

Emerging Technologies Initiative ‘Smart Grid Communications’: Information Technology for Smart Utility Grids

H.-P. Schwefel¹, Y.-J. A. Zhang², C. Wietfeld³, H. Mohsenian-Rad⁴

¹GridData GmbH, 83454 Anger, Germany, and Aalborg University, 9220 Aalborg, Denmark

²Chinese University of Hong Kong, Hongkong, China

³Technical University Dortmund, 44227 Dortmund, Germany

⁴University of California, Riverside, CA, USA 92521

Abstract: The Emerging Technologies Initiative Smart Grid Communications has originated within IEEE in 2010. This position paper describes the scope and future technology vision for the technical committee and explains how the future committee work will contribute to its realization.

I. SCOPING OF SMART GRIDS FOR THE EMERGING TECHNICAL COMMITTEE

A ‘Grid’ in this paper is any type of geographically distributed infrastructure that connects producers and consumers of a certain physical product. We talk about a Smart Grid or synonymously ‘Digital Grid’, when digital sensor information about the status of the grid and its connected systems is automatically collected and digitally processed, enabling thereby improved planning, deployment, operation, and maintenance of the grid as well as supporting new types of usage and operation scenarios. Due to the distributed nature of grids, this collection of information and the actuation involves distributed intelligent sensing, computing, and actuation nodes, which therefore need to be connected by a communication solution.

The scope of the Emerging Technologies Initiative (ETI) Smart Grid Communications (ETI-SGC) is delimited to Utility Grids, focusing in particular on electricity grids, and the intelligent systems that are connected to it, such as electric vehicle charging stations or smart buildings. Out of scope are purely virtual grids, e.g. computation grids, and transportation grids such as intelligent road infrastructure or logistics systems for goods.

All utility grids show a hierarchical structure; we use subsequently the terminology from the electricity grids: The so-called transmission grid thereby covers long distances and uses high-voltages (110kV and higher). The so-called distribution grids use lower voltages, 10kV or 20kV in the medium-voltage (MV) grid, 400V in the low-voltage (LV) grid, to supply electricity to the connected customers, and to connect the in the last 20 years strongly increasing number of distributed generators. The digital operation of the transmission grid thereby has a long history of 30+ years,

while only more recently the need and the opportunity for it has started to move information technology into the distribution grids. The latter evolution is expected to be amplified by the upcoming technology maturity of Internet of Things, see Section III.

The ETI-SGC covers both the transmission grids and the distribution grids, while it is expected that the digitalization of the distribution grid will specifically be a source of many concrete questions and work items.

Communication here covers not only the transmission and reception of bits and messages between multiple nodes through a wired or wireless medium, but the ETI-SGC addresses all layers in a layered communication model (such as OSI). In particular, this scope includes also the application layer. In the latter, there are substantial touch points to other societies and domains, in particular to Control Systems, Energy Technology (PES), Information processing in distributed Systems (ACM, IFIP), and dependable system design. The important angle of ETI-SGC is thereby to understand how the distributed nature of the sensing, computing, and actuation in Smart Grid scenarios affects the design and operation of such data processing and networked control applications.

II. THE PAST 8 YEARS: HYPE AND CONSOLIDATION

At the creation of the Emerging Technical Committee Smart Grid Communications in 2010, the belief was that Smart Grids will be one of the first success stories for actual deployment of intelligence based on communication technology and it will create huge saving in infrastructure investments to handle the transition to distributed generation of energy, while at the same time increase the dependability and operation efficiency of the energy supply. Due to the large number of measurement and actuation points in the utility grids, it was the expectation that strong challenges for communication technologies will appear and subsequently be resolved on

- Scalability
- Real-time behavior
- Reliability
- Privacy (sensitive data on prosumer side)

- Security (grids as critical infrastructure)

In Europe, the development of Smart Grid Communications has been supported through efforts in research (e.g. FP7 and Horizon 2020 research projects related to communications in Smart Grids, such as the SmartC2Net project [1]) and standardization. One major outcome of these activities has been the Smart Grid Architecture Model (SGAM) [2], which describes the complex challenges associated with the introduction of Smart Grids from different angles by introducing multi-dimensional approach with dedicated business, functional, information and communication architectures.

In the U.S., the development of Smart Grid technologies initially received a boost by the American Recovery and Reinvestment Act of 2009; followed by other initiatives such as the National Institute of Standards and Technology (NIST)'s Framework and Roadmap for Smart Grid Interoperability Standards [3]; and Department of Energy (DoE)'s Grid Modernization Initiative [4]. State-wide initiatives also played roles in the research and development of smart grid technologies. For example, the California Energy Commission has contributed to the development of the California Utility Vision and Roadmap for the Smart Grid of 2020 [5] or Rule 21 for Smart Inverters [6].

The actual deployment of smart grid solutions in the distribution grids and the urgency for resolving the expected communication challenges was however slowed down due to several reasons:

- ‘Smartness’ has not yet been deployed for the LV grids, so the huge scale has not yet been reached. It is expected that communication related work will become more important, when deployment in LV grids will take place.
- In the MV grid, many Distribution System Operators (DSOs) still prefer separate, deterministic, always available communication solutions.
- Several distribution grid control use-cases were shown to be not very challenging with respect to real-time properties of the ICT/communication solution: the required time-scales for set-point communication involve several minutes, and the spatial distribution of the grids alleviates scalability problems for ICT.

The consequences of this slower deployment of smart distribution grids were clearly visible in the SGC community:

- The number of papers related to communication technologies in IEEE SmartGridComm has been decaying in the last years. This effect is only partially explainable by increased number of conferences in the field: In 2010, SGComm was the only conference with this focus, while now the topics have spread to any communications related conference (ICC, Globecom, etc.). This increase in number of events is generally a success for the field, but it also spreads out the community.
- Drop of funding support in US, China and large parts of Europe: Traditional Power Systems groups take over

more of the funding. One exception is Germany, where the political decision for the termination of nuclear power generation and the increased targets for the CO2 efficiency together raised attention to the infrastructure costs, yielding more funding for communications-related smart grid research.

- A lot of attention in the research community is on 5G communication solutions, but in 5G development Smart Grids are not seen as the driving use-case (rather transportation and industry 4.0). Communication researchers are attracted more strongly to 5G as opposed to Smart Grid communications.

So in summary, the practical deployment has happened at a slower speed compared to the expectation 8 years ago and some consolidation of the smart grid communications research has taken place in the past few years.

III. THE PATH TO THE FUTURE

III.1 Emerging topics – Energy System Evolution

We now list our selection of emerging topics that start to have a strong impact on the field of Smart Grid Communications (SGC) in the scope as defined in Section I. The list starts with emerging topics of broad scope and then moves into certain enabling technologies with high potential to shape SGC research.

Transactive Energy: Over the past decade, demand-side participation of distributed energy resources for grid reliability and efficiency has attracted tremendous attention. The concept of Transactive Energy has emerged to facilitate decentralized coordination of distributed energy resources based on economic incentives. In particular, Transactive Energy refers to the use of a combination of economic and control techniques to not only improve the grid efficiency, but also maintain the reliability and stability of the system. This requires information exchange among many entities, such as demand response resources, storage devices, grid monitoring and control devices, markets, utilities and customers, and service providers. It also requires high-speed and large-scale information processing to make timely economic and control decisions in a system with a vast number of independent agents, individuals, and devices.

Multi-Energy Systems and Interdependencies of Grids: While energy grids so far have mainly operated in isolation, there is an expected benefit for energy efficiency by managing demands, storage, and generation across different types of energy systems. This obviously introduces new interfaces for data exchange and coordination of control actions, while this additional layer of a ‘systems-of-systems’ architecture can add interdependencies such as propagating and cascading faults. Target of SGC research here needs to be an efficient and resilient way to support such interaction and coordination of multiple energy systems.

III.2 Emerging topics – enabling technologies

The two topics above are high-level evolution scenarios for SGC, which provide a top-down perspective to derive a

research agenda. The combination with a bottom-up perspective is typically a successful approach; this means the analysis of enabling technologies that are expected to take a main role in future SGC scenarios. These enabling technologies are identified and their relevance for SGC is pointed out below:

Data analytics/Big Data: Big Data is often defined as a high-volume, high-velocity and high-variety information asset that requires and demands cost-effective, innovative forms of information collection, storage, and processing for enhanced insight and decision making. The science of Big Data Analytics (BDA) is evolving and a wide range of methodologies are being developed across multiple disciplines to support BDA. These methodologies can facilitate predictive analytics and forecasting, classification, regression, clustering, cognitive simulation, expert systems, perception, pattern recognition, statistical analysis, natural language processing, and advanced data visualization.

Novel distributed approaches for secure transactions: Distributed approaches for security and privacy have already a long history, while a large scale practical deployment and the achievement of substantial user support has only had recent breakthrough via so-called blockchain deployments. A natural application to smart energy systems is via the support of new peer-to-peer energy trading models, in which a trusted authority, previously the utility or a financial institution, is now not needed any more. While the applications of blockchain technology can go beyond energy trading to so called smart contracts, the concrete use-cases for those are still under investigation at this stage. The costs in terms of performance (e.g. in particular in chain forking situations) and scalability, and the actual financial transaction costs in blockchain deployments have to be analyzed in comparison to the gained security features.

Scalable computing architectures: As more and more computing intelligence is moving into energy systems, different architectural models to provide this computing power can have strong impact on deployment and operation costs of the ICT infrastructure for intelligent energy systems. Virtualized computing resources can provide the scalability and flexibility that is needed to support different future evolution paths. Requirements on real-time behavior and data security and privacy may in some deployment scenarios put preference on computing hardware that is from a geographic or ICT perspective close to the actual physical grid environment – frequently then called fog computing or edge computing. The deployment of fog or cloud based computing architectures on the other hand poses requirements and challenges to the communication solution, as the amount of local processing is reduced. Intelligent choices for data aggregation and data preprocessing are required for such settings.

IoT platforms for heterogeneous data and control: in the past, the energy sector has developed dedicated solution for communication and control, such as the IEC 61850 specification. Those approaches reuse technology which partially date back to the 1980ies (e.g. the IEC 61850 MMS

format originates from the ISO 9506 standard released in 1988). Although IEC 61850 is certainly a valid approach to automate parts of the energy network, it is very useful from a research stand-point to investigate the suitability of existing and emerging IoT platforms. Those platforms build on state-of-the-art web, cloud and Internet technologies and support multiple vertical sectors, ranging from Smart Home to production and logistics. Potential candidates emerge from various directions, such as:

- Internet/IT background such as Watson IoT (IBM), Azure (Microsoft) or Google Cloud
- Industry background: such as Predix (GE), OSGI (Bosch) or Mindsphere (Siemens)
- New players, such as Kaa,

Some of those platforms are proprietary, some are open and even open-source. Intensive research efforts are required to identify future-proof, state-of-the-art Smart Grid compliant IoT-platforms, which go clearly beyond established IEC 61850 concepts.

Communication as a sensor: The behavior of communication links and the information carried in different protocol layers can be used to derive interesting information for smart utility grids. For electricity grids, due to the impact of electricity outages on communication networks, one major example is the detection and localization of electricity outages in distribution grids; such detection can be done by a DSO through the detection of the unreachability of devices such as Smart Meters or cable/DSL modems in connected homes. The ICT behavior thereby provides an indirect observation for the underlying grid status. Other interesting information for energy systems can be obtained from cellular networks – though the detection of device types and extrapolation of personal mobile devices to number of people, building or area occupancies by humans can be inferred and this information can be beneficial for real-time prediction or anomaly detection of energy consumption. Finally, in scenarios of Power-line communication, the detailed behavior of the underlying PLC channels can be used to infer about types and locations of grid related faults.

III.3 Structure of Research Agenda

The introduced set of emerging topics shapes the structure of a research agenda as outlined in the following and implemented in the ETI-SGC by a structure of eight Special Interest Groups (SIGs) as described in the following. Similarly to the emerging topics, the structure of these SIGs starts from a smart grid scenario perspective and then moves to a technology perspective; the overlap between these different perspectives is intentional and seen as strength.

ICT-Enabled Transactive Energy (TE) and Grid Economics: TE is broadly defined as “a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter”. Due to the complicated coupling among various entities in

the grid, TE involves joint optimization of multiple objectives that potentially span multiple timescales and hierarchical levels of the grid system [7]. In addition to physical networks, information and communication networks are indispensable parts of TE due to the following reasons. First, information is to be exchanged among transacting parties (such as users, distributed energy resources, etc.), system operators, control devices, and monitoring devices in a timely, reliable, and secure manner. In addition to supporting existing control and sensing functionalities in today's grid, information exchange renders customers more exposed to the energy infrastructure and value stream in the new environment. Secondly, information integration, analysis, and processing are needed for multiple transacting parties to reach a consensus that yields the optimal system objective. In particular, information integration and analysis are useful in establishing the economic and engineering values of a transaction to customers and other transacting parties. This is the key to designing market mechanisms that incentivize selfish transacting parties to make transactive decisions that benefit the whole system [8]. Moreover, information-based optimization decomposition serves as a mathematical foundation for decentralized control and coordination. Challenges in focus for this SIG are: First, the formulation of optimal transaction problems is often based on mathematical models that precisely describe the underlying system and data. Deriving precise models from the information collected is not always an easy task. Second, TE involves decisions across multiple timescales, leading to complicated nested optimization problems. Thirdly, the market and control decisions are subject to topological, physical and logical constraints, which add to the difficulty in optimizing distributed market and control decisions. Last but not least, the design of TE mechanisms will be further complicated in multi-energy systems, where storage may be of electricity or some derived energy product (e.g., heat or hydrogen), curtailment may be some energy services (e.g., thermal comfort), and transactions may be coordinated among different energy sectors (e.g., electricity, coal, gas, oil, and heat).

Energy Internet and Energy System Integration: Energy Internet is an emerging concept to realize the integration of energy flow, information flow, and business flow. It is a new energy ecosystem with better interconnection, openness and flexibility, aiming to accommodate deep-penetration clean energies, improve energy efficiency, and create a novel sharing economy to reduce the cost of energy assumption significantly.

The impact of Energy Internet goes beyond the electricity sector [9]. Through the deep integration of Internet concepts, Energy Internet supports open interconnection of multiple energy sources along with a self-organizing network architecture. As such, it will play a significant role in the development of new domains such as smart city, where the energy sector is to be co-designed with other sectors, namely, building and transportation.

Energy Internet will be achieved by Information and Communication Technology (ICT)-enabled information exchanges and distribution platforms that allow power resources to be accessed and managed through the universe of mobile, PC, and Internet connected appliance-based applications [10]. Similar to Internet, a key facility in the Energy Internet is the energy routers that are designed to support open access and free exchange of energy. Serving multiple roles of power storage, power switching, and data centers for information exchange and processing, large-capacity energy routers are currently too expensive to be practical. Modelling, planning, operation, and control of the Energy Internet are therefore important research topics for improving the cost effectiveness of future Energy Internet. Meanwhile, energy management systems are necessities for exchanging and routing energy on the Energy Internet. Emerging ICT technologies, such as cloud computing, big data, Internet of things and blockchain, will be the key enablers. Overall, the Energy Internet represents a new ecosystem that transforms the energy industry from top to bottom. Being in its infancy stage, its business values and social benefits are becoming increasingly apparent with the advances in ICT.

Active Distribution Grids and Microgrids: Active distribution grids implement a distributed or centralized control architecture that uses communication to Distributed Energy Resources (DERs) as well as to configurable components such as On-Load Tap Changers in the primary or secondary substation in order to realize applications. These applications typically target the increase of distribution system availability, of operation efficiency and of power quality. The control applications therefore cover a wide range, including voltage control, energy reference tracking, loss minimization, protection and fault management, and the time scales, at which the corresponding control loops operate, range from sub-second level (protection and certain fault-management scenarios) up to several minutes for energy reference tracking and voltage control for voltage variations and voltage unbalance [1], up to hours or days for cases of grid operation efficiency enhancements. These time-scales however also depend on the aggregation levels of the grid (MV versus LV) and also on the expected dynamics of loads and generators in the grid. A stronger set of requirements and shorter time-scales of the control applications result [11], when operating parts of the distribution grid temporarily or permanently in island mode (called 'microgrid'), since the inertia and the balancing capability of the transmission grid are then not present any more.

As there is a wide variety of control applications and the control architectures and algorithms are still in evolution, the analysis of the requirements of these control applications regarding communication network performance and reliability is still a research topic. The operation of the control algorithms thereby depends on the end-to-end communication delays and losses, but also on the information exchange strategy between sensors and

controllers and between controllers and actuators. The obtained understanding from this analysis supports the design of robustness enhancement schemes. The latter can work on communication network layer (network QoS schemes), on information access and setpoint forwarding session layer (e.g. adaptive schemes that switch from periodic to event-driven notifications), and system level mechanisms such as adaptive control strategies that react to communication network property changes, e.g. by changing controller gains or by eliminating certain nodes from the participant set of a control application. In summary, the SGC angle of the research in this topic addresses the impact of communication on information age of input information to control algorithms, the impact of delay and loss of setpoint communication to actuators, and the mitigation of those impacts by protocol extensions and advanced processing algorithms on all layers of the communication stack.

Smart Metering, Demand Response and Dynamic Pricing: Demand response has been considered as an increasingly valuable resource option whose capabilities and potential impacts are expanded by grid modernization efforts. It is to motivate changes in power consumption by end-use customers, with the purpose to induce lower electricity use at times of high wholesale market prices or when grid reliability is jeopardized. To engage customers in demand response programs, dynamic pricing strategies, including time-of-use pricing, critical peak pricing, variable peak pricing, real-time pricing, etc., have been advocated to link retail prices with short-term wholesale market prices, so that the customers “see” the real cost of electricity and alter their usage patterns accordingly [12]. Meanwhile, wide deployment of smart meters is an essential condition for moving towards a Smart Grid environment with demand response functionality. Smart metering technologies allow utilities to monitor usage patterns in greater detail, introduce new billing and pricing options to customers, and make timely and sensible decisions that lead to improved grid reliability [13] and energy efficiency.

The design and deployment of smart meters and demand response programs involve many issues and challenges. In particular, the selection of the communication network and design of communication devices (e.g., smart meters, sensors, base station, utility data center, etc.) must satisfy multiple requirements, including the ability of connecting a high density of devices, transferring a large amount of data that are collected at high frequency, prioritizing the delivery of data based on their features and values, ensuring data privacy, integrity, and security, and maintaining a low communication cost. Moreover, the operation of smart meter and demand response systems involves collection, transmission, processing, maintenance, and storage of an unprecedented data volume and velocity. It is important to design appropriate tools and technology to realize the hidden value and power in such data. Finally, the advances in big data analytics offers unique opportunities for demand response programs to in develop forecasting models,

understand customer behaviors, and define pricing models for customers of different kinds.

Energy Storage and Electric Vehicles: Energy storage can be deployed in different levels of the grids and take different forms, from mechanical energy in rotating masses or water pump storages, to thermal storage in hot water, and chemical storage. Special cases of mobile storage with clear potential result from electric vehicles [14,15]. Main interest is to use the flexibility that such storage systems provide for different targets, which range from energy price optimization to grid stabilization and emergency operation in outage scenarios. Storage can be one strong facilitator to handle variable demands or generation, as for instance resulting in many cases of renewable energy generation.

The ETI-SG focuses on system level challenges that include communications and control, specifically on electromobility integration in the power grid (e.g., EV charging and vehicle-to-grid (V2G) services), energy storage for smart grid applications (including microgrid applications, grid services, electricity markets, balancing across multi-energy systems) and on the data interfaces and interaction between the energy storage and management systems and the intelligent transportation systems.

Communications and Networks to Enable the Smart Grid: Smart Grids require reliable connectivity at locations [16], at which public network infrastructures originally have not placed a focus: remote areas (e.g. off-shore windparks), basements and inside metal fuse boxes. At the same time high availability and further specialized requirements such as black-out resilience are typically not fulfilled by current commercial public networks. Therefore, numerous dedicated solutions, such as Power Line Communications [17], RF mesh, modified LTE, CDMA at sub GHz bands, dedicated fibre along high voltage lines, etc have been investigated and deployed. Some of those established options approach their end of the technology life cycle and call for replacement. Additionally, future 5G networks promise to provide the QoS of dedicated networks through a multi-purpose infrastructure by network slicing [18]. 5G also shall support high scalability for massively distributed Smart Grid deployments as well as ultra-reliable low latency communications for automation and protection mechanisms [19]. No single technology has yet proven itself to be “the” solution for Smart Grids. Given the long-term impact of the choice of the “right” mix of communications and network technologies, intensive research efforts are needed to compare options and optimize solutions for Smart Grids. The ETI-SG aims to consolidate and strongly voice , Smart Grid requirements and most recent Smart Grid-related research results in the networking research community in order to shape upcoming 5G and 6G technologies appropriately.

Big Data Management and Analytics: The ongoing digitalization, e.g. deployment of advanced metering infrastructure and phasor measurement units as well as intelligent automation systems is drastically increasing the amount, quality, and variety of data that utilities and grid

operators are collecting on supply, transmission, distribution, and demand [20]. Furthermore, there are recent advance in applying deep learning techniques for load forecasting and clustering of different types of customers in utility grids [21]. Therefore, there are limitless opportunities for Big Data Analytics (BDA) in the electric power industry. The ETI-SG will focus on the following:

- Strategies for Big Data visualization in smart grids
- Software and cloud architectures for BDA in smart grids
- Reliable and privacy-preserving data storage to support BDA in smart grids
- Communications technologies to support BDA in smart grids
- Data mining and machine learning for BDA in smart grids
- Applications of BDA in state estimation, event detection, resource aggregation, etc.
- Development of grid simulation tools, virtual grids, and digital twins for data intensive grid studies.
- Interfaces and data fusion for BDA across different energy systems and across different smart systems, e.g. BDA fusing data from electricity systems and transportation systems in a smart city context.

Cyber Security, Privacy, and Resilience for the Smart Grid:

Resilience is the ability to deliver, maintain, and improve service when facing threats (accidental and malicious) and evolutionary changes. In the context of ETI-SGC, the ultimate goal of utility grids is to provide energy to the connected consumers and take in energy from (distributed) generators; however, ensuring an uninterrupted supply is challenging for such a complex utility infrastructure, which is exposed to various threats of accidental and malicious nature [22]. Furthermore, the binary ON-OFF view on availability of energy supply in some circumstances may need to be extended to a multi-level state, e.g. in order to account for the parameters characterizing voltage quality, see e.g. EN50160.

With the fast deployment of smart grids and increasing involvement of consumers in the power grid operation via information and communication technologies (ICT), cyber security and privacy issue are gaining increasing attention. To achieve a more resilient and secure electric power system, various technical challenges need to be addressed [23] spanning from planning to operation, and involving investment, preparation, prevention, response, mitigation, and recovery. Collaboration among multidisciplinary fields, including power engineering, operation research, computer science, data analytics, communications, and transportation, play an essential role to facilitate the target.

IV. SUMMARY AND CONCLUSIONS

The ETI-SGC mission is to understand how the distributed nature of the sensing, computing, and actuation in Smart Utility Grids affects the design and operation the current and future data processing and networked control applications.

This paper has introduced a set of emerging topics, from which the structure of the research agenda that is pursued by ETI-SGC is derived. A set of 8 Special Interest Groups have been formed accordingly, which will provide a forum for the exchange and interaction of researchers and which will organize specific events to foster and disseminate the research work. Planned future versions of Best Readings in Smart Grid Communications [24] will be structured according to these 8 SIGs. As the related research requires a multi-disciplinary approach, ETI-SGC is welcoming cooperation initiatives from related organizations; the cooperation with IEEE PES and IEEE Control will be actively initiated by ETI-SGC members that take part also in the other societies.

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V. REFERENCES

- [1] H. P. Schwefel, N. Silva, R. Olsen, F. Kurtz, G. Dondossola, F. D. Giandomenico, D. Iacono, R. Terruggia, C. Wietfeld, T. Kristensen, S. Marzorati, "Smart Control of Energy Distribution Grids over Heterogeneous Communication Networks - Impact of communication network performance on voltage control and energy balancing", In CIGRE Science & Engineering, February 2018.
- [2] CEN-CENELEC-ETSI Smart Grid Coordination Group, Smart Grid Reference Architecture, Nov 2012, available online: https://ec.europa.eu/energy/sites/ener/files/documents/xpert_group1_referece_architecture.pdf
- [3] <https://www.nist.gov/engineering-laboratory/smart-grid>
- [4] <https://www.energy.gov/grid-modernization-initiative>
- [5] www.energy.ca.gov/2011publications/CEC-500-2011-034/CEC-500-2011-034.pdf
- [6] http://www.energy.ca.gov/electricity_analysis/rule21/
- [7] U.S. Department of Energy: "GridWise Transactive Energy Framework", Gridwise Architecture Council, 2015, available online: https://www.gridwiseac.org/pdfs/te_framework_report_pnnl-22946.pdf
- [8] P. De Martini, K. Chandy, and N. Fromer (Eds.), "Grid 2020: Towards a Policy of Renewable and Distributed Energy Resources", California Institute of Technology Resnick Institute, Technical Report, 2012. Available online: http://resnick.caltech.edu/docs/R_Grid.pdf
- [9] Mancarella P. MES (multi-energy systems): An overview of concepts and evaluation models. *Energy*, 2013,65:1-17.
- [10] H. Sun, Q. Guo, B. Zhang, W. Wu, B. Wang, X. Shen, J. Wang: "Integrated Energy Management System: Concept, Design, and Demonstration in China." *IEEE Electrification Magazine*, 2018,6(2):42-50.
- [11] R. Pedersen, M. Findrik, C. Sloth, H.-P. Schwefel: "Network Condition Based Adaptive Control and its Application to Power Balancing in Electrical Grids", *Sustainable Energy, Grids and Networks*, Vol. 10, p. 118–127, June 2017.
- [12] F. Rahimi, A. Ipekchi: Demand response as a market resource under the smart grid paradigm. *IEEE Transactions on Smart Grid*, Vol 1, No 1, 2010, p. 82-88.
- [13] S. Bessler, M. Kemal, N. Silva, R. Olsen, F. Iov, D. Drenjanac, H.-P. Schwefel: Distributed Flexibility Management Targeting Energy Cost and Total Power Limitations in Electricity Distribution Grids', *Sustainable Energy, Grids and Networks*, 14, p. 35-46, Elsevier, 2018.
- [14] F. Mwasilu, J. J. Justo, E.-K. Kim, T. D. Do, J.-W. Jung: "Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration", *Renewable and Sustainable Energy Reviews*, Volume 34, 2014, Pages 501-516.

- [15] N. Sadeghianpourhamami, N. Refa, M. Strobbe and C. Develder, "Quantitative analysis of electric vehicle flexibility: A data-driven approach", *Int. J. Electr. Power Energy Syst.*, Vol. 95, Feb. 2018, pp. 451-462.
- [16] S. Goel, S. Bush, D. Bakken. (Ed.s): "IEEE Vision for Smart Grid Communications: 2030 and Beyond", IEEE, ISBN: 97807388184609, 2013.
- [17] C. Cano, A. Pittolo, D. Malone, L. Lampe, A. M. Tonello, A. Dabak, "State-of-the-art in Power Line Communications: from the Applications to the Medium," *IEEE Journal on Selected Areas in Communications*, Vol. 34, Issue 7, pp. 1935 - 1952, July 2016.
- [18] A. Aijaz, M. Dohler, A. H. Aghvami, V. Friderikos and M. Frodigh, "Realizing the Tactile Internet: Haptic Communications over Next Generation 5G Cellular Networks," in *IEEE Wireless Communications*, vol. 24, no. 2, pp. 82-89, April 2017.
- [19] F. Kurtz, C. Bektas, N. Dorsch, C. Wietfeld, "Network Slicing for Critical Communications in Shared 5G Infrastructures - An Empirical Evaluation", In 4th IEEE International Conference on Network Softwarization (NetSoft 2018), Canada, Juni 2018.
- [20] H. Mohsenian-Rad, E. Stewart, E. Cortez, "Distribution Synchronphasors: Pairing Big Data with Analytics to Create Actionable Information", *IEEE Power & Energy Magazine*, vol. 16, no. 3, pp. 26-34, May/June 2018.
- [21] H. Akhavan-Hejazi and H. Mohsenian-Rad, "Power Systems Big Data Analytics: An Assessment of Paradigm Shift Barriers and Prospects", *Energy Reports*, vol. 4, pp. 91-100, 2018.
- [22] S. Sridhar, A. Hahn, M. Govindarasu, "Cyber-Physical System Security for the Electric Power Grid", *Proceedings of the IEEE*, vol. 100, no. 1, pp. 210-224, 2012.
- [23] R. Lu, X. Liang, X. Li, X. Lin, X. Shen, "EPPA: An Efficient and Privacy-Preserving Aggregation Scheme for Secure Smart Grid Communications", *IEEE Transactions on Parallel and Distributed Systems*, vol. 23, no. 9, pp. 1621-1631, 2012.
- [24] Best Readings in Smart Grid Communications, September 2014, available online: <https://www.comsoc.org/best-readings/smart-grid-communications>