would improve the overall amount of energy available during the brown-out phases, and thus, this measure would increase the number of supplied consumers. We propose new algorithms that leverage the power of local producers, but still keep a fair energy distribution for all consumers. Therefore, we evolve the current notion of fairness to improve the overall quality of service by taking into account equal supply times, as well as maximizing the number of supplied consumers. The proposed algorithms are compared to the current state of the art approach in the German electrical grid. Therefore, extensive simulations based on real-world low-voltage residential area networks were conducted. The results indicate an improved quality of service during brown-out phases. Moreover, the proposed method is not limited to low-voltage residential areas, but also applies to all hierarchy levels of the energy grid, ranging from the distribution grid down to future households implementing smart grid technologies.**

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

I. INTRODUCTION

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 increased 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 [1]. Furthermore, in contrast to the fossil-fuelled producers, the production of the DERs is highly fluctuating and thus, difficult to plan for [2]. 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) [3] 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 and wind turbines. 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 capacities 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 German state of the art procedure to cope with the problem of D&R in a brown-out-scenario works as follows: the network is logically divided into (preferred equally consuming) subnets. Each of these subnets has to be separable and reconnectable 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 based 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, otherwise additional subnets are disconnected. 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 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 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. This, however, will also deactivate the production capabilities, in terms of DERs, which are located in these subnets. Therefore, this attempt might even promote further destabilization of the network if the consumers are capable of producing high amounts of electricity. To face these challenges of the future energy grid it is important to develop new rules, policies and algorithms that take these DERs into account while concurrently providing fair electricity distribution.

 ISBN: 978-1-61208-556-2

In this work, *fairness* is introduced as a measure for extending the definition of quality of supply in the electrical grid. Additionally, algorithms are presented that allow to use the production of DERs, to increase the number of subnets that can be supplied in the brown-out-scenario. However, there is no general definition of fairness. As of this, our fairness definition focuses 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.
As a use case, the introduced approach is tested in a simulation of a low-voltage distribution system of an residential area. It is, however, not limited to this scenario. The proposed approach can be used at all hierarchical levels of the electrical grid, ranging from the distribution grid to low-voltage areas. Moreover, with future technological progress, this approach can be applied to single consumers in the grid.
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. Section III describes a formal model for representing a micro grid in an undersupplied state and introduces a new fairness metric, which takes the equal distribution of electricity, as well as the average number of supplied busses into account. In Section IV, fair electricity distribution algorithms are presented. Followed by Section V, where the simulation process is described and the results are discussed. Finally, the paper concludes with Section VI.

II. Related Work

Fairness is a term discussed in many fields, most prominently in economics [4] and psychology [5]. However, fairness also became an important criterion in application of information technology [6] and especially in the area of scheduling algorithms [7] and resource allocation [8]. 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 [9] 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 [10], 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 [11] 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 [12]. 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 [13]; 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 [14] 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. System Model Definition

In this Section, a model to represent a microgrid in an undersupplied state is presented. In particular, the relevant parts of the microgrid are described and formalized. Subsequently, a formal definition of an undersupplied state is presented. The Section concludes with the introduction of assumptions about minimal provided supply and a presentation of the novel fairness metric.
The system considered in this work is a microgrid that encompasses multiple residential areas. This can be, for instance, the electrical network that connects several streets in a city. The microgrid is connected to the main grid (MG) through an adjustable transformer that handles incoming energy from the MG, as well as outgoing electricity into the MG. This transformer allows the measurement of electrical values for the different streets like phase voltage, phase angles, and ingoing and outgoing energy. Furthermore, this component provides the functionality of enabling and disabling incoming and outgoing connections, such that parts of the microgrid can be disconnected and reattached to the MG. In the following, a more formal definition of the system model will be provided. Let the overall system be a set of street busses $ST = \{st_0, \dots, st_n\}$, $n \in \mathbb{N}$. Each of these busses represents a prosumer, which is connected to the adjustable transformer (*tr*). This scenario is shown by Figure 1.

Each street bus st_i has a combined consumption and production, which is in general the sum of the consumption and production of all houses that are located in this street. The production capabilities of houses are non-zero if DERs are installed, otherwise they will be neglected (We will not go into further detail about production and consumption behaviour of the houses, but stay at the street abstraction level). Each prosumer can be a consumer or a producer at each specific point in time during the day. Let all prosumers be represented as a set C and the producers likewise as a set P. A prosumer is a consumer $c_j \in C$ if the consumption of electricity in the street is higher than the production provided by its local DERs. Whereas a prosumer is a producer $p_j \in P$ if the electricity provided by its local DERs exceeds the local demand. A more

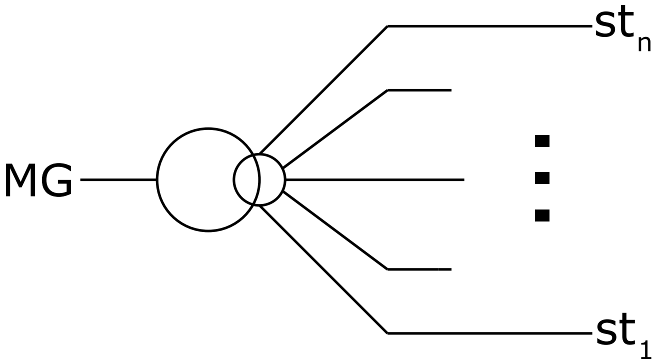


Figure 1. Representation of the considered scenario, where the street busses (st) are connected to the main grid (MG).

formal representation of these relations can be expressed as follows:

$$\forall t, i\ 0 \leq i \leq n\, \{st_i \in C \,|\, cons(st_i, t) > prod(st_i, t)\} \quad (1)$$

$$\forall t, i\ 0 \leq i \leq n\, \{st_i \in P \,|\, cons(st_i, t) \leq prod(st_i, t) \quad (2)$$

Parameter t represents a certain point in time during a time interval $[0, \ldots, T-1]$. The functions $cons(st_i, t)$ and $prod(st_i, t)$ provide the current consumption or respectively the production of electricity of street bus st_i at the time t. Equation 3 provides a formal description of the production function $prod(st_i, t)$ and, similarly, Equation 4 refers to function $cons(st_i, t)$.

$$prod(st_i, t) := \sum_{j=0}^{m} \int_{t}^{t+1} y_j(t)\mathrm{d}t \quad (3)$$

$$cons(st_i, t) := \sum_{j=0}^{m} \int_{t}^{t+1} x_j(t)\mathrm{d}t \quad (4)$$

The production and consumption of a street bus st_i at given point in time t is the sum of the integral of the production/consumption $y(t)/x(t)$ over the time step t for all the houses j connected to that bus. Without loss of generality it will be assumed for the remainder of the paper that the granularity of the time interval T is based on the hours of a 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. With further technological progress, in the future it will be possible to refine this model by transitioning from the level of street busses to houses or even to the devices that are located in the houses.

In the following, a formal definition for an undersupplied state (brown-out) is provided. A microgrid is a part of the larger MG and either receives electricity from it or acts as a producer if the local production is high enough. However, since we are dealing with a situation of undersupplyment, we assume that the main grid can not provide enough energy to supply all street busses of the micro grid simultaneously. Moreover, we assume that this holds for at least one timestep during a day. The formal definition of an emergency state is as follows:

$$\exists t\, 0 \leq t < T\, prod(MG, t) < \sum_{i=0}^{n} cons(st_i, t) \quad (5)$$

Where $prod(MG, t)$ represents the amount of electricity the MG can provide for supplying the prosumers of the microgrid. As long as the production of the MG is high enough to partially supply the micro grid, the system is in a brown-out-state. However, if the MG does not provide electricity at all, the systems status changes to a black-out-state. Without loss of generality, this work focuses on an undersupplied state that is critical (brown-out), but not fatal (black-out) for the microgrid. In particular, this means that the amount of energy provided by the MG should at least cover the demand of some of the street busses located in the micro grid. A formal definition can be as follows:

$$prod(MG, t) \geq \max\{cons(st, t) | st \in ST\} \quad (6)$$

This definition guarantees that, for each point in time, the MG provides enough energy to supply a single street in the microgrid. Without this assumption we may have situations where the electricity is not enough to supply a single bus. This, however, represents a black-out-state in our model, and is not part of the current work. Note that in this case the model still holds considering future technological development and thus the possibility to transfer the problem recursively to individual streets. In addition to the electricity that is provided by the MG to supply the micro grid, the street busses contain local producers. Examples for such local producers are 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 bus is supplied, the local producers are active and increase the amount of available electricity. However, if a bus is not supplied the corresponding DERs are deactivated. To successfully supply a bus st_i at time t it is sufficient to provide the amount of electricity such that the sum of electricity provided by local DERs and the supply of the MG equal the demand of the bus. The formal definition is as follows:

$$cons(st_i, t) \leq prod(MG, t) + prod(st_i, t) \quad (7)$$

The function $prod(MG, t)$ hereby represents the amount of energy that is centrally provided by the MG. 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 metric 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 bus, where they are located, is connected to the network. One part of the novel fairness metric is based on the assumption that strategies, which maximize the use of DERs, are able to supply more busses than other strategies. To represent this in the metric, the average number of supplied busses is used as a parameter. Furthermore, to include the fairness of handling the consumers, the sum of differences between the supplied time of all consumers is calculated. If an algorithm can supply a large number of busses, 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. 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:

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

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 takes the DERs of the busses into account, is described. Finally, an algorithm that aims to maximize the use of DERs and, additionally, equalises the number of supplied time for each bus, 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 works in a round-robin based manner and solves the problem of fair supply distribution as follows. The algorithm uses a list of busses and the information about the amount of production, which is centrally provided by the MG, to determine a subset of supplyable elements for the current timestep. Since the algorithm uses a round-robin approach, it is not allowed to activate a specific component for a second time before all other busses have been activated at least once. With this design it is ensured that each component 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.

B. IIA - Improved Iterative Approach

The Improved Iterative Approach (IAA), which is shown in Figure 3, iteratively selects busses from its list and tries to supply them. In contrast to TRR 2 it takes the production of the local DERs on the busses 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:

```
procedure TRR(production, timestep, busses)
    for i ← busses.length() do
        bus ← getLowestUptimeBus(busses);
        if bus == null then
            break;
        else
            if supplyable(bus) then
                activate(bus);
            end if
        end if
    end for
    return activeBusses;
end procedure
```

Figure 2. TRR - Traditional Round-Robin.

```
procedure IIA(production, timestep, busses)
    while consumption < production do
        bus ← getNextBus(busses);
        if supplyable(bus) then
            activate(bus);
            production += bus.getProduction();
        else
            markUnfit(bus);
            if AllBussesProcessed then
                return activeBusses;
            end if
        end if
    end while
end procedure
```

Figure 3. IIA - Improved Iterative Algorithm.

first, if there still remains unused capacity, iteratively choose a street bus from the list of busses and check if the required demand can be met. If this is the case, then activate the bus and add the resulting production capabilities of its DERs to the overall production. If the selected bus cannot be supplied in this timestep mark it as unfit. After the algorithm terminates, it returns a list of busses that will stay active in this timestep and all remaining busses 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 maintaining equal supplied times for the busses. To achieve this, the algorithm distinguishes in a first step between consumers and producers. Second, all producers are supplied and their local production capabilities are added to the central production. This is possible as we are in the brown-out-scenario, where the central production provides at least enough electricity to supply a single bus each. After the activation of the bus, the local DERs are providing enough energy to sustain the bus. After all the producers are activated, the algorithm chooses a bus that is currently inactive and has a minimal amount of supplied time. In the next step, the algorithm checks if the selected bus can be supplied. If this is the case, the bus is activated, otherwise it is marked as unfit. After all busses are supplied or marked as unfit, the algorithm returns a list of busses that will stay active during this timestep and all remaining busses will be deactivated.

 ISBN: 978-1-61208-556-2

```
procedure UEA(production, timestep, busses)
    while consumption < production do
        for all bus ∈ busses do
            if isSelfSustaining(bus) then
                activate(bus);
                production += bus.getProduction();
            end if
        end for
        bus ← getMinUptimeBus(busses);
        if supplyable(bus) then
            activate(bus);
        else
            markUnfit(bus);
        end if
        if AllBussesProcessed then
            return activeBusses
        end if
    end while
end procedure
```

Figure 4. UEA - Uptime Equalizing Algorithm.

V. 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 simulation framework was developed using the Java programming language. It implements the model described in Section III and is able to simulate a microgrid consisting of an arbitrary number of street busses. For the current simulation, a total number of five busses was chosen. Each bus has a combined consumption, as well as a combined production for each timestep. 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 street busses and one production curve of a solar panel are used. For simulating a brown-out scenario, the central production is derived using 6.

1) Load Set: For realistic load data of street busses in residential areas, real recordings of an adjustable transformer are used. 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 bus with a very high electricity demand, whereas the second set represents the consumption of a smaller street. Figure 5 shows the load curves of the busses for a day.

2) DER Production Set: For modeling realistic production behaviour, real-world solar panel production data is taken from Kronberg, Germany. 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 low demand bus and three to the high demand bus. Figure 6 shows the production curve of the solar panel over a day.

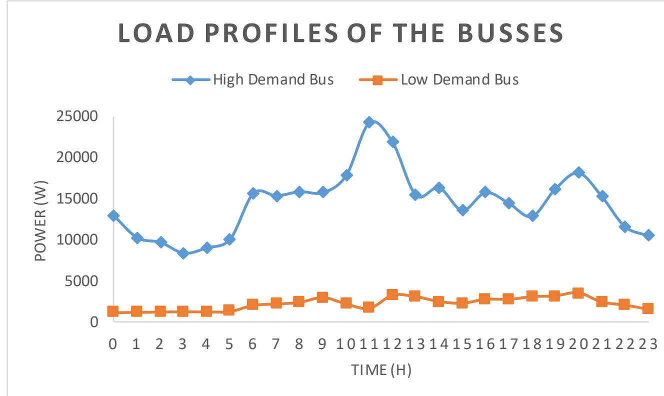


Figure 5. Load curves of the high/low demand busses connected to the adjustable transformer in Saarland (Germany).

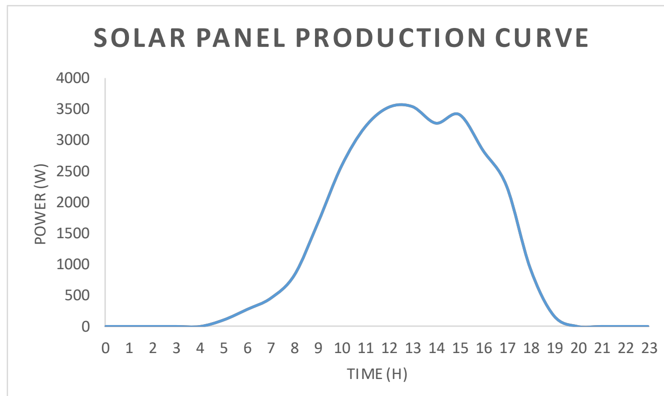


Figure 6. Production profile of a 4.51 kWp solar panel located in Kronberg Germany.

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 busses in each run, are busses that stay online in the current timestep, either, because they are self-sustainable, or are supplied by the MG. 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 7 shows the average results for 1,000 simulation runs with the data set of the low demand bus. From this set, five busses are generated and used for evaluation. Figure 7 shows the average number of supplied components during the corresponding time of the day for each of the algorithms.

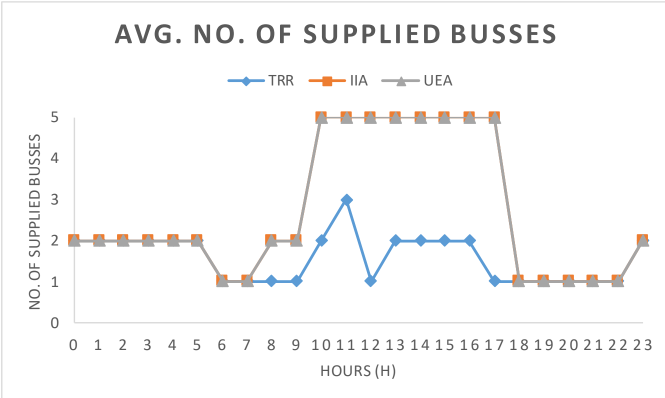


Figure 7. Average number of active low demand street busses during a time interval of 24 hours.

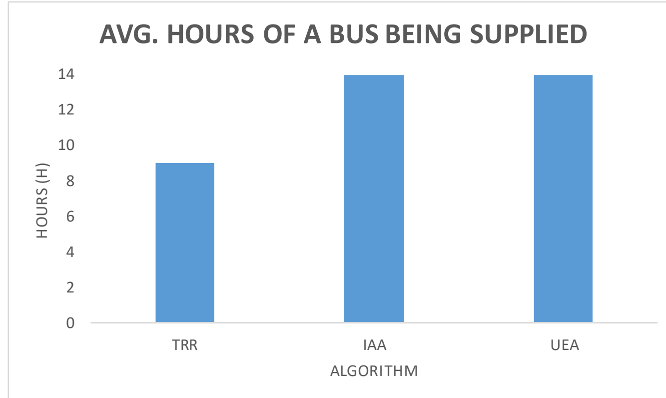


Figure 8. Total average number of how long busses were active during a day using the different algorithms in the low demand scenario.

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

IIA 3 and UEA 4 perform equally in this scenario as shown in Figure 7. 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 7 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 8. 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 9 shows the performance of the algorithms with regard to the fairness metric.

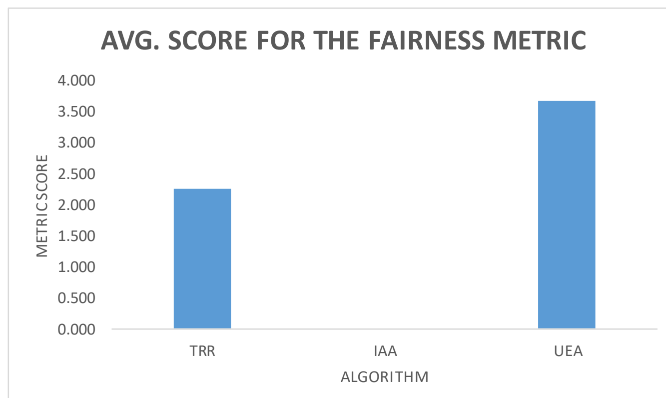


Figure 9. Average metric score of the algorithms in the low demand scenario.

As mentioned in Section III, this metric is based on the average performance of the algorithms while treating all consumers 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. This, however, 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 10 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

 ISBN: 978-1-61208-556-2

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.

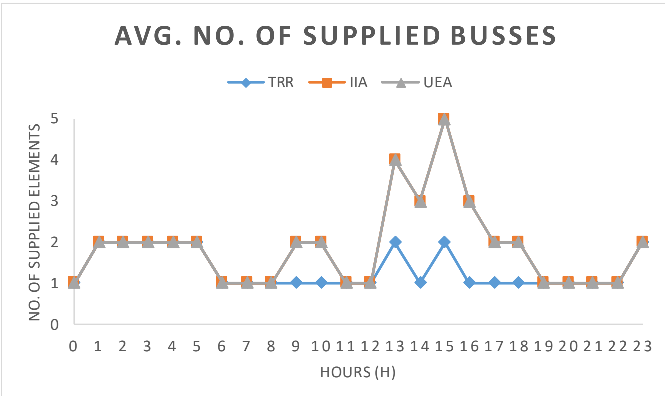


Figure 10. Average number of active high demand street busses during a time interval of 24 hours.

Most of the time TRR 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 3 and UEA4 at 12pm is due to the demand spike that can be seen in Figure 5 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.

VI. 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. Moreover, further technological progress will allow to apply our approach to all hierarchy levels of the energy grid, ranging from the distribution network to single consumers. 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.

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.

Acknowledgment

The work in this paper was partially performed in the context of the PolyEnergyNet (PEN) research project and partially funded by the Germany Federal Ministry for Economic Affairs and Energy (BMWi) under grant no. “0325737E”.

References

[1] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, and W. Dhaeseleer, “Distributed generation: definition, benefits and issues,” Energy policy, vol. 33, no. 6, 2005, pp. 787–798.

[2] N. D. Hatziargyriou and A. S. Meliopoulos, “Distributed energy sources: Technical challenges,” in Power Engineering Society Winter Meeting, 2002. IEEE, vol. 2. IEEE, 2002, pp. 1017–1022.

[3] “Renewable energy sources act,” https://www.gesetze-im-internet.de/bundesrecht/eeg_2014/gesamt.pdf, accessed: 2017-02-02.

[4] A. Falk, E. Fehr, and U. Fischbacher, “Testing theories of fairnessintentions matter,” Games and Economic Behavior, vol. 62, no. 1, 2008, pp. 287–303.

[5] E. A. Lind, L. Kray, and L. Thompson, “The social construction of injustice: Fairness judgments in response to own and others’ unfair treatment by authorities,” Organizational behavior and human decision processes, vol. 75, no. 1, 1998, pp. 1–22.

[6] A. Wierzbicki, Trust and Fairness in Open, Distributed Systems, ser. Studies in Computational Intelligence. Springer Berlin Heidelberg, 2010.

[7] M. Zaharia and et al., “Delay scheduling: a simple technique for achieving locality and fairness in cluster scheduling,” in Proceedings of the 5th European conference on Computer systems. ACM, 2010, pp. 265–278.

[8] S. K. Baruah, N. K. Cohen, C. G. Plaxton, and D. A. Varvel, “Proportionate progress: A notion of fairness in resource allocation,” Algorithmica, vol. 15, no. 6, 1996, pp. 600–625.

[9] Z. Baharlouei, M. Hashemi, H. Narimani, and H. Mohsenian-Rad, “Achieving optimality and fairness in autonomous demand response: Benchmarks and billing mechanisms,” IEEE Transactions on Smart Grid, vol. 4, no. 2, 2013, pp. 968–975.

[10] G. Koutitas, “Control of flexible smart devices in the smart grid,” IEEE Transactions on Smart Grid, vol. 3, no. 3, 2012, pp. 1333–1343.

[11] P. Samadi, A.-H. Mohsenian-Rad, R. Schober, V. W. Wong, and J. Jatskevich, “Optimal real-time pricing algorithm based on utility maximization for smart grid,” in Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on. IEEE, 2010, pp. 415–420.

[12] M. Shinwari, A. Youssef, and W. Hamouda, “A water-filling based scheduling algorithm for the smart grid,” IEEE Transactions on Smart Grid, vol. 3, no. 2, 2012, pp. 710–719.

[13] T. Sousa, H. Morais, J. Soares, and Z. Vale, “Day-ahead resource scheduling in smart grids considering vehicle-to-grid and network constraints,” Applied Energy, vol. 96, 2012, pp. 183–193.

[14] F. Ye, Y. Qian, and R. Q. Hu, “Energy efficient self-sustaining wireless neighborhood area network design for smart grid,” IEEE Transactions on Smart Grid, vol. 6, no. 1, 2015, pp. 220–229.

 ISBN: 978-1-61208-556-2

Modelling Energy Balance and Storage in the Design of Smart Microgrids

Mark Apperley
Department of Computer Science
University of Waikato
Hamilton, New Zealand
e-mail: mark.apperley@waikato.ac.nz

Abstract—**This paper introduces and demonstrates appropriate and realistic modelling approaches for smart microgrids, with a focus on local energy balance. There is an increasing interest in microgrids, as the nature of large-scale electricity generation and distribution changes, with a conscious shift to more sustainable and renewable energy sources. However, the modelling and design techniques traditionally used have tended to be based on economics and design criteria more suited to the top-down planning for power generation and distribution typical of legacy grids, than to bottom-up energy balance incorporating localised distributed generation and storage, significant characteristics of these new systems. Several aspects of microgrid design and specification are modelled using an example based on an installation incorporating solar photovoltaic panels and battery storage. Important features of each of the models shown are the associated visualisations, which lead to improved understanding of design implications, compromises, and consequences, and the true context of a renewable-energy based microgrid.**

Keywords-energy balance; smart microgrid; solar PV; battery capacity; Grid-lite

I. INTRODUCTION

There are recent significant shifts of interest to new renewable energy sources, as concerns relating to greenhouse gas emmisions, climate change, and finite fossil fuel resources grow [1][2]. The electricity supply industry world-wide has been characterised for the past 100 years by national and international grids, operated with the goal of balancing *power* generation with demand in real-time [3]. The industry has become very skilled and adept at managing this challenge, and it is this which has determined the complexities, the risks, and the costs, of present day power systems [3]. In this context, longer term seasonal variations in *energy* demand have generally been accomodated by ensuring sufficient reserves of energy are held – fossil fuels in the case of oil, gas and coal systems, water in the case of hydro systems. The design and management of such systems can be characterised as one of top-down planning of power generation, driven by economic considerations, load anticipation, resource availability, and the need for grid-wide security of supply.

But also fueled by those environmental concerns and rapidly advancing technology, dramatic changes are occuring through the combination of new renewable energy sources (solar, wind, tidal), energy storage technologies (at this stage mainly batteries), and automation systems, which enable effective and tolerable distributed load matching/shifting. Two specific technologies – solar photovoltaics (PV) and lithium batteries – are of particular interest because they lend themselves to a significant degree of distribution, which coupled with load matching/shifting technology in microgrids [4], challenges many of the notions of the traditional, or *legacy*, grid [5]-[8]. Concerns with long-distance hierarchal/radial energy transfer and real-time load following from centralised generating systems, grow less and less relevant and appropriate when microgrids, with their highly distributed generation, storage, and load management, become more prevalent [3][9][10].

New renewables in themselves bring challenges under the traditional model, since their contributions tend to be non-deterministic and variable, so adding further complexity to that real-time load-following approach. However, when such generation is combined with short-term storage, and located close to the point of consumption, then these technologies have the potential to radically change the nature of the grid in the longer term [3]. Although the integration of renewable sources into the legacy grid has been the subject of much research, discussion and debate [11][12], to fit with the on-demand delivery and economic models, typical renewables require significant, and unrealistic, energy storage capacity. A range of storage concepts have been explored, including the exploitation of electric vehicle batteries (V2G) [13], but for centralised renewable generation, such as wind or solar farms, the distributed nature of such storage in contrast to the generation, places increased energy transfer demands on the grid.

However, microgrids have the potential to lead to an entirely fresh approach to planning, a bottom-up technique based on localised energy balance, maximising the balance between local generation and local load, and minimising the dependence and impact on the remote resources of the grid. The effect then of such an installation on the legacy grid is not so much one of increased non-deterministic generation capacity, but one of reduced load. Coupled with this approach go a new set of imperatives for consumers, typified by a growing bourgeois off-grid population; a great deal can be learned from the experience and motivations of these people, in terms of shifted demands and expectations, and modified behaviour [14][15].

 ISBN: 978-1-61208-556-2

This paper explores design approaches to smart microgrids based on energy-balance techniques, and shows how such perspectives result in and project far more realistic specifications and expectations, and can be presented in such a manner that leads to a better understanding of the design compromises, and that will in turn lead to a more enlightened next-generation grid development.

Section II introduces a representative microgrid example, which is then used in Section III to explain the Net Zero Energy Balance concept, and the strengths and weaknesses associated with that concept. Discussion in Section IV turns to the implications of non-deterministic generation, and to the limitations of the short-term storage typified by batteries. Finally, in Section V, the paper develops an argument for reducing grid dependency in such installations, and introduces and explains the Grid-lite concept.

II. A Representative Microgrid Installation

The data and graphs used in this paper are based on a representative residential installation located in New Zealand, at approximately -38° lattitude. Real electricity consumption data for a family home, at hourly intervals, has been captured over a year. The analysis explores the effect of local generation. For this purpose, a real data set using actual solar radiation at this location, at hourly intervals over a year, combined with characteristics of a representative contemporary PV panel, has been used [16]. Different parts of the following analyses assume different configurations in relation to the grid. However, the energy balance terminology that is used in relation to the energy flows between the major functional components of the system is shown in Figure 1. While the inclusion of the battery flows in both the *local consumption* and *local generation* totals may appear to account for the stored energy twice, this is necessary in order to examine flows over short time scales, where in one interval the battery may be charging, and in another, discharging, using energy produced in the previous interval [17].

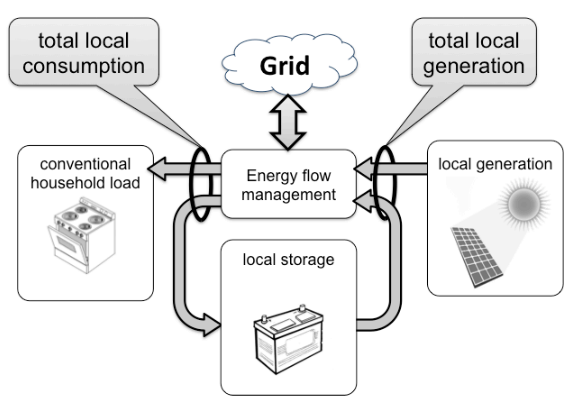


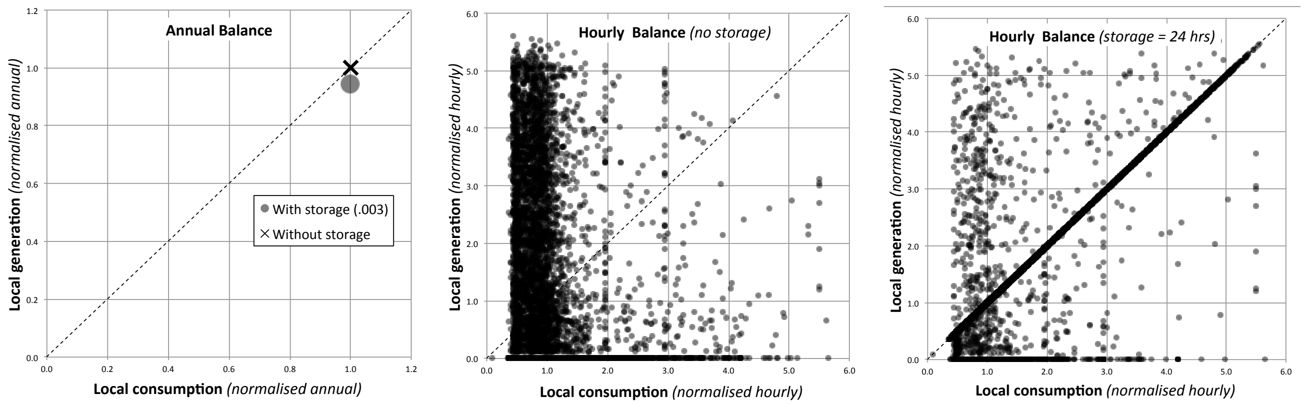
Figure 1. Energy flows within the smart microgrid, and the definitions of local generation and local consumption.

For this example installation, the total annual electricity consumption is 6.446 MWh, equating to a daily average of 17.661 kWh, and an hourly average of 736 Wh. Many of the subsequent figures in the paper use normalised values; these have been normalised to the relevant load figure, be it annual, daily or hourly, as indicated in the axis labels.

III. Net Zero Energy Balance (NetZEB)

A useful starting point in considering smart, renewable-energy based microgrids is the concept of *Net-Zero Energy Buildings* [18][19], buildings with an annual total energy consumption of zero. The total energy used over a year is equal to the total renewable energy generated on the site. A NetZEB buiding is by necessity a grid connected one, since it is the annual balance which is of concern, and to accomodate short-term (hourly or daily) or even seasonal variations in balance between generation and load, necessitates both grid feed-in at times of excess generation, and grid-supply in times of excess load, even with local battery storage. For the example configuration (see Section II) to achieve NetZEB, solar PV has been chosen to exactly match the total load over a full year, requiring panels with a name-plate capacity of 4.03 kW.

Figure 2 illustrates the apparent contradictions of the NetZEB approach. These three graphs use the *interval energy balance space* [17] to show the balance between local generation and local consumption, as defined in Figure 1, over different intervals. In each of these graphs, total local generation over the interval in question, is plotted against total local consumption over the same interval; each point on the graph identifies one such interval during the year. Points on the leading diagonal are those where for that interval, perfect balance is achieved between generation and consumption. Figure 2(a) represents the interval of a whole year, so just a single point is shown, and as expected from the design specifications mentioned, NetZEB is achieved over this period without any need for battery storage – the X on the balance diagonal. Reliance on the grid to both store and supply energy enables this balance, as Figure 2(b) highlights. Here, with an interval of just one hour, it can be seen that in very few of the 8760 hours of the year is perfect balance achieved. In many of these intervals there is zero generation but some load (those points on the horizontal axis, invariably night-time hours), and in others there is relatively low load (0.4 to 1.1), but much higher generation (the stack of points parallel to the vertical axis, invariably representing hours of high sunshine). Figure 2(c) however, shows that the introduction of local battery storage can improve the situation. With a storage capacity equal to 1 average day's consumption (in this case 17.661 kWh, equivalent to 1.3 Tesla Powerwall 2s – a normalised energy capacity of 24 on this hourly plot), many of the previously scattered points are now located on the balance diagonal. Since some of the locally generated energy now passes through the battery, then the annual goal is slightly compromised because of battery losses, as is seen from the shaded circle point on the annual balance plot of Figure 2(a) (here the normalised battery capacity for annual data is 1/365 ~ 0.003). This could be readily corrected by a small increase (<10%) in PV capacity. A battery efficiency of 90% has been used in these calculations, the indicated efficiency associated with the Tesla Powerwall [8].



(a) (b) (c)

Figure 2. Interval energy balance plots for the example configuration; (a) the annual balance, with and without storage; (b) hourly balance without storage; and (c) hourly balance with storage equivalent to an average day's consumption. Note that all energy values have been normalised, as indicated.

The difference in grid dependency between the no-storage and storage scenarios can also be seen from the *balance duration* plots of Figure 3. These duration plots take the 8760 hourly balance values over the year from Figures 2(b) and 2(c), and show them sorted, largest to smallest. Again it can be seen that for the no-storage scenario, almost none of the hours lie on the balance line, but now for the storage scenario, it can be seen that for only 5% of the time, is generation in excess of load, and grid feed-in required, and for 17% of the time, load exceeds generation so that grid supply needed. For the remaining 78% of the hours of the year, the central horizontal band, perfect balance is achieved.

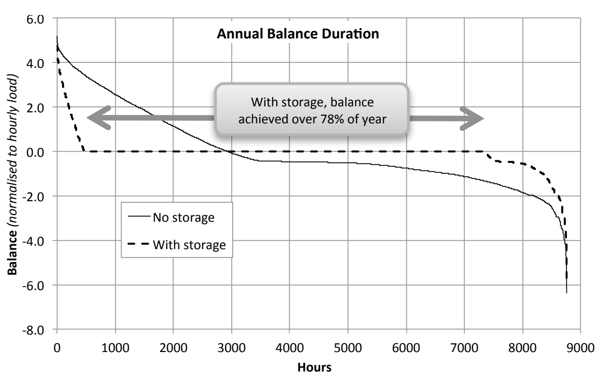


Figure 3. Balance duration plots for the storage and no-storage scenarios of Figure 2.

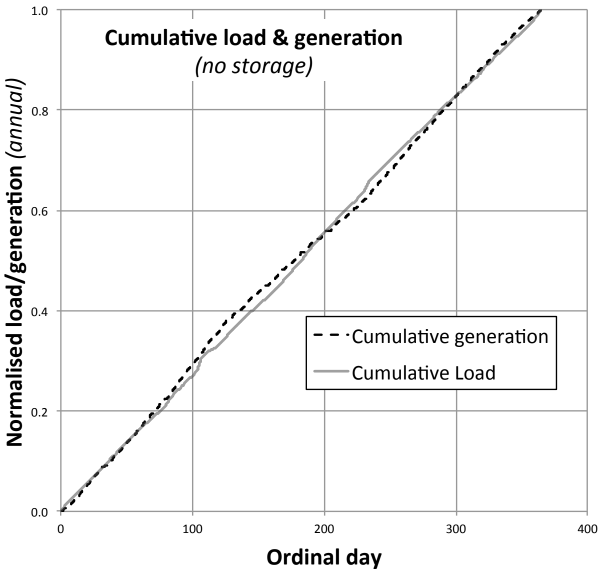
Although the figures used here are hourly ones, so that within a balanced hour there may well be periods of imbalance, it can be safely assumed that battery storage of one day's duration will normally smooth this, or in extreme cases, load management technology can be utilised to avoid peaks in either direction.

IV. IMPLICATIONS OF NON-DETERMINISTIC GENERATION AND FINITE BATTERY STORAGE

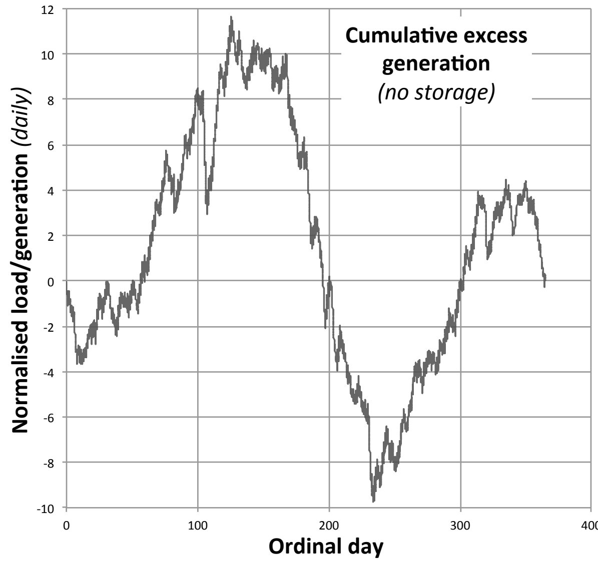
It is apparent from Figures 2(c) and 3 that the battery capacity used in this example (1/365 = 0.0027 of annual load) is insufficient to produce continuous balance over the whole year for this specific installation. In fact, balance is achieved for only 78% of the year. In general, batteries are really viable only for short-term storage. If one considers a solar PV microgrid installation, there are three levels of fluctuation in the generation capability that must be accommodated before load variations are even considered. (i) The first is the daily cycle attributable to the rotation of the earth. No energy is generated during the night-time hours, and during the day, output begins at a low level as the sun rises, peaks in the middle of the day, and fades away to nothing as the sun sets. (ii) The second is related to weather events – when cloud cover and precipitation are present, the ouput at any time of day is reduced, from relatively minor impact for high cloud, to significant reduction for low cloud or precipitation. Such events may last from just minutes (cloud in front of the sun) to several days (major weather event). (iii) The third is the seasonal variation. With the sun at a lower angle in the winter, peak daily output can be significantly lower than in the summer, with the effect increasing with lattitude. For a residential installation, the reduced winter generation is compounded by what is normally an increased winter demand because of longer darkness hours and lower temperatures.

Figure 4 illustrates an approach to determining the effectiveness of battery storage solutions [20]. Figure 4(a) shows the cumulative load and generation patterns over a year for our example, without any battery storage. It can be seen that accumulated generation (on a daily basis) generally exceeds accumulated consumption until day ~200 (mid-winter). Figure 4(b) then shows the difference between the generation and load lines, essentially the same data used in the balance duration plot of Figure 3, but arranged chronologically rather than sorted by decreasing value. The distance between the maxima and minima of this plot gives the battery capacity that would be required to achieve continuous energy balance throughout the year, without any grid dependency (21.42 average days' consumption, equivalent to 28 Tesla Powerwall 2s). The *hourly* interval energy balance plot with this battery capacity provided is shown in Figure 4(c), where it can be seen there remain a

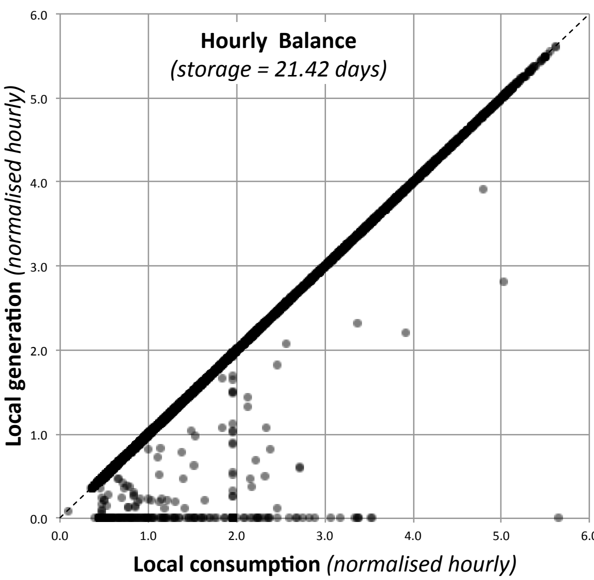
 ISBN: 978-1-61208-556-2



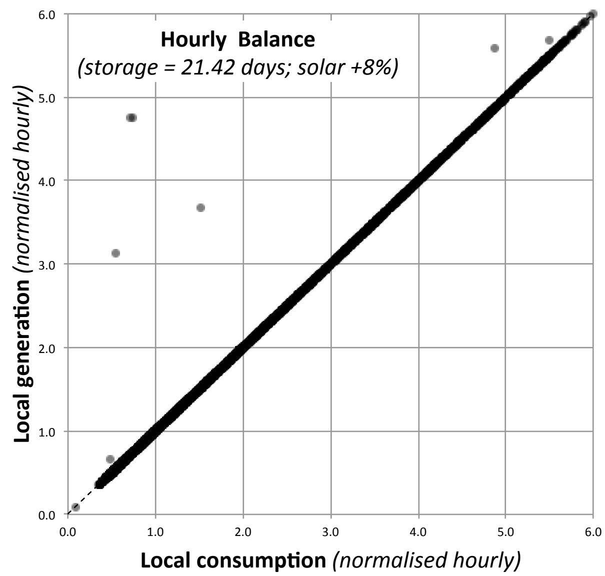
(a)



(b)



(c)



(d)

Figure 4. An approach to battery sizing: (a) Cumulative load and generation; (b) cumulative balance; (c) interval energy balance with the large battery resulting from interpreting this difference; and (d) the further effect of a small increment in PV size.

number of hours where there is excess load. However, an increase in the solar capacity of just 8% can correct this, as shown in Figure 4(d), which demonstrates that these exceptions were caused simply by the battery losses.

Clearly the battery capacity proposed here is impractical, and in fact, not a lot is typically gained, in terms of balance hours, as the battery capacity is increased beyond just a few days. Much smaller increases in the PV capacity are usually more fruitfull. Weniger [21] provides useful contour plots showing the tradeoff between battery and PV capacity in terms of self-sufficiency (proportion of load delivered by locally produced electricity). Their analysis, however, is based on annual totals, so assumes that any excess can be accomodated by the grid.

For the previous example, a more satisfactory grid-load-free solution can be achieved by starting with a 38% increase to the solar capacity, and using just 6 days' battery storage.

The cumulative generation curve shown in Figure 4(a) does demonstrate the typical seasonal sigmoidal shape. At increased lattitudes, this effect becomes much more pronounced, with signficantly reduced winter output. With the type of analysis just described, this can be best dealt with by increasing to solar capacity to provide adequate winter generation, accepting that there will be increased excess in the summer months, but certainly not by trying to increase battery storage to carry excess energy from summer through to winter [22].

V. Reducing Grid Dependency

One approach to reducing the grid dependency of a microgrid installation is to plan for a restricted capacity grid connection – say a maximum X kW load and a maximum Y kW generation feed [17]. The advantages of this *Grid-lite* approach are (i) to ensure a level of self-sufficiency for the consumer, but more importantly (ii) to allow the grid and the electricity provider to plan their systems with a greater confidence. This notion is consistent with the idea that microgrids incorporating PV and battery storage are best not treated as non-deterministic generators, but rather as reduced loads. Grid-lite puts some numbers on this concept.

Figure 5(a) shows the hourly energy balance for a Grid-lite implementation based on our example system. Here the maximum grid flow has been set to 1 (normalised hourly) in both directions, the battery capacity to 1 day, and the PV capacity also to 1 (normalised). The goal of the smart management system is to keep the balance within the limits that clearly show in the plot. While there are some hours where the balance falls below the limit, these can be eliminated by increasing the solar capacity by 38% and doubling the battery capacity. This modification is shown in Figure 5(b). The positive imbalance hours need to be

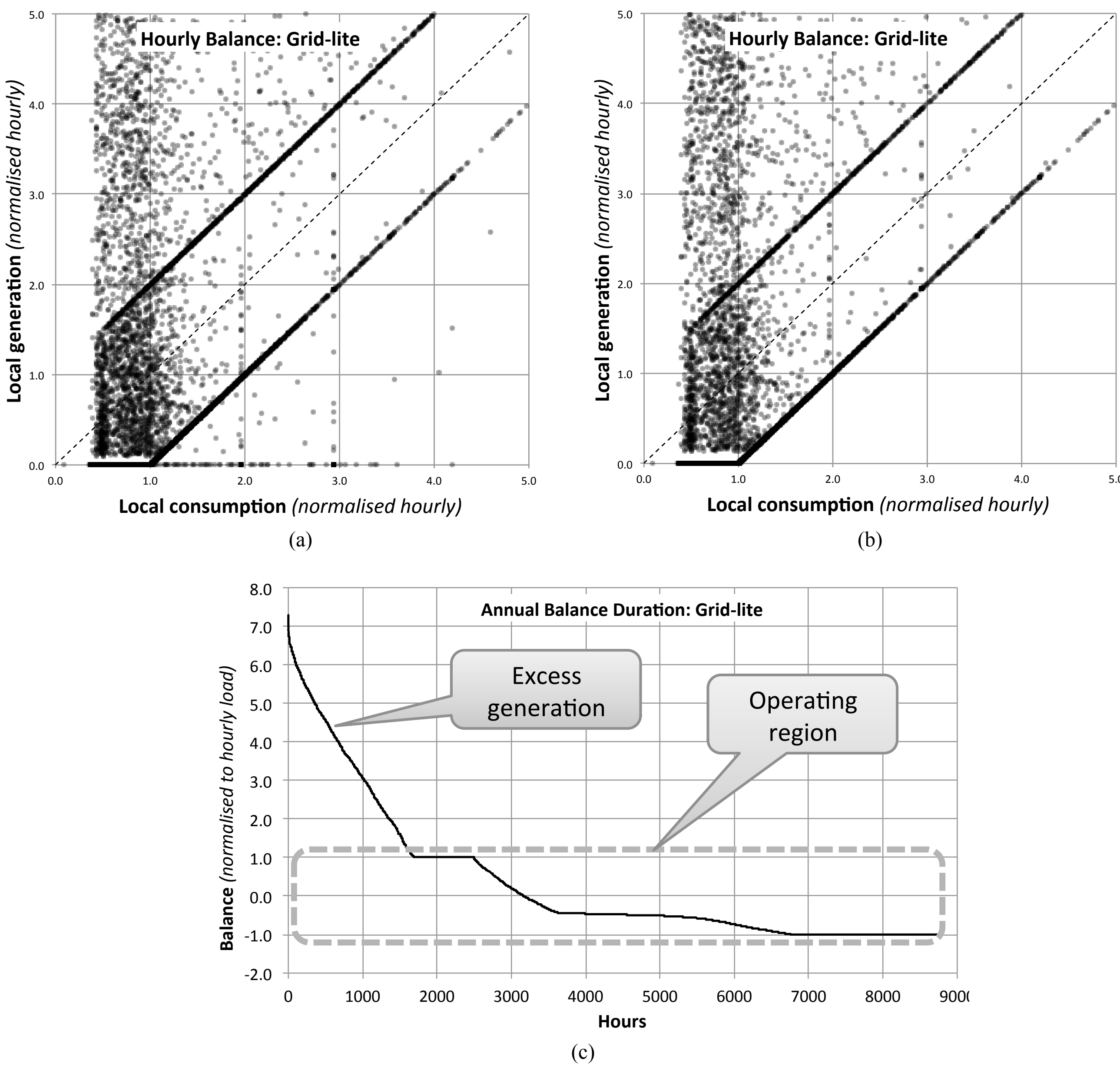


Figure 5. The Grid-lite model: (a) Hourly balance with grid-flow restricted to 1; (b) with increased solar capacity and storage to eliminate excess load; and (c) the balance duration plot for this latter configuration showing 18% of hours with excess or wasted generation.

regarded simply as wasted generation, and the effect can be assessed from the balance duration plot of Figure 5(c), which shows there are 1650 hours of excess generation (18%).

VI. CONCLUSION

This paper has explored and demonstrated a range of approaches to modelling microgrids incorporating solar PV and batteries. While other renewable generation technologies are equally applicable (they differ mainly in the extent and manner of their variability) the focus has been on solar because (i) it is the obvious distributed choice for urban environments, where by far the greater proportion of the population of the world resides, and (ii) its rapid penetration has caused the electricity supply industry to seriously consider its implications.

The approach has highlighted the need to primarily consider local energy balance, using the particular model for energy balance defined in Figure 1, where local supply is considered to come from both the solar PV and the battery, and where battery charging is also considered to be a part of the local load.

With a better appreciation of the motivations for local balance, microgrids incorporating solar PV and storage can be seen to contribute to the longer-term planning of electricity grids, not because of the generation capacity the solar PV provides, which is considered of dubious value by some, but because of the load such systems, if well designed, remove from the grid.

While the analysis is this paper has been based on a single household, because of the success of the approach in demonstrating the possibilites of local energy balance, the situation for multiple households (say a street) can be no more challenging, and is likely, because of parallel generation patterns, but probably different consumption patterns, to be complimentary, with balance able to be achieved with slightly less total storage. The wasted excess generation from one house may contribute to the shortfall of another, so effectively implementing grid-edge transfers within the microgrid.

REFERENCES

[1] J. Hansen, "The threat to the planet," New York Rev. Books, vol. 53, no. 12, p12, Juy 13, 2006.

[2] N. Klein, This changes everything: Capitalism versus the climate, NY: Simon & Schuster, 2015.

[3] "Transmission Tomorrow," 2016. [Online]. Available: https://www.transpower.co.nz/resources/transmission-tomorrow-2016-0. [Accessed: Mar. 10, 2017].

[4] D. Zelazo, R. Dai, and M. Mesbahi, M. "An energy management system for off-grid power systems," Energ. Syst., vol. 3, no. 2, pp. 153-179, 2012.

[5] Forbes, "Could The Cost Of Solar Power Fall By 75% By 2020?" Aug 21, 2013. [Online]. Available: http://www.forbes.com/sites/williampentland/2013/08/21/could-the-cost-of-solar-power-fall-by-75-by-2020/. [Accessed: Mar. 10, 2017].

[6] R. Hensley, J. Newman, and M. Rogers, "Battery technology charges ahead," McKinsey Quarterly, vol. 3, pp. 5-50, 2012.

[7] T. Seba, Clean disruption of energy and transportation, CA: Clean Planet Ventures, 2014.

[8] Tesla, "Powerwall," 2017. [Online]. Available: https://www.tesla.com/en_NZ/powerwall. [Accessed: Mar. 01, 2017].

[9] A. Ipakchi and F. Albuyeh, "Grid of the future," IEEE Power Energy M., vol. 7, no. 2, pp. 52-62, 2009.

[10] J. P. Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, and N. Jenkins, "Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities," Electr. Pow. Syst. Res., vol. 77, no. 9, pp. 1189-1203, 2007.

[11] Y. Riffonneau, S. Bacha, F. Barruel, and S. Ploix, "Optimal power flow management for grid connected PV systems with batteries," IEEE Trans. Sustain. Energy, vol. 2, no. 3, pp. 309-320, 2011.

[12] J. von Appen, M. Braun, T. Stetz, K. Diwold, and D. Geibel, "Time in the sun: the challenge of high PV penetration in the German electric grid," IEEE Power Energy M., vol. 11, no. 2, pp. 55-64, 2013.

[13] P. Monigatti, M. Apperley, and B. Rogers, "Improved grid integration of intermittent electricity generation using electric vehicles for storage: A simulation study," Proc. 2012 Intl Green Computing Conference (IGCC), IEEE Press, pp. 1–10.

[14] Canadian Mortgage and Housing Corporation, "Energy Use Patterns in Off-Grid Houses," Research Highlights, Technical Series 01-103, 2001. [Online]. Available: https://www.cmhc-schl.gc.ca/publications/en/rh-pr/tech/01-103-e.html. [Accessed Mar. 10, 2017].

[15] M. Wolsink, "The research agenda on social acceptance of distributed generation in smart grids: Renewable as common pool resources," Renew. Sust. Energ. Rev., vol. 16, no. 1, pp. 822–835, 2012.

[16] J. Suppers and M. Apperley, "Interactive solar panel simulation tool – From GHI to PV output," Proc. Interact 2015 workshop: Fostering Smart Energy Applications (FSEA 2015), Bamberg, Germany.

[17] M. Apperley, P. Monigatti, and J. Suppers, "Grid-Lite: A network integrated semi-autonomous local area electricity system," Proc. 4th Intl Conf. on Green IT Solutions (ICGreen 2015), Milan, Italy, SciTePress, pp. 27-33.

[18] J. Salom et al, "Understanding net zero energy buildings: evaluation of load matching and grid interaction indicators," Proc. Building Simulation 2011, vol. 6, pp. 2514-2521.

[19] P. Torcellini, S. Pless, M. Deru, and D. Crawley, "Zero energy buildings: a critical look at the definition," National Renewable Energy Laboratory and Department of Energy, US, 2006.

[20] I. Mason, "Comparative impacts of wind and photovoltaic generation on energy storage for small islanded electricity systems," Renew. Energ., vol. 80, pp. 793–805, 2015.

[21] J. Weniger, T. Tjaden, and V. Quaschning, "Sizing of Residential PV Battery Systems," Enrgy Proced., vol. 46, pp. 78–87, 2014.

[22] Energy Matters, "How much battery storage does a solar PV system need?" May 11, 2015. [Online]. Available: http://euanmearns.com/how-much-battery-storage-does-a-solar-pv-system-need/. [Accessed: Mar. 01, 2017].