5th D-A-CH+ Energy Informatics Conference
in conjunction with
7th Symposium on Communications for Energy Systems (ComForEn)

September 29-30, 2016
Klagenfurt, Austria

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5th D-A-CH+ Energy Informatics Conference 2016
Managing Data and Complexity in Energy Systems

in conjunction with

ComForEn 2016
7. Symposium Communications for Energy Systems

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Message from the Chairs

5th D-A-CH+ Energy Informatics 2016
„Managing Data and Complexity in Energy Systems“

A decade ago, pioneers across the world began to think of information and communication technologies as key contributors to the transition of our energy system to a network of sustainable low-carbon producers and consumers. This idea was dreamt up some time before, but with recent technological advances in terms of computing power, communication bandwidth and significant reduction in system costs, more and more approaches became feasible. The worlds of electrical engineering on one side and informatics/information and communication technologies on the other side had a new connection point, which was called “smart grid”. In those days, strong day-to-day efforts were required to explain the motivation for smart grid research.

In subsequent years, the field experienced a strong push with rising interest from industry and even energy infrastructure operators. Many basic concepts such as demand response or voltage control became common sense. In addition, from the beginning on, the research field was well supported by research agendas throughout Europe, with policy makers demanding and happily adopting better clarity and common definitions.

Some years later, the field had developed from a set of early concepts to a spectrum of component and system solutions of much higher maturity. Many approaches were validated in the field in the frame of national and European research programs such as FP7, e-Energy in Germany or “Energiesysteme der Zukunft” in Austria. With this, a substantial research community had developed. It was time to identify the field of “Energy Informatics” as a full-grown research field.

Young researchers entering the field today will have very different experiences compared to the situation ten years ago. The available literature now exceeds by far what can be overseen by a single person. However, many concepts are clearly described now, taught in lectures and defined in books. It is no longer possible to compare innovative solutions to the old or “conventional” power system; applications of Energy Informatics have found their way into most aspects of design, planning and operation of power systems where required. The vision of a technological “smart grid” revolution has been replaced by the insight that there will be an incremental update of existing infrastructure with a large number of different innovative aspects applied to different parts of the system. Furthermore, with the D-A-CH+ Energy Informatics conference series a researcher today has a good starting point to learn about important research challenges and to network with other researchers in the area.

The objective of D-A-CH+ Energy Informatics 2016 is to further support this process of a research-based development and implementation phase of adequate information and communication technologies (ICT) and to foster the transfer between academia, industry, and service providers in the D-A-CH region Germany, Austria and Switzerland in close cooperation with other European partners. The conference addresses both scientists and practitioners.

The guiding topic of this issue is „Managing Data and Complexity in Energy Systems“. A strong contribution from Informatics is required to handle the sharply growing complexity of energy systems with a large share of renewable energy sources and more and more dynamic operation paradigms. At the same time, it is mandatory to gain deeper insights into the behavior of the infrastructure and its users, taking into account the resulting challenges in privacy and data analysis. All submitted papers focus on this field and can be categorized into four main topics:

Energy networks – digitalization of electricity network infrastructure, integration of renewable energies, behavioral and forecast models for system users, modelling of future scenarios.

Mobility – coordinated charging management for e-cars and second use of batteries

Buildings – optimization of the interaction between building management systems, HVAC and energy networks, innovative techniques for energy management.

Cross cutting - Privacy enhancing technologies, validation of networked smart grid systems, analysis of energy data, market modelling

We would like to thank all authors who have submitted their work to the conference. Following the successful conferences in Oldenburg 2012, Vienna 2013, Zurich 2014 and Karlsruhe in 2015 respectively, 48 manuscripts have been submitted in 2016, whereof twenty revised versions have been included in the special issue of the Springer Journal “Computer Science – Research and Development”[1].

D-A-CH+ Energy Informatics is a yearly event organized on joint initiative of Smart Grids D-A-CH – a cooperation of the German Federal Ministry for Economic Affairs and Energy, the Austrian Ministry for Transport, Innovation and Technology, and the Swiss Federal Office of Energy (see also http://www.smartgrids-dach.eu/).

Friederich Kupzog is Senior Scientist at the AIT Austrian Institute of Technology GmbH. His research interest lies in verification methods for networked smart grid systems. He coordinates the thematic field “Smart Grids ICT & Controls”, managing research projects together with industry, power grid operators and other research partners.
He achieved the Diploma Engineer degree of electrical engineering and information technology from RWTH Aachen. In 2006, he joined the Institute of Computer Technology at Vienna Technical University, Austria, where he achieved his PhD Degree in 20008. Until 2012, he stayed at the University as Post-Doc and managed the research group “Energy & IT” at the Institute of Computer Technology. Since 2012, Dr. Kupzog is with AIT Austrian Institute of Technology GmbH.

Wilfried Elmenreich is professor for Smart Grids at the Institute of Networked and Embedded Systems at the Alpen-Adria-Universität Klagenfurt, Austria. He is also affiliated with the Lakeside Labs cluster in Klagenfurt, a research and innovation cluster on self-organizing networked systems. He studied computer science at the Vienna University of Technology, where he received his doctoral degree in 2002 with distinction. He was granted venia docendi in the field computer engineering from Vienna University of Technology in 2008. He was a visiting researcher at the Vanderbilt University in 2005 and at the CISTER/IPP-Hurray Research Unit at the Polytechnic Institute of Porto in 2007. In 2007 he moved to Alpen-Adria-Universität Klagenfurt as a senior researcher. In Winter term 2012-2013 he was acting professor for complex systems engineering at the University of Passau. Since April 2013, he holds a professorship for Smart Grids at Alpen-Adria-Universität Klagenfurt. He is editor of 5 books and published over 150 papers in the field of networked and embedded systems. Elmenreich is senate member of Alpen-Adria-Universität Klagenfurt, Senior Member of IEEE and counselor of the Klagenfurt’s IEEE student branch.

Ronald Bieber is Secretary General of the Austrian Computer Society since 2011. Before he was project manager (level B of IPMA as well as PMP) for several companies (Siemens, ATOS) in different fields of IT.
Between 2003 and 2006 he was leading projects at the Austrian Institute of Technology (AIT) aiming to evaluate the security research in Austria in general as well as for the analysis of teh technology transfer at the universities of Vienna. From 2000 till 2003 Ronald managed the German contribution for an ESA satellite project (Herschel) at the university of Cologne, Germany. He did his PhD at one of the Joint Research Centers of the European Union in Belgium. Afterwards he worked for more than two years as Postdoc at the University of Groningen, The Netherlands, in the field of few body physics.

[1] These papers are freely available during the conference: http://link.springer.com/journal/450/onlineFirst/

Arbeitskreis Energie-Informatik

in der Österreichischen Computer Gesellschaft (OCG)

Die OCG unterstützt "die umfassende und interdisziplinäre Förderung der Informatik und der Kommunikationstechnologie (IKT) unter Berücksichtigung ihrer Wechselwirkungen mit Mensch und Gesellschaft" mit einer Vielzahl von Maßnahmen.

Die Entwicklungen im Bereich der Energieversorgung erfordern eine Verstärkung genau dieser Sichtweise und Ableitung von Maßnahmen für eine starke Positionierung Österreichs in der Beherrschung des Kreislaufes Forschung - Entwicklung - Wirtschaft. Dazu gehören insbesondere die Beratung zur Schwerpunktsetzung künftiger Förderprogramme (z.B. „IKT der Zukunft“, bmvit), Empfehlungen zur Sicherung des wissenschaftlichen Nachwuchses und Bildungsmaßnahmen in die breite Gesellschaft für die aktive Mitgestaltung und Akzeptanz des Energiesystems der Zukunft. Die OCG hat deshalb den Arbeitskreis "Energie-Informatik" (E-IKT) gegründet.

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Über OCG:
Die Österreichische Computer Gesellschaft (OCG) ist ein gemeinnütziger Verein mit Mitgliedern aus den Bereichen Wissenschaft, Anwendung, Lehre und Ausbildung sowie Unternehmen im Bereich Informationstechnologie (IT). Vereinsziel ist die Förderung der Informatik und IT unter Berücksichtigung ihrer Wechselwirkungen mit Mensch und Gesellschaft. www.ocg.at

Keynotes

Andrea Tonello

Alpen-Adria-Universität, Klagenfurt

“Power Line Communications for the Smart Grid: Status and Future” - The applications to be implemented in the Smart Grid require bi-directional connectivity among a multitude of nodes with a reliable, high speed, low latency, energy efficient and cost effective communication technology. Power line communication (PLC) has reached a high level of maturity and has the potentiality to meet the requirements. In this talk, we discuss state-of-the-art PLC technology, address the main questions related to the usage of narrow band and broad band PLC, and highlight the current research directions to improve further the performance.

Andrea Tonello is Professor and Chair of the Embedded Communication Systems Group at the University of Klagenfurt, Austria.
He received the Laurea degree (summa cum laude, 1996) and the Ph.D (2002) in electrical engineering from the University of Padova. From 1997 to 2002, he was with Bell Labs-Lucent Technologies, Whippany, NJ, USA, first as a Member of the Technical Staff. Then, he was promoted to Technical Manager and appointed to Managing Director of the Bell Labs Italy division. From 2003 to 2014 he was Aggregate Professor, and later Associate Professor, with the University of Udine, Italy where he founded the Wireless and Power Line Communications Lab and the spin-of company WiTiKee.
Dr. Tonello received several awards, including eight best paper awards (among which the IET Premium Award 2016 for the best paper on physical layer security in PLC networks), the Bell Labs Recognition of Excellence Award (1999), the Distinguished Visiting Fellowship from the Royal Academy of Engineering, U.K. (2010), and the IEEE VTS Distinguished Lecturer Award (2011-2015).

Further Information: www.andreatonello.com

Part 1

D-A-CH+ Energy Informatics

We would like to thank all authors who have submitted their work to the conference. 48 manuscripts have been submitted, whereof twenty revised versions have been included in the special issue of the Springer Journal “Computer Science – Research and Development”[2].

[2] These papers are freely available during the conference: http://link.springer.com/journal/450/onlineFirst/

Session 1 | Tuesday, September 27, 9:50

Simulation and Validation of Networked Smart Grid Systems

Chaired by Sebastian Lehnhoff

Incremental Development of a Co-Simulation Setup for testing a Generation Unit Controller for Reactive Power Provision

Jorge Velasquez, OFFIS
Klaus Piech, OFFIS
Sebastian Lehnhoff, OFFIS
Lars Fischer, OFFIS
Steffen Garske, Leibniz Universitaet Hannover

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Abstract – The German energy perspective is changing at an accelerated pace. This change is due to the high diffusion of decentralized energy resources in the electricity mix. Moreover, the role of these generation units is going beyond the provision of active power, and moving towards the supply of ancillary services for grid stabilization (e.g. frequency control, voltage regulation and reactive power compensation). In addition, there is a continuous increase in the complexity of distribution and transmission grids as the need for automation and Information and Communication Technologies (ICT) take an important role in the optimized operation of decentralized energy resources. This raises the requirement for sophisticated design and validation methods for the analysis of complex energy systems. An innovative approach in this field is the joint operation of multidisciplinary simulation tools in a coordinated fashion providing realistic environments for introduction of HiL-testing of grid automation components.

OpenGridMap: Towards Automatic Power Grid Simulation Model Generation from Crowdsourced Data

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Johannes Leimhofer, Technische Universität München
Hans-Arno Jacobsen, Technische Universität München

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Abstract – OpenGridMap is an open source project that crowdsources realistic power grid data to be used for research purposes. In this paper, we propose an approach for the automatic generation of power gird simulation models from crowdsourced data. The proposed approach orders the crowdsourced data into a power circuit relation which is then used to produce a CIM description file and subsequently a power grid simulation model. We provide experiments which demonstrate the effectiveness of the approach on OpenGridMap data. Given the large amount of crowdsourced data available, our approach has the potential to generate power grid simulations of larger size, more variety and more accuracy than the currently available state-of-the-art test power grids.

Session 2 | Tuesday, September 27, 11:00

Scheduling of Flexibility

Chaired by Friederich Kupzog

Demand-Response Optimized Heatpump Control for Service Sector Buildings

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Cyril Picard, Lucerne University of Applied Sciences and Arts - Engineering & Architecture, CC-iHomeLab
Patrick Huber, Lucerne University of Applied Sciences and Arts - Engineering & Architecture, CC-iHomeLab
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Abstract – With an increasing amount of volatile renewable electrical energy, the balancing of demand and supply becomes more and more demanding. Demand response is one of the emerging tools in this new landscape. Targeting service sector buildings, we investigated a tariff driven demand response model as a means to shave electrical peak loads and thus reducing grid balancing energy. This paper presents a software framework for load shifting which uses a tariff signal for the electric energy as minimization target. The framework can be used both on top of an existing building management system to shift heat generation towards low-tariff times, as well as to simulate load shifting for different buildings, heat pumps and storage configurations. Its modular architecture allows us to easily replace optimizers, weather data providers or building management system adapters. Our results show that even with the current TOU tariff system, up to 34% of cost savings and up to 20% reduction in energy consumption can be achieved. With Sub-MPC, a modified MPC optimizer, we could reduce computing times by a factor 50, while only slightly affecting the quality of the optimization.

Distributed Demand Side Management Using Electric Boilers

Lorenzo Nespoli, SUPSI, Alessandro Giusti, IDSIA, Nicola Vermes, IDSIA, Marco Derboni, IDSIA, Andrea Rizzoli, IDSIA, Luca Gambardella, IDSIA, Vasco Medici, SUPSI

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Abstract – Demand side management is a promising approach towards the integration of renewable energy sources in the electric grid, which does not require massive infrastructural investments. In this paper, we report the analysis of the performance of a demand side management algorithm for the control of electric boilers, developed within the context of the GridSense project. GridSense is a multi-objective energy management system that aims at decreasing both the end user energy costs and the congestions on the local feeder. The latter objective is minimized exploiting the existent correlation between the voltage measured at the connection point to the grid and the power flow measured at the low voltage transformer. The algorithm behavior has been firstly investigated by means of simulation, using typical water consumption profiles and a simplified thermodynamic model of the electric boiler. The simulation results show that the algorithm can effectively shift the boiler's electric consumption based on voltage and price profiles. In the second phase, we analyzed the results from a pilot project, in which the GridSense units (GSU) were controlling the boilers of four households, located in the same low voltage grid.

Impacts of Domestic Electric Water Heater Parameters on Demand Response

Tobias Lübkert, Hamburg University of Technology
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Volker Turau, Hamburg University of Technology

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Abstract – This paper analyzes the impact of the high dimensional parameter space of domestic electric water heaters (DEWH) for demand response (DR). To quantify the consumer comfort a novel metric is introduced considering a stochastic distribution of different water draw events. Incorporating three control algorithms from literature, it is shown that all considered parameters of a DEWH except the heat conductivity have a significant impact on consumer satisfaction. The effect on DR is mainly influenced by the temperature range and the planning horizon, but also by the heat conductivity and the volume. In contrast, the rated power of the heating element and the nominal temperature have no significant impact on the effect on DR. The impacts are analyzed by varying these parameters in a simulation of 1000 DEWHs considering three different controllers: a common thermostat, an exchange price dependent nominal temperature changing mechanism and an energy scheduling algorithm proposed by Du and Lu.

Targeting Customers for an Optimized Energy Procurement - A Cost Segmentation Based on Smart Meter Load Profiles

Simon Albrecht, Institut für Energiewirtschaft INEWI, Hochschule Fresenius - University of Applied Sciences
Manuel Fritz, Hochschule Furtwangen - University of Applied Sciences
Prof. Dr. Jens Strüker, Institut für Energiewirtschaft INEWI, Hochschule Fresenius - University of Applied Sciences
Prof. Dr. Holger Ziekow, Hochschule Furtwangen - University of Applied Sciences

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***Abstract* –** This research paper investigates consumer-specific costs on power spot markets. We use real-world smart meter data and market prices to analyze an energy procurement strategy based on the newsvendor model. The outcome displays a segmentation into an ordinal array of different costs-per-customer, which allow for a sensitivity analysis to examine appropriate measures and policy implications. We find the most relevant customer class to be the costliest one percent. These prime targets' share of total costs is 1.5 times as high as the respective share of total consumption. Reallocating the targets into incentive based contracts may allow for a significant reduction of utilities' costs while remaining on a relatively steady public good provision level.

Session 3 | Tuesday, September 27, 16:00

Advanced Technologies for Distribution Grids

Chaired by Silvia Santini

GridBox Pilot Project Results

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Marco Mangani, ewz
Florian Kienzle, ewz
Marc Eisenreich, BKW
Yamshid Farhat Quinones, BKW
Rainer Bacher, Bacher Energie AG
Alexandros Ketsetzis, ewz
Florian Müller, Supercomputing Systems AG

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Abstract – GridBox is an open platform for monitoring and active control of distribution grids. It is based on an innovative concept that comprehensively addresses the challenges DSOs will be exposed to in the context of increasing amounts of decentralized and often fluctuating generation as well as the electrification of the heat and transportation sector. In this paper, we outline the principles of the GridBox concept, we describe its key elements in terms of hardware and software and we specify functionalities and applications. The practical implementation of the concept is illustrated by presenting an overview and first results from field tests in two different regions in Switzerland one in an urban grid area in the city of Zurich and one in a rural grid area in the canton of Bern.

A Framework for Disturbance Analysis in Smart Grids by Fault Injection

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Filip Obradovic, ALaRI, Faculty of Informatics, University of Lugano
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Abstract – With a growing complexity of electric power systems, a total number of disturbances are expected to increase. Analyzing these disturbances and understanding grid's behavior, when under a disturbance, is a prerequisite for designing methods for boosting grid's stability. The main obstacle to the analysis is a lack of relevant data that are publicly available. In this paper, we design and implement a framework for emulation of grid disturbances by employing simulation and fault-injection techniques. We also present a case study on generating voltage sag related data. A foreseen usage of the framework mainly for prototyping, root-cause analysis and for designing and comparing methods for disturbance detection and prediction.

Providing Primary Frequency Control with Residential-Scale Photovoltaic-Battery Systems

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Verena Tiefenbeck, ETH Zurich
Elgar Fleisch, ETH Zurich
Thorsten Staake, University of Bamberg

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Abstract – Decentralized photovoltaic (PV) battery systems have recently received great attention from consumers around the world. PV battery systems allow consumers to reduce their dependence on the local electricity supplier at lower or equivalent costs. However, the profitability of PV battery systems depends greatly on the local meteorological conditions and the local electricity retail tariff. In central European countries, PV battery systems generate and store less electricity in winter months due to lower irradiation. The battery, in particular, can be reserved to provide grid stabilizing services (ancillary services) during winter months, which improves the overall systems economics. In this study, a large dataset consisting of individual load profiles is used to simulate a virtual power plant (VPP), which provides ancillary services during battery idle times. The results show that participants with large batteries can greatly increase their overall systems economics by participating in reserve markets. However, participants with small battery capacities may not be able to recover the additional costs for communication with the virtual power plant and are thus not suitable candidates to provide grid stabilizing services (ancillary services).

Provisioning, Deployment, and Operation of Smart Grid Applications on Substation Level

Mario Faschang, AIT Austrian Institute of Technology GmbH
Stephan Cejka, Siemens AG Austria
Mark Stefan, AIT Austrian Institute of Technology GmbH
Albin Frischenschlager, Siemens AG Austria
Alfred Einfalt, Siemens AG Austria
Konrad Diwold, Siemens AG Austria
Filip Pröstl Andrén, AIT Austrian Institute of Technology GmbH
Thomas Strasser, AIT Austrian Institute of Technology GmbH
Friederich Kupzog, AIT Austrian Institute of Technology GmbH

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Abstract – The transition of classical power distribution grids towards actively operated smart grids locates new functionality into intelligent secondary substations. Increased computational power and newly attained communication infrastructure in thousands of secondary substations allow for the distributed realization of sophisticated functions, which were inconceivable a few years ago. These novel functions (e.g., voltage and reactive power control, distributed generation optimization or decentralized market interaction) can primarily be realized by software components operated on powerful automation devices located on secondary substation level. The effective and safe operation of such software is crucial and has a broad set of requirements. In this paper, we present a flexible and modular software ecosystem for automation devices of substations, which is able to handle these requirements. This ecosystem contains means for high performance data exchange and unification, automatic application provisioning and configuration functions, dependency management, and others. The application of the ecosystem is demonstrated in the context of a field operation example, which has been developed within an Austrian smart grid research project.

Session 4 | Friday, September 30th, 9:40

Power Grid Automation & Protocols

Chaired by Thorsten Staake

Message-oriented Machine-to-Machine Communication in Smart Grids - An Approach for and Experiences from Mapping IEC 61850 and CIM to XMPP

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Martin Winter, Siemens AG
Christian Glomb, Siemens AG
Michael Specht, OFFIS e.V.

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Abstract – Smart Grids constitute massively distributed systems with many interconnected entities that require flexible and reliable machine-to-machine (M2M) communication among each other. Providing such flexible and reliable communication enables the complex algorithms and control mechanisms that are necessary to ensure reliable grid operation and to trade energy generation and energy consumption to the mutual benefit of all involved entities. Messaging protocols such as the Extensible Messaging and Presence Protocol (XMPP) provide all the necessary mechanisms for implementing these tasks. Thus, they lend themselves to transmitting messages and data in Smart Grids by mapping Smart Grid protocols and data formats such as IEC 61850 and Common Information Model (CIM) to suitable messaging protocols. In this paper, we present an approach for mapping IEC 61850 and CIM to XMPP and elaborate on our experiences from implementing and evaluating this approach in a field trial conducted within the research project In2VPP.

Accurate Clock Synchronization for Power Systems Protection Devices over Packet Switched Networks

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Abstract – Channel based clock synchronization in packet switched networks (PSNs) is considered for, but not limited to, the time and safety/security critical application of power system protection. The synchronization accuracy requirement of power system protection devices used for line current differential protection is 10 µs, which could be achieved in time division multiplexing networks (TDM) that were traditionally used in that domain. In PSN, highly accurate synchronization can be achieved with the standard synchronization method IEEE 1588-2008 Precision Time Protocol (PTP) when devices in the communication network are equipped with so called boundary clocks (BCs) or transparent clocks (TCs). However, when BCs or TCs are not available, the required accuracy can hardly be achieved. In this work, a modification of the PTP is proposed that replaces the clock parameter estimation and the computation of the clock control signal. Thereby, the statistics of measured packet delays are considered to select optimum estimation schemes. It is shown that the here proposed method outperforms the Linux PTP in terms of timing accuracy by a factor of 2 in enterprise local area networks and by a factor of 10 in Carrier Ethernet wide area networks.

Session 5 | Friday, September 30th, 11:00

Privacy

Chaired by Günther Eibl

Preserving Privacy in Distributed Energy Management

Daniel Brettschneider, University of Applied Sciences Osnabrück
Daniel Hölker, University of Applied Sciences Osnabrück
Alfred Scheerhorn, University of Applied Sciences Osnabrück
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Abstract – The smart power grid transforms into a distributed system of manifold stakeholders by integrating communication technology into the former static power grid. Distributed Energy Management (DEM) will play a vital role in future demand supply matching. An important and often overlooked factor in this concept is privacy. In this paper we present PrivADE, a privacy preserving algorithm for DEM. It utilises homomorphic encryption to privately gather aggregated data and perform energy management based on the max-min fairness principle. Simulations show that PrivADE achieves similar consumption results as two comparative approaches, while in contrast preserves privacy at all times. The computational and communicational complexity is analysed. Furthermore, the privacy concept is adopted to PowerMatcher.

Differential Privacy for Real Smart Metering Data

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Abstract –The collection of detailed consumption data through smart metering has led to privacy concerns. Aggregating the consumption data over a number of smart meters can be used to strike a balance between functional and privacy requirements. A number of contributions have proposed the use of differential privacy in smart metering to perturb aggregates in order to provide a proven privacy property for end consumers. However, as differential privacy has originally been proposed for very large datasets, the applicability in real-world smart metering is not guaranteed. In this paper, the effect of differential privacy on real smart metering data is studied, especially with the respect to balancing utility and privacy requirements. The main finding is that even after some improvements of the basic method the aggregation group size must be of the order of thousands of smart meters in order to have reasonable utility.

Session 6 | Friday, September 30th, 11:40

Electric Vehicles

Chaired by Wilfried Elmenreich

Coordinated Charge Management for Battery Electric Vehicles

Felix Braam, Fraunhofer Institute for Solar Energy Systems
Arne Groß, Fraunhofer Institute for Solar Energy Systems
Michael Mierau, Fraunhofer Institute for Solar Energy Systems
Robert Kohrs, Fraunhofer Institute for Solar Energy Systems
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Abstract – Compared to refueling gasoline powered vehicles, the charging of battery electric vehicles (BEVs) takes considerably more time which renders a single-purpose charging infrastructure inconvenient. More likely, the charging stations will be integrated into the parking infrastructure (parking decks, public, private and commercial parking sites). On average the duration of the parking will be longer than the duration of the charging process which creates a potential for load shifting. In turn this implies that the rated power of large charging infrastructures can be chosen to be smaller than the sum of rated powers of all charging points, provided that the load shifting potential can be activated.
In this paper a complete description of the problem at hand is given in terms of a mixed integer linear program (MILP) which can readily be integrated into the operation management of charging infrastructures. It allows to coordinate the charging processes of multiple BEVs to fully exploit the load shifting potential while taking into account the limitations of the distribution grid, the charging infrastructure, and the BEVs. In addition to ensuring the safety of the operation, the objective of the optimization can be adapted to set use-case specific incentives.

Ensembles of Context and Form for Repurposing Electric Vehicle Batteries – an Exploratory Study

Daniel Beverungen, University of Paderborn
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Abstract – The electric vehicle battery is the crucial component in electric vehicles. It propels the vehicle's engine and causes around 25% of the vehicle's overall costs. Unfortunately, due to deterioration, the battery's use gradually restricts the vehicle's driving range, acceleration, and charging speed over time. Only a battery replacement restores the vehicle's performance. Despite its deterioration, the used battery can be repurposed to serve as a battery energy storage system in less demanding second-life application scenarios. Examples are home storage solutions for energy from photovoltaic panels or larger buffer storage solutions for stabilizing energy from wind parks or solar farms. With strongly increasing numbers of electric vehicles world-wide, some hundred thousand aged batteries can be assumed to be available soon. Considering the necessity for a reliable fit of the targeted second-life application scenario (as context) and the battery energy storage solution built from aged batteries (as form), the decision for which scenario a battery should be repurposed needs to be supported by information systems.
Since current research falls short of identifying and prioritizing the requirements that characterize second-life application scenarios, information system developers lack justificatory knowledge to guide and constrain the design of corresponding information systems. In an explorative multi-method study, we set out to identify the requirement categories and metrics that need to be elicited for repurposing batteries. The study (a) contributes a prioritized list of requirement categories and metrics for repurposing batteries, and (b) documents how they were instantiated respectively why they were important in an analyzed case.

Session 7 | Friday, September 30th, 14:00

Forecasting and State Estimation Approaches

Chaired by Hartmut Schmeck

Analysis and Model-Based Predictions of Solar PV and Battery Adoption in Germany: An Agent-Based Approach

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Abstract – In order to tackle energy challenges faced in Germany, a Feed-in Tariff (FiT) program was created in 2004 to aid the adoption of solar photovotaic (PV) systems by paying owners of such systems a certain amount for each unit of electricity generated. Solar PV electricity generation is limited due to its intermittency but this can be managed using batteries. In this paper, we study the adoption of PV and battery (PV-battery) systems in Germany, and consider policies that might improve the adoption of these systems and we evaluate the resulting future scenarios for the electric grid. To do this, we create an Agent-Based Model (ABM) that is simulated to estimate the impacts of different policies; this model is informed by an online survey. Simulating adoption over a period of 10 years, the results show that increasing electricity prices could result in improved PV-battery adoption better than reducing PV-battery system prices could. In addition, given the high level of affinity of people towards PV systems in Germany, disconnection from the grid would be a viable option within the next 10 years.

Photovoltaic Power Forecasting Using Simple Data-Driven Models Without Weather Data

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Abstract – The present contribution offers evidence regarding the possibility of obtaining reasonable photovoltaic power forecasts without using weather data and with simple data-driven models. The lack of weather data as input stems from the fact that the constant obtainment of forecast weather data might become too expensive or that communication with weather services might fail, but still accurate planning and scheduling decisions have to be conducted. Therefore, accurate one-day ahead forecasting models with only information of past generated power as input for offline photovoltaic systems or as backup in case of communication failures are of interest. The results contained in the present contribution, obtained using a freely available dataset, provide a baseline with which more complex forecasting models can be compared. Additionally, it will also be shown that the presented weather-free data-driven models provide better forecasts than a trivial persistence technique for different forecast horizons. The methodology used in the present work for the data preprocessing and the creation and validation of forecasting models has a generalization capacity and thus can be used for different types of time series as well as different data mining techniques.

Evaluation of Network State Estimators for Adaptive Power-Balancing Controller in a Microgrid scenario

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Abstract – The Smart Grid applications are going to reach the LV grid units and household in order to efficiently use the resources in distribution grids. A cost effective way to connect these devices is utilize the existing network infrastructure or to deploy dedicated networks such as the power communication. In this work we have shown how PLC communication can have signifficant impairments for load-frequency control operations in the microgrid. Moreover, we have demonstrated how such bad network performance can in uence the control performance on a case study of the low voltage grid controller. Furthermore, we have compared two network estimation algorithms which are used for adaptive gain scheduentt ce gaingttly utlContacct t5ntllet n ue-

Hybrid Simulation and Energy Market Based Optimization of Cement Plants

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Abstract – This paper presents an approach for equipping a cement plant with a wind power plant, a battery storage and an optimized control in order to reduce electricity supply cost and carbon dioxide (CO2) emissions as cement manufacturing is a traditional energy-intensive industrial process, that accounts for around 5 % of global CO2 emissions. This work aims at analyzing the potential of using existing flexibilities of current cement plants for process optimization and adding renewable energy sources (e.g., wind) in combination with storage to lower cost and emissions. Therefore, a hybrid simulation model of a cement plan with an integrated optimized control algorithm, a wind turbine model including 24-hour forecasts, and market access to the German day-ahead electricity market and the FRR market was built up.

The results show, that applying only an optimized control of the cement plant without offering its flexibilities and renewable power supply in combination with a battery storage only causes a slight benefit. Adding flexibility and marketing to the model provides significant cost savings. Adding renewable energy sources and a battery storage to the cement plant can cause a further significant decrease of electricity supply cost per produced ton cement under certain conditions. Regarding the CO2 emissions, installing a wind turbine has an decreasing impact, depending on the location.

Part 2

ComForEn 2016

The following invited submissions reflect currently ongoing research activities in the D-A-CH region in the context of energy informatics as well as information and communication technologies for energy systems. These submissions are presented with posters during the conference.

KIT Energy Smart Home Lab – Hardware-in-the-Loop Research Environment with Hybrid Energy Storage System

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Ingo Mauser, Karlsruhe Institut of Technology - Institut of Applied Informatics and Formal Description Methods
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Abstract – The KIT Energy Smart Home Lab is a smart residential building comprising building automation, metering systems, sensors, intelligent appliances, heating, ventilation, and air-conditioning equipment, distributed generation, and energy storage systems. Currently, the lab is extended by a hybrid energy storage system and a linear voltage amplifier for real-time simulations, to facilitate fully functional power hardware-in-the-loop simulations and evaluations. This paper presents the setup of the lab, the hardware-in-the loop research environment, and first measurements when using a simulated artificial mains network.

Synthetic Aggregate Household Consumption Trace Generation with SHoCo

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***Abstract* –** Smart meters have emerged as invaluable tools for utility companies, as they allow for the automated collection of energy consumption readings and enable multi-tariff billing. However, smart meters have not primarily been designed to provide collected data to customers; often, they do not even feature interfaces for users to view the data. A second line of products has hence emerged to bridge this chasm. Plug-level power sensors, also referred to as smart plugs, are tailored to provide consumption information to users. By making consumption data available for processing, both smart meters and smart plugs lay the foundation for many user-centric energy-based services, such as attributing consumption to individual appliances. However, there is one major obstacle for developing such services, namely the limited availability of previously collected data on which the efficacy of such services can be tested. We tackle this challenge by presenting our synthetic household consumption trace generation tool called SHoCo. It facilitates the generation of synthetic, yet realistic-looking, household power consumption traces based on the re-combination of snippets of existing device-level consumption traces. SHoCo is capable of creating traces for a set of different appliance types and models, and is easily extensible by new input data. In order to demonstrate its efficacy, we present and discuss generated traces for several synthesis configurations.

iniGrid

A brief description of the main activities and project goals

Mark Stefan

Abstract – The funded research project iniGrid deals with the development of innovative sensor and actuator technologies providing essential future functionalities for actively managed and fault-protected distribution grids. Additionally, monitoring and control systems are investigated and adapted for the integration of the new devices. Radically new semiconductor-based components, alongside the necessary IT and secure networking concepts will address this shortcoming and are aimed for commercial and grid applications.

1. Introduction

The research project iniGrid innovates the way electric energy is brought to end-use equipment for actively managed and fault-protected distribution grids. The use of renewable energies goes along with smart grids. Essential future functionalities such as dynamic management of power line loading as well as fault detection and fast recovery from power interruptions require appropriate sensors and actuators in place. These sensors and actuators are missing today on the distribution level of a power grid. Radically new semiconductor based components are developed by iniGrid, alongside the necessary IT and secure networking concepts.

The so-called Smart Breaker provides protection functions, power management, measurement services and communication for domestic and industrial applications, based on a new and innovative technology. An air-insulated medium voltage sensor, integrated into post insulators allows easy retrofit of sensors in existing power grid infrastructure. To use this new technologies, the existing monitoring and control technologies are adapted within this project and cost-benefit analysis are done.

The project consortium consists of the following partners: AIT Austrian Institute of Technolgy GmbH, Eaton Industries (Austria) GmbH, Infineon Technologies Austria AG, Zelisko GmbH, Sprecher Automation GmbH, Technische Universität Wien – Institut für Computertechnik, Fachhochschule Oberösterreich – F&E GesmbH, Linz Strom Netz GmbH, and MOOSMOAR Energies OG.

Section 2 gives an overview of the project goals, the new components and their main functionalities are explained in Section 3 and Section 4 shows the important aspects regarding system integration. In Section 5 information about cost-benefit analysis is given, whereas Section 6 deals with the validation of the single components and the complete system.

2. Project goals

The aim of *iniGrid* is to develop and validate innovative sensor and actuator components for smart distribution grids. Due to the increasing number of renewable energy sources, active capacity management will become necessary in order to avoid high investments in grid reinforcements. Appropriate cost-effective components that provide advanced functionality such as integrated communication capabilities and can be retrofitted with reasonable effort are missing today at the distribution level. As the market starts to request such devices on low voltage networks as well as on medium voltage levels, *iniGrid* targets this window of opportunity and develops new devices providing the necessary functionality.

Fig. 1 illustrates the smart distribution grid including an increased monitoring and control of integration of innovative sensors and actuators. The red circles show new components developed in *iniGrid* – the Smart Breaker in low voltage networks, the Medium Voltage Sensor, and the Automation System (both in medium voltage networks). The blue circles represent several systems in smart grids, whereas some of them already exist (Distribution SCADA, Meter Data Aggregation, and Meter Data Management) and the others are partly or fully covered by the innovations within the project.

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Fig. 1 Increased monitoring and control of integration of innovative Smart Grid Sensors and Actuators

3. Innovative Sensor and Actuator Technologies

As already mentioned, *iniGrid* deals with the development and integration of two innovative sensor and actuator technologies which are explained in the following.

3.1 Smart Breaker

The key-innovation of *iniGrid* is the so-called Smart Breaker integrating several functionalities into a single device and planned to be used in customer premises. The following functionalities are provided:

- Protection functions such as overcurrent and short-circuit protection to avoid damages.
- Power management based on remote switching.
- Monitoring of local current and voltage values.

Fig. 2 shows a comparison between the power distribution in low voltage networks today (left) and in future networks by using the Smart Breaker (right) providing a bi-directional wireless communication between the Smart Breaker Gateway and the Smart Breaker itself. Obviously, the communication infrastructure becomes much simpler by using the Smart Breaker and the corresponding gateway as well as the number of different devices can be reduced (Smart Breaker instead of circuit breaker and smart meter).

3.2 Medium Voltage Sensor

Passive voltage sensors with sufficient accuracy are based on the ohmic divider principle. Existing solutions are built into cable plugs, which results in a defined value of the unavoidable parasitic capacitances to the earthed parts. In a significant number of important applications however, sensors for air insulated equipment are needed. Here accurate and stable voltage sensors have to be integrated into post insulators or other insulating X. In such an environment, the required accuracy of at least class 0.5 according to IEC 61869 is not easily achievable, since these isolators have no earthed cover and therefore suffer from parasitic capacitances to geometrically and electrically (switching state) undefined external structures. The developed medium voltage sensors (for 10 kV networks and for 20 kV networks) are able to achieve the requirement above and can be retrofitted in the existing infrastructure.

4. Integration of Automation Systems

To provide an efficient energy management system with protection functions using new technologies such as the Smart Breaker, the integration and advancement of existing subsystems are necessary or new parts must be developed, respectively. In particular, the focus is on

Fig. 2 Power distribution in low voltage networks today (left) and by using Smart Breakers (right)

- the intercommunication between Smart Breaker, the Smart Breaker Gateway, and a local energy management system (Customer Energy Management System or Customer Control System),
- interfaces to grid operators, and
- connections to the process control technique of grid operators.

Therefore, the project deals with selecting suitable protocols and communication media, as well as security aspects regarding data transmission and control system engineering for the new sensor and actuator technologies. Existing systems must be adapted, for example to handle with analogue signals received from the automation infrastructure.

5 Cost-Benefit Analysis

Due to the fact that grid expansion (e.g. cable installation) involves a great deal of expanse, the integration of smart grid technologies can help to decrease these costs. On the other hand, a high number of current smart grid applications are developed for restricted purposes and thus, the development costs of hard- and software are high. Within this research project, the benefits of *iniGrid* technologies regarding the costs are examined within each project phase. A final version of the cost-benefit analysis will be given at the end of the project within the validation phase but it can be already foreseen that the overall costs can be reduced by using the new technologies.

6 Lab & Field Validation

To show that the new technologies are feasible for the integration into smart grids, lab validation as well as field validation are an important part of the project. Therefore, each of the devices will be tested within the lab and integrated into a complete system-test afterwards which will be done at dedicated test structures within the distribution grid of LINZ STROM Netz GmbH and the SmartEST laboratory at the Austrian Institute of Technology GmbH. Additionally, the University of Applied Science Upper Austria and Sonnenwelt Großschönau will be used for tests under realistic conditions.

7 Conclusion

Within the research project *iniGrid* new sensor and actuator technologies as well as monitoring and control system are developed or at least refined. The components have been developed and tested in the lab and will be integrated into systems to validate their behavior under realistic conditions. Cost-benefit analysis have shown a positive effect on the integration costs as well as on operational costs so far and will be finished by the end of the project.

Acknowledgements

This paper gives an overview of the main activities of the project *iniGrid – Integration of Innovative Distributed Sensors and Actuators in Smart Grids* (845018), which was commissioned as Flagship project by the Österreichische Forschungsföorderungsgesellschaft mbH (FFG) as part of the e!MISSION.at 4th.

Dr. Mark Stefan studied Computer Science at the Vienna University of Technology. He started his professional career at Robert Bosch AG in Vienna. In 2012, he joined the Institute of Computer Aided Automation at the Vienna University of Technology, working as project assistant and doing his PhD-studies. Since June 2014, he is working as Research Engineer and Project Manager at the AIT Austrian Institute of Technology GmbH. Dr. Stefan holds lectures at St.Pölten University of Applied Sciences (Application of Graphs in the Railway Sector).

Architecture and Quality Standards for the Joint Development of Modular Open Source Software for Power Grid Distribution Management Systems

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Abstract – Regulatory effects, business pressure and the transformation to smart grids foster the need for up-to-date software systems for managing and operating the grid operators' electric power grids. The complexity of these systems has grown over decades. This makes enhancements and development of new functionalities in existing systems cost intensive, vendor/system specific and often prevents meeting time to market and quality requirements. Public interfaces and open data formats allow development of enhancements and new functionality as re-usable modules by 3rd parties, thus allowing the integration of best-of-breed systems in the system landscape at grid operators. A significant reduction of system complexity is a precondition to develop such re-usable modules while meeting time to market and quality requirements in critical infrastructure. This is accomplished by defining a common architecture framework, common processes and quality standards.

1. Motivation

The steadily growing integration of decentral renewable energy resources, regulatory effects, business pressure in the unbundled energy sector and the transformation to smart grids foster the need for up-to-date software systems of grid operators for managing and operating their electric power grids. The complexity of existing systems has grown over decades: Each IT-System (e.g. Distribution Management System (DMS)/Supervisory Control and Data Acquisition (SCADA), Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), Geographic Information System (GIS)) only holds parts of relevant grid data. Via direct coupling between these systems, data are made accessible specifically for each business process and proprietary at each grid operator/vendor [1]. A net of point-to-point connections leads to dependencies between the systems that are unmanageable. Each of the named systems has a five to 15 years interval of major updates. The respective upgrade projects are highly complex and cost intensive because of a steadily growing range of functional adaption extensions, or new development of the interfaces.

This situation results in a vendor lock-in of grid operators to their system vendors and requires enormous effort by the vendors for integration, thus binding development capacities needed for new development or updates forced by regulation authorities.

These problems are addressed by a consortium called openKONSEQUENZ[3] (oK), which target is, to reduce maintenance costs of their systems landscape by reducing system complexity and vendor dependency as well as increasing software quality and software development efficiency.

The oK consortium brings together German and Netherlands Distribution System Operators (DSOs) supplying over 15 million German inhabitants with electrical power and 5,7 million Dutch customers with gas and power, software vendors, service providers and researchers. It started up 2013 with the idea of developing open source software to solve the vendor lock-in problems explained above. The consortium is organized in the Eclipse Foundation structure as Driver Members (a number of German DSOs), User Members (DSOs with focus on development), Service Providers (including software vendors) and Guest Members (universities and research institutes, interested service providers, a Dutch DSO).

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[3] http://www.openkonsequenz.de

This paper discusses the architecture and quality standards development by the oK. Chapter 2 describes the related work. Chapter 3 shows the current results and chapter 4 sums the work up and gives an outlook on future projects.

2. Related Work

Ensuring interoperability and making software development vendor independent and faster, while keeping software quality, leads to questions for standards on data exchange and architectures for combination of modules of different vendors. These fields are discussed briefly in the context of the electricity domain in the following subchapters.

2.1 CIM Standards – IEC 61970, IEC 61968, IEC 62325

In the energy domain, the Electric Power Research Institute (EPRI) started developing a Common Information Model (CIM) in the 1990s to solve vendor lock-in at Energy Management Systems (EMSs) [2]. Since now, it is developed further by the International Electrotechnical Commission (IEC) as series of Standards: IEC 61970 for EMS, IEC 61968 for Distribution Management and IEC 62325 for Energy Markets. Core of the CIM is a sematic data model for data exchanges in and between electric utilities. The CIM data model describes all necessary structures/elements of electricity networks, their relationships and multiplicities, their semantical meaning, and their syntactical values from the point of view of the IEC but is still growing to meet future requirements, and therefore should be stressed for data exchange instead of proprietary developments. The European Network of Transmission System Operators for Electricity (ENTSO-E) uses the CIM as basis for their Common Grid Model Exchange Standard (CGMES) to exchange grid models between different Transmission System Operators (TSOs) and achieving interoperability between TSOs software systems. It might be reasonably assumed, that needed future model exchanges between TSOs and DSOs for power grid stability calculations may underlie the same standard.

2.2 Reference Architectures

Reference Architectures are proven, generical Software-Architectures for concrete domains and apply across product and organizational borders.

Enterprise Application Integration (EAI) [3] deals with business-critical systems that are hard to adapt to communicate and share information with more advanced systems, which are long known issues. Point-to-Point connections are not appropriate to facilitate interoperability. A central message broker like an Enterprise Service Bus (ESB) is an adequate solution. It moves messages from any type of application to any other, changing the format of messages according to target systems.

Service Oriented Architecture (SOA) [4] is derived from EAI. It is the combination and recombination of services, which base on existing enterprise components, to a business process choreography. SOA has several layers that match to the energy domain in the following way: Operational Systems are existing IT-Systems and Sensor-Systems of network operators. Enterprise Components build on that first Layer, to enable e.g. DMS, SCADA, ERP, CRM. In a SOA, on top of that layer, services provide single or combined functionality, which can be reorganized in business processes in the next layer and get presented in a top layer. The integration and Security/Management/Monitoring lie vertical to these tiers as cross-cutting issues.

The Open Smart Grid Platform (OSGP)[4] is a platform for open, generic, scalable and independent “Internet of Things” (IoT) services. According to the SOA concept, it provides information on wide spreaded sensors like a SCADA kernel does to a DMS/SCADA and can be used as basis to get data from the field.

Using the CIM’s information model (see previous subchapter) on an ESB as core concepts in the interoperability architecture on top of existing enterprise applications, a set of central energy domain services/modules can be built to provide energy systems data/services and be recombined to high-level decision and optimization functions.

2.3 Quality Standards in Agile Development

Software Quality [5, chapter 10] is fundamental in software engineering and essential in development of long-living and safety/security critical software systems, e.g. critical infrastructure. Such software systems have to guarantee quality attributes, foremost extended maintainability and security goals, commonly termed “CIA Triad” (confidentiality, integrity and availability). Quality standards have been put into place to standardize the meaning of software quality with respect to said quality attributes (e.g. ISMS[5], BSI[6], BDEW[7]). These quality standards mainly focus on the operation of software and not on the development.

Agile methods have become a mainstream in software engineering [5, section 4.4], and are also applied successfully in safety critical environments such as critical

[4] https://smartsocietyservices.com/osgp/

[5] https://www.bsi.bund.de/SharedDocs/Downloads/DE/BSI/Publikationen/ITGrundschutzstandards/BSI-Standard_1001.pdf

[6] https://www.bsi.bund.de/SharedDocs/Downloads/DE/BSI/Grundschutz/Hilfsmittel/Extern/Diplomarbeiten/Erstellung_IT-Profil_Lefin.pdf

[7] https://www.bdew.de/internet.nsf/id/232E01B4E0C52139C1257A5D00429968/$file/OE-BDEW-Whitepaper_Secure_Systems%20V1.1%202015.pdf

infrastructure. As one of the specific methods, Scrum has proven to deliver fast results with high quality. The low project management overhead of Scrum and the self-organizing team culture of all agile methods make Scrum the method of choice for open source development.

From a safety and security point of view, open source software is considered by the BSI to have significant advantages[8].

3. openKONSEQUENZ Approach

The oK drives modularization of DMS functionalities with a SOA like communication over an ESB with oK-CIM-Profiles. The oK develops open source and agile with the goal to establish a reference architecture in the electricity domain to allow an independent development of modules by vendors and to integrate these efficiently in critical infrastructure.

3.1 oK Multilayer Architecture

Existing systems, (possible) externally developed modules, oK User Modules, and oK Platform Modules (Core Modules and Domain Modules) interact on the basis of standardized interfaces (the oK APIs) and run on an underlying system following a reference architecture concept.

Figure 3: oK Multilayer Architecture.

Figure 1 shows the oK Multilayer Architecture, which provides a general structure to ensure reusability, integratability, modularization and extendibility. Each module (i.e., components, systems and adapters) has to be located at some point in this architecture (e.g., shared backend services in the platform layer and GIS, DMS and ERP in the source system layer). Platform Modules provide reusable basic functionality to multiple User Modules and organize tasks such as source system data access. Platform Modules are distinguished into Domain Modules and Core Modules: Core Modules provide services for cross cutting concerns in a standardized way, while Domain Modules provide specific services to the domain of higher level functions for operating power systems. User Modules implement the use cases of end users. They contain business logic and may have an own private data storage and own user interfaces. The modules communicate using the APIs shown in Figure 1.

Figure 4: Technical Architecture.

A technical architectural view is shown in Figure 4. This shows that oK makes extensive use of open source technology to implement the Modules. A typical oK application (i.e., a User Module and required Platform Modules) is implemented in Java, has a Web-Interface and stores own data in a PostgreSQL database. A concrete implementation may use other technologies, such as for instance other database management systems.

3.2 oK Quality Standards

The oK platform consists of open source software modules, developed by independent parties using an agile methodology. To engineer and safeguard quality requirements – foremost the security goals and maintainability – of all modules as well as the integrated platform, rigorous quality standards for the software development are mandatory.

oK defines its quality standards in three categories[9]: code quality, design quality, and product quality.

Code quality is maintained by defining

- a set of coding guidelines,
- file naming conventions,
- configuration management conventions,
- build, package and test mechanisms,
- and run-time diagnosis functions common for all modules.

The coding guidelines and the common conventions ensure conformity of the modules developed by independent organizations. Central elements of quality assurance on code level are static analysis, automated testing, and dynamic analysis. These mechanisms are

[8] https://www.bsi.bund.de/DE/Themen/DigitaleGesellschaft/FreieSoftware/freiesoftware_node.html

[9] https://wiki.eclipse.org/images/0/08/OK-QualityCommitteeHandbook-Current.pdf

implemented by reviews (see below) and by nightly builds on a continuous integration system which includes static analysis (enforcing the coding guidelines), unit-tests, and code coverage analysis.

Design quality is maintained by defining a set of design documents common for all modules. The central design document of each module is its architecture concept. The outline and contents of these documents are defined[10]. A test specification document is also required for each module, defining integration test cases that are also run during the nightly builds. Design quality is maintained by a peer review setup. Design documentation – as well as the code itself – of each module is examined by a third party, typically the architects and developers of another module.

Product quality is maintained by using a reference installation environment ("QA environment"). After each sprint, the module is deployed into an oK platform installation in the QA environment. Each module has to produce a test specification and a validation concept to describe the test steps to be performed on the QA environment. As far as possible, these test steps should be automated, but manual tests will be required on product level. The manual tests are executed at least once at sprint end, before a feature/user story will be accepted. The product documents are also subject to peer review. Depth and rigor of the review methods used to ensure quality are determined by the classification of a module in terms of criticality and complexity. The documents will be created and filled according to the agile development method. Availability of the document contents relevant for a feature/user story is part of the "done" criteria. This helps keeping the documents up to date, and also helps to keep the review scope in each sprint small.

The rules defined in the quality handbook are independent of technology as far as possible and may be comfortably adjusted to technologies applied in oK now or in the future. At the time this paper is written, the technologies shown in Figure 4 are included.

4. Summary

The oK consortium drives architecture and quality standards in their field of electricity network management and operation to overcome the existing vendor lock-in and system complexity that hinders development of new, needed functionalities for smart grids. Therefore, the consortium uses CIM standards intensively for ensuring interoperability and quality assurance approaches from the open source development. The work does not fall in the category of IoT. Wide spreaded sensors and actors are not directly integrated, as a SCADA kernel is also not directly integrated, but interconnections can be established via the current SCADA.

The oK already developed a pilot for feed-in-management. This pilot is divided in two different modules: (i) a platform module for the work with and caching of topologies of the energy grid – an existing DMS/SCADA/GIS must not be queried permanently for this data – yielding higher stability. (ii) a user module for the feed-in-management, using the mentioned platform module for topology management.

With a number of core modules of oK maintained as open source software, in the long-term modules implementing new functionalities for the users can be developed as open source by the consortium as well as closed source by interested vendors with the possibility of easy integration in the landscape of electricity grid operators.

[10] https://wiki.eclipse.org/images/3/3d/OK-ArchitectureCommitteeHandbook-Current.pdf

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Andre Goering studied computer science at Technical University Dortmund in Germany and finished his diploma in 2012. Since then, he is working for OFFIS - Institute for Information Technology in Oldenburg, Lower Saxony, Germany in the R&D Division Energy in terms of architecture development and interoperability.

Methodical Reference Architecture Development Progress

Beneficial Implications Developing a Secure Reference Architecture for Future Smart Grid Solutions in Austria

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Abstract – The *Reference Architecture for Secure Smartgrids Austria* (RASSA) project aims at developing a secure, interoperable reference architecture for Austrian smart grids. Building on the strength of the project's consortium, this architecture is being specified in close coordination with all relevant stakeholders in Austria. By instantiating parts of the reference architecture, secure, and compatible smart grid components can be implemented in a consistent and efficient way. This paper shows the progress of this effort and illustrates methodical consequential benefits, as well as the potential to integrate reactive and active security attributes into the reference architecture.

1. Motivation

A broad agreement of the energy sector concerning next steps for evolving the electrical grid into a smart grid, was a motivating starting point for developing a secure reference architecture for future smart grid applications in Austria. Triggered by the *Technology Roadmap for Smart Grids* [1], one of the most pressing concerns addresses the development of an overall ICT architecture for smart grids. These findings are the basis of the current development of the Austrian reference architecture. A first outlook on the attributes of the reference architecture, based on finding of the RASSA stakeholder process project was presented in [2].

In [3], the authors describe in detail for the first time a complete big-picture of the topic smart grid architecture modeling. This paper is describing the progress of the first steps implementing the described recipes.

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2. Traceability in Modeling

Modelling RASSA with the freely available SGAM-Toolbox (www.en-trust.at/SGAM-Toolbox), a clear and traceable interconnection between RASSA, Österreichs Energien Domänenmodell.AT [4], and NIST Logical Reference Model (LRM) [5] has to be deposited in the model. In a fast-paced developing environment such as the smart grid, traceability is a cornerstone of RASSA since the changing security requirements, adding smart components, new market players, or the integration communication technology to previously "blind" components are not just happening once but constantly. A reference architecture has to be able to allow these changes and additions with minimal effort for the involved stakeholders.

2.1 Modeling Implications

The SGAM-Toolbox allows to satisfy the need to adapt the whole reference architecture to core changes, reflecting national or international development decisions, as well as allowing RASSA users inside the SGAM-Toolbox to model, using existing components and their predefined interfaces. As shown by one example component in *Fig. 1*, components in the original appearance of the NIST LRM Distributed Energy Resources (DER)-actor are visible in the upper part in the green box of NIST LRM. Due to the fact, that the Domänenmodell.AT model did not change the role of actors but adapted the naming of the components to match Austrian needs, the name of the component changed in the model. To visually distinguish the components, the Österreichs Energie (OE) logo was placed on the upper right corner of the DER-actor, as can be seen in the light-red box. The RASSA role actor of "Erzeugung und Speicherung von Energie auf Kundenseite" was defined as a physical component during splitting of the NIST-LRM. A new visual representation is introduced, by having a cube as physical object with the RASSA logo on the upper right, to also provide a visual distinction for the actor role not to be mistaken as a DER-actor from either NIST-LRM or OE.

Fig. 1 Traceability of NIST-LRM, Domänenmodell.AT and RASSA in SGAM-Toolbox, own representation

2.2 Tracing Interfaces inheriting Security Requirements

The interface U1 component in *Fig. 1*, placed in the NIST LRM box, is used by the <<realizes>> relationship in Domänenmodell.AT as well as by the RASSA model. This depiction emphasizes the benefit of reusing already existing knowledge, as well as the capability of the SGAM-Toolbox to include proven concepts from other sources, such as reactive security supervision methods for interfaces, possible attack vectors for interfaces, or active security threat analysis results for generic or instantiated specific components.

3. Modeling Progress

For exploring possible risks, it is necessary to describe (high level) use cases in detail. The SGAM-Toolbox already offers its ability to generate UML activity and sequence diagrams, linked to pre-existing RASSA/OE/NIST components in the model, merely through inserting their exact names in a sentence describing a behavior or a necessary action. For example, "DSO sends meter data request to Smart Meter" and "Smart Meter replies sending requested meter data to DSO". using RASSA "Netzbetreiber" instead of DSO defines to inherit all interfaces of the differently modelled actor/component/entity that can be different from the NIST or OE one.

Working through use cases with stakeholders or experts step by step, identifying involved services and components, can reveal potential errors in course of actions and are planned further steps in the modelling phase. Herewith, RASSA is attempting to set a state of the art description of a growing list of use cases relevant for critical infrastructures such as for smart grids in Austria.

Fig. 2 shows an automatically generated sequence diagram of five exemplary chosen use cases modelled by the SGAM-Toolbox. This is the most basic architecture view of any smart grid application, where one actor is connected to one final device, disregarding all intermediary connections and steps necessary in between.

Fig. 2 First five basic system architecture representing Use-Cases Modelled in SGAM-Toolbox, own representation

From this input, the SGAM-Toolbox will be further enabled to automatically generate all intermediary components and connections, suggesting all possible protocol or device instantiations, and exporting a complete system model specification within the existing electrical grid.

3.1 Patterns automating modeling

Patterns allow modeling engineers to automate a tedious manual process. A cyber-physical system such as the smart grid and future applications being modelled with RASSA is prone to human error if security-by-design stops at creating the model and does not consider the modeling process. SGAM-Toolbox assists the RASSA architecture modeling by offering the patterns for:

- communication security requirements
- network security requirements
- system security requirements

These patterns are the first attempt to increase security-by-design during the modeling phase.

3.2 Machine Readable Descriptions

Another benefit of using SGAM-Toolbox as modeling infrastructure for a reference architecture is its capability to export a designed model as machine readable XML files. These files allow specialized software tools to provide additional functionalities such as risk management, using the descriptions provided within the components, connections, or actors.

Detailed descriptions (additionally to their position in the different SGAM layers) can include:

- complexity of the component
- status (approved, implemented, mandatory, proposed, validated)
- requirement specifications with status, difficulty, priority, and stability
- constraints like pre- or post-condition
- relation to risk analysis

The risk analysis schema allows comparison throughout various devices, interfaces, or services co-existing in a modeled smart grid application. For example, a resulting calculated higher estimated “Calculated Risk” value, aggregated over all the used components of the modelled smart grid application suggests, that more effort should be made to counter the possible risks.

To provide a set of risk and security attributes to entities being modelled is one of the benefits the reference architecture provides.

4. Security Attributes

The RASSA project investigates the use of reactive and active security for the detection of attacks on the smart grids.

4.1 Reactive Security in Smart Grids

One very challenging field is the detection and mitigation of data integrity attacks in wide area monitoring protection and control (WAMPAC) applications. Sensors supervise the power grid and their data can be used as input to control decisions. Any tampering with the input data can lead to wrong decisions with potentially critical effects on the power grid.

Classical WAMPAC structures consist of many different elements with different security levels. Sensors in the field (e.g., distributed phasor measurement units) are usually less protected and easier accessible than devices in the control center. Sensors also have to be cost efficient and therefore often do not provide sophisticated security measures.

A takeover of the control center provides the highest value for an attacker but may be hard to achieve. On the other hand, access to sensors in the field may be much easier and can provide a way to influence control decisions. Possibilities to influence higher level control elements depend on the structure of power grids and on ICT infrastructure. The impact of different grid structures to the distribution of malware is discussed in [6]

Other relevant element in WAMPAC structures are data aggregation points (e.g., phasor data concentrators) or classical ICT elements on the path (routers, middle boxes). Gaining access to those allows tampering with multiple sensor data flows.

Several methods have been already proposed to mitigate data integrity attacks in wide area monitoring. One possibility is checking sensor data for consistency with other types of sensor data or data from other locations. Based on static/dynamic state estimation, larger deviations can be identified. But it is difficult to detect small, slow changes (e.g., stealthy techniques by sophisticated attackers) and to detect deviations if multiple devices are compromised or attackers collude. Other possibilities are to secure the aggregation process to prevent any changes during aggregation. One example is to use homomorphic encryption to prevent aggregation devices needing access to cryptographic keys. A third method uses anomaly detection to notice unusual network behavior during an attack or attack preparation. With this it is also possible to detect new previously unknown attacks (e.g., due to zero-day exploits). An overview of potential attack vectors for wide area monitoring structures and on currently proposed mitigation strategies is provided in [7].

Currently protocols used for grid control are under investigation and further supervision methods for the WAMPAC communication network are being researched.

4.2 Active Security in Smart Grids

Currently threat modeling approaches connected to the first RASSA use cases are to be evaluated. To base later security tests with real products on established standards, security auditing requirements have been defined, based on ISO/IEC 1508 (Common Criteria). The possible analysis methods range from general (high level analysis, attacker classification, low level analysis) such as passive sniffing of protocols and data or active port scan, replay attacks, or fuzz testing, up to advanced analysis techniques such as:

- probing
- side-channel attacks (e.g., power analysis)
- fault injection (e.g., voltage glitching)
- analysis of integrated circuits (e.g., decapsulation, delayering/deprocessing, microscope imaging, reverse engineering)

5. Summary and Outlook

This paper described the work in progress concerning the modeling of the RASSA system architecture based on the SGAM-Toolbox, taking into account potential security attributes for reactive and active security investigations.

Next steps will be to include the ENTSO-E market role model as potential business actors, matching e-control actors in the reference architecture, increasing the modelled components of the current energy system, and linking existing interfaces to all models to serve as a blueprint for stakeholders to model their new smart grid applications compatible to existing infrastructure, while relying on interface-wise defined requirements on all reference architecture components to provide security.

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iNIS integrated Network Information System

Daten-getriebene Methoden für Netzplanung und Netzbetrieb

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Abstract – integrated Network Information System soll als Synonym, für die immer größer werdende Rolle von digitaler Daten und Informationen für Unternehmen im Bereich elektrischer Netzinfrastruktur, stehen. Historische und auch Echtzeit Daten von Zählern und Sensoren ermöglichen Einsicht in verschiedenen Bereichen bei wichtigen Prozessen wie Netzplanung, Verwaltung von Betriebsmitteln, Netzbetrieb sowie Kundensystemen, wodurch diese optimiert werden können. Anforderungen für den Umgang mit großen Mengen an Daten und die Potentiale zur operativen als auch Kosten-Effizienzsteigerung von Prozessen wird an Hand von Anwendungsfällen vorgestellt.

1. Motivation

Die steigenden Verfügbarkeit von Messdaten (z.B.: Smart Meter und Sensor Daten) ermöglicht eine bessere Kenntnis der Netzzustände. Hintergrund und Treiber sind einerseits die Digitalisierung der Energieverbrauchserfassung durch elektrische Zähler, aber auch die Notwendigkeit über genauere Kenntnisse von Vorgängen und Zuständen des Netzes bei steigender Anzahl von erneuerbaren Energietechnologien. Die Menge und Durchsatz von Daten erfordert aber auch neue Methoden der Speicherung, Verarbeitung und Analyse der eingehenden Messdaten. Die Digitalisierung und der Trend zum Betrieb von Informationssystemen erfordern daher Änderungen und Erweiterungen der IT-Strukturen von Energieversorgungsunternehmen.

1.1 Analyse großer Datenmengen und damit verbundene Herausforderungen

Die in anderen Bereiche etablierten Analyse- und Verarbeitungsmethoden großer Datenmengen (‚Big Data Analytics‘) steht 6 Herausforderungen gegenüber [1]:

- Komplexe Datenstrukturen und –modelle
- Hohe Dimensionalität der Daten
- Hohe Anzahl von verschiedenen Datenklassen
- Schwache Zusammenhänge
- Unskalierbare Verarbeitungsmöglichkeiten
- Unsicherheit und Uneindeutigkeit, bzw. Daten Konsistenz

Damit verbunden sind Strategien und Methoden der Daten Analyse genannt:

- ‚Teile und Herrsche‘
- Parallelisieren
- Inkrementelles Lernen
- Abtastung, Stichprobenprüfung
- Granulare Verarbeitung
- Merkmalauswahl
- Hierarchische Einteilung und Klassifizierung
    - o Herausforderungen an die Daten-zentrierte Digitalisierung in der Energietechnik

Netzbetreiber als auch andere Unternehmen der öffentlichen Stromversorgung, wie Händler, Energielieferanten, Marktakteure oder Stadtwerke sehen sich folgenden Herausforderungen gegenüber:

- *Handhabung großer Datenmengen*: speziell Speicherung und parallele Verarbeitung, sowie kostengünstige Aufbewahrung historischer Datenmengen (‚data lake‘), die Möglicherweise zu späteren Zeitpunkt analysiert werden, bzw. Fragestellungen zum jetzigen Zeitpunkt noch nicht existieren.
- *Vorhandene, funktionierende IT Strukturen und unterschiedliche Datenbanken (‚Silos‘)*: Existierende Systeme sind sorgfältig aufgebaut und funktionieren zuverlässig; Erweiterungen sind Eingriffe in den Betrieb. Auch bereichsübergreifende Abfragen wären denkbar, die aufgrund regulatorischer oder bedingt durch die Konzernstruktur getrennt sind.
- *Konsistenz der Datenhaltung und Integration der Datenstrukturen:* Oft werden die Daten parallel gehalten, da unterschiedliche Anwendungen verschiedene Anforderungen an den Umfang oder Details haben. Der Aspekt der Datensicherung (Backup) verbergen sich aber meist Inkonsistenzen.

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- *Anwendung neuer daten-basierter Verfahren:* Integration in die täglichen Arbeitsprozesse, bzw. deren Adaptierung ist oft ein schwieriger Innovationsprozess, der aufgrund von Zeitdruck oder der Angst vor Neuem nicht umgesetzt wird.
- *Visualisierung sowie interaktive Darstellung für explorative Methoden:* Komplexe Ergebnisse und Zusammenhänge so darzustellen, dass sie wesentlichen Informationen verständlich kommunizieren ist ein notwendiges Kriterium für den Erfolg. Integration in bestehende Werkzeuge (z.B.: Geographische Informationssysteme - GIS), anstatt einer neuen Anwendung, kann die Akzeptanz verbessern.
- *Neue Technologien und Umstellung der Datenverarbeitungssysteme:* Vernetzung und Rechenleistung ermöglichen Konzepte wie verteilte Systeme und ‚Cloud-Services', die effizienter sind, deren Zuverlässigkeit und Sicherheit sich bewähren müssen.
- *Investitions- und Kosten für den Betrieb der IT Systeme*: Komplexität und Migration der Systeme müssen besonders im Zusammenhang mit dem möglichen Steigen operativer Kosten durch Infrastruktur und zusätzlichem Personal darstellbar sein. Kleinere Sondierungsprojekte und Studien sind größeren Investitionen möglicherweise vorzuziehen.
- *Neue und zukünftige Forschungsfelder:* Vorbereitung für die zum jetzigen Standpunkt noch nicht absehbaren Möglichkeiten müssen bedacht werden.
-

1.2 Zukünftige Anforderungen und Handlungsfelder

Das Committee on Analytical Research Foundations for the Next Generation Electric Grid des National Academies of Science (U.S.) hat kürzlich den Handlungsbedarf für zukünftige Forschungsschwerpunkte im Bereich der statistischen Analyse für Energiesysteme veröffentlicht [2]. Unter anderen wird empfohlen mathematische und numerische Methoden auf Basis belastbarer realer Daten, bzw. synthetisierter, realistischer Daten zu entwickeln (Empfehlung 3 und 4). Des Weiteren wird empfohlen Forschung im Bereich anwendungsorientierter, daten-getriebener, analytischer Methoden (z.B.: Maschinelles Lernen, Klassifizierung, Clustering, prädiktive Modelle, Visualisierung) zu forcieren (Empfehlung 7). Die Integration dieser Methoden mit anderen Feldern im Bereich Regelung und dynamischen Systemen, sowie deren Anwendbarkeit und Koordination zwischen Forschung und Industrie, mit Labor- und Kompetenzzentren steht im Vordergrund (Empfehlungen 5, 10-12).

Europäische Initiativen wie ‚Digital Europe' [3] oder ‚(Energy) Big Data Europe' sehen ähnliche Chancen und Möglichkeiten im Bereich Energie. Hervorgehoben sei hier die auch im Projekt verfolgten Ziel für ‚Supporting Low Voltage distribution network operation' - Monitoring, Spannungsregelung, Optimierung, Netzzustandsschätzung und Analyse, sowie der Support für optimale Integration von erneuerbaren Energieträgern [4].

2. Beispiele für Anwendungsfelder

Im Folgenden werden die im Projekt iNIS behandelten Daten-basierten Methoden für unterschiedliche Unternehmensbereiche und deren Anwendung und mögliche Nutzen und Vorteile vorgestellt.

2.1 Netzplanung – 'long term forecasting'

Der massive Ausbau von Photovoltaik erfordert eine kosteneffiziente Integration von erneuerbaren Energieträgern. Zuverlässiger Netzbetrieb und neue Methoden für einen aktiven Verteilnetzbetrieb erfordern auch entsprechende Planungsmaßnahmen und deren Analyse. Die wachsende Anzahl von Sensoren in den Netzen (wie z.B.: für die Erfassung von Strömen und Leistungen in Netzabschnitten und Strängen) liefern wertvolle Informationen für die Netzplanung, wie z.B., Anschluss von neuen Lasten oder Erzeugern. Annahmen von Leistungsreserven können durch genauere, datengestützte Trends abgelöst werden, wie z.B.: Planung von Netzausbau. *Abbildung 1* stellt Leistungen eines elektrischen Netzes dar. In der ersten Phase (Pa) treten im Durchschnitt wesentlich höhere Leistungen auf, was eine unsymmetrische Belastung zur Folge hat.

Abbildung 1: Exemplarische Häufigkeitsverteilung der Wirkleistungen je Phase für einen Netzabschnitt.

Diese Informationen können verwendet werden, um Planungsprozesse für z.B.: für Reserven zu ermöglichen. Verbesserung der Genauigkeit gegenüber Standard Lastprofilen durch Aggregation der Smart Meter Daten erfassten Haushaltsprofile wurde in [5] untersucht.

2.2 Forecast – 'mid term forcasting'

Aufgrund des Wandels von reinen Verbrauchern zu Erzeugern ('Prosumer') ändert sich, die als statistisch aggregiertes Standard Last Profile bekannte, Charakterisierung von Haushalten. Dieses statistische Model gilt für eine größere Anzahl, wie z.B., auf Ortnetzebene. *Abbildung 2* zeigt die für einen Tag aggregierte Charakteristik der Jahreszeitreihen von ca. 40 Haushalten ohne Erzeugung als Verteilungen für jedes 15 Minuten Intervall. Die Darstellung als Boxplots repräsentiert die Verteilung der einzelnen Werte innerhalb eines Intervalls. Dem gegenübergestellt sind in *Abbildung 3* dieselben Haushalte unter Berücksichtigung der PV Erzeugung dargestellt. Es ist notwendig, dass diese Änderung der Charakteristik in den Planungsprozessen berücksichtigt wird, wie z.B., der Umkehr des Leistungsflusses.

Abbildung 2: Tages-Charakteristik und statistische Verteilung (Boxplots) von ca. 40 Haushalten (ohne PV)

Abbildung 7: ... i11(N(IS)6(U)5(dS)6anode)9(ne)9(s)6(k)-1(t)5(i)5(v)5(i)-5(t)-5(ä3)-5e435n(g)5(s)2(t)5(u fh)6
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Abbildung 3: Charakteristik und statistische Verteilung (Boxplots) von ca. 40 Haushalten (mit PV)

Historische als auch Echtzeit-Messdaten ermöglichen die Vorhersagen für den Zeithorizont von einen oder mehreren Tagen zu verbessern.

2.3 Netzbetrieb – ‚short term forecasting'

Für den, vorher angesprochenen, aktiven Betrieb des Niederspannungsverteilnetzes kann es notwendig werden neben dem Monitoring des Netzzustandes auch Regelungsmaßnahmen einzuleiten. Dezentrale Strukturen (‚Cloud-Edge Architecture') für die Verarbeitung und Speicherung von Messdaten innerhalb der Niederspannungsortsnetzstationen ermöglichen den zuverlässigen Betrieb mit zentraler Überwachungs- und Eingriffsmöglichkeit. Dabei werden Daten lokal verarbeitet und gespeichert und nur aggregierte Daten bzw. Meldungen weitergeleitet um die Komplexität und Datenmengen zu reduzieren.

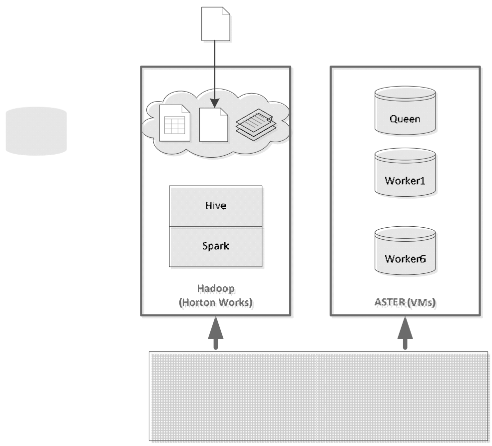
Abbildung 4 zeigt exemplarisch Echtzeit-Daten eines Sensors (Grid Monitoring Device) die zur Überwachung oder Analysemöglichkeit abgefragt werden können.

Abbildung 4: Zeitreihe der Leistungen eines Sensors (Grid Monitoring Device)

Ein wesentliches Konzept für die automatisierte Verteilung und Ausführung von Anwendungen für den aktiven Netzbetrieb werden derzeit im Projekt iNIS und auch Smart City Demo Aspern entwickelt und getestet.

Das Konzept des ‚Application Provisioning' ist in *Abbildung 5* dargestellt. Abhängigkeiten und Voraussetzungen der einzelnen Anwendungen (‚Apps') werden vom System automatisch aufgelöst und installiert.

Dateisystem basierend auf ‚GlusterFS‘, einem verteilten Speichersystem für Daten Analyse und Bandbreiten-intensiven Rechenaufgaben. Das Netzwerk basiert auf ‚Infiniband‘ Technologie und garantiert sehr hohe Bandbreite und Geschwindigkeit. Das Basissystem der Knoten unterstützt offene Virtualisierung für hoch-flexible Verarbeitung und parallele Anwendungen, welches für Daten Analysen notwendig ist. Das System unterstützt verschiedene Explorationsmethoden, basierend auf unterschiedlichen open-source Anwendungsumgebungen (z.B.: Hadoop Ecosystem). Teradata/ASTER, eine analytische, verteilte Datenbank ist im Rahmen von iNIS im Betrieb. In Verbindung mit parallelisierten Funktionen (MapReduce) – z.B.: via Java/Python/R – können Netzdaten hoch-performant analysiert werden. Virtuelle Arbeitsrechner und deren Daten Analyse Software unterstützen verschiedenste Anwendungen für die Datenverarbeitung (z.B.: Anaconda-Python, Eclipse, Teradata Studio) und bieten Zugang zu verschiedenen anderen Datenbanksystemen. *Abbildung 6* zeigt eine Übersicht des Labs.



Smart Grid Cyber-Security Simulation Environment

Norbert Wiedermann ˜Mislav Findrik

Abstract – The current power grid is going to be extended with various field devices, which will under the control of the Distribution System Operator (DSO) be responsible to efficiently handle the demand and supply of electricity. This new system requires more interconnected ICT components than there are now, in order to collect all necessary measurement values to perform grid control operations in a fast and effective way. Before deploying new infrastructure and control functionalities it is important to understand the risk associated with potential cyber-attacks. Hence, it is very important to assess the impact cyber-attacks might have on the electrical grid and dependent infrastructure, in future smart grid scenarios. In this work, a software-software co-simulation environment for the impact assessment of cyber-attacks is presented, together with software/Hardware-in-the-loop (HIL) conceptual realization of a testbed environment dedicated for development and evaluation of security countermeasures.

1. Introduction

Today's power grid is controlled with support of ICT systems. These ICT systems are operating in closed environments where the operators are in full control of their hardware and software components. However, such closed ICT systems are being extended to allow interconnection of renewable energy resources and other field devices. The evolved ICT system shall perform new grid control operations in a fast and effective way. The control operations firstly need to be validated using appropriate tools and also underlying risk associated with potential cyber-attacks needs to be well understood.

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In this work we present a simulation environment for impact analysis of cyber-attacks on future smart grid control scenarios. Impact assessment in simulation environments is important for early identification of potential critical vulnerabilities of novel control concepts and it is a helpful step towards understanding and identifying risks arising from new infrastructures. Since comprehensive investigation on real world power grid is neither feasible nor cost effective, simulation and hardware-in-the-loop environments offer a good approach to quantify effects a cyber-attack could have on a particular Smart Grid setting. In this work, four building blocks are introduced, describing the key components necessary to model a Smart Grid environment. With those blocks, the challenge of establishing a model of Smart Grid is split in smaller parts, which are already available and can be further used in combination with cyber-attack models to perform an impact assessment analysis.
This paper is organized as follows: in Section II the conceptual building blocks are described. Section III describes a co-simulation framework that instantiates the conceptual building blocks via co-simulation environment, while Section IV introduces a Hardware-in-the-Loop (HIL) concept for testbed realization. Finally, Section V gives an example of an integrity attack on a low voltage grid constructed in our co-simulation environemt..

2. Conceptual Simulation Environment

A future power grid will consist of many different devices which are going to be seamlessly integrated into a Smart Grid. This will be very complex systems and it is necessary to get an understanding how different subsystems will react in case they are targeted by a cyber-attack. This section presents a general concept of building blocks which are seen as components necessary to construct any type of Smart Grid environment for evaluation of cyber-attacks.
Four building blocks are identified in Fig. 1, which describe the essential parts for developing such a simula-

tion environment for a smart grid. On the one hand, a power grid model together with an according data network model is required to describe the physical part of the smart grid environment.

Fig. 1 Building blocks of security simulation environment.

Realizing a **power grid** block within the environment for analyzing cyber-attacks on Smart Grid infrastructures can be achieved in different ways. One could use real power equipment hardware such as voltage regulators, transformers or controllers and interconnect them with a power grid modelled in software. This approach is denoted as HIL and it is discussed in more detail in Section 4. Another option is to model the whole power grid and related components in software and use a simulation environment to evaluate the power-flow for different time intervals.

A **data network**, like the power grid, can be realized using software simulators (NS-3, OMnet++, etc.), using a real hardware, or in some other way (e.g. emulation).

Attacker actions can be modeled using predefined **patterns** that described how an attacker is influencing particular control loop. For example, he could learn about the available consumers in the power grid and identify those with a constant load. By analyzing the exchanged messages he could find trigger points that cause these consumers to draw power from the grid. With this information, he could then switch these loads on and off in a periodical manner, and to give an edge to it, even during peak times each day.

Like the attacker, a **consumer** can also be modeled using different consumption **patterns**. By using reference load profiles the power consumption of typical end user appliances can be mapped quite easily. Such profiles contain the amount of consumed electricity over a period of time in fixed time intervals. Usually, a one day period is described in intervals of one minute. In case this information is available for the region of interest in an anonymized way, real world load profiles can be used. A more general approach would be to use constant or random load models.

The core components of the conceptual simulation environment are **Power grid** and **Data network** building blocks, which need to be jointly connected to build a simulation backbone, that can further allow usage of **consumer** and **attacker pattern** blocks on top of them. In the following sections, we present two frameworks that exemplify software-to-software and HIL-to-software realization of the backbone simulations.

3. Co-simulation Framework

In this section a realization of software-to-software co-simulation environment is described.

For simulation of power grids there are several open-source and commercial tools already available [1]. We have used gridLAB-D [2] simulator since it is well established and well tested. For simulation of the data network OMNeT++ framework [3] is selected, since it is also open-source software and free for non-profit use, and by that easy to get started for research.

The two software simulation frameworks are interconnected with a scheduling and information exchange environment (see Ref. [4]). The control sequence of the co-simulation scheduler governing the two simulation framework is depicted in Figure 2.

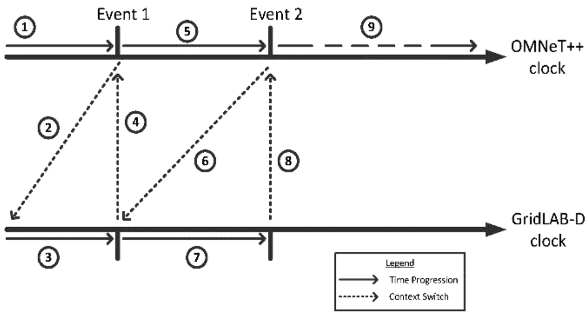

Figure 2. Simulation environments are executed asynchronous based on events in the simulated data

The co-simulation consists of two applications addressing the power grid domain (gridLAB-D) and the communication domain (OMNeT++). The sequence of execution steps according to Figure 2 is:

1. Determine the stop time for the power grid simulation step based on the time the event is triggered by a received message.
2. Update the power model with the new stop time and switch to gridLAB-D for next step.
3. Perform the power grid simulation until the provided stop time is reached.

4. Gather generated information and update the communication model. Switch to OMNeT++ to run next step.

5. Update start time of new power model for next power simulation step.

6. After "Event 2" was triggered by a received message, the according stop time is used to update the power model.

7. In the power grid simulation the next simulation step is executed.

8. Derived information is again passed back to update the communication model.

9. These steps are repeated according on the incoming events on the communication network until the simulation is finished.

Considering this sequence the asynchronous property gets clear. The power grid simulation is always one time step behind the simulated communication network. Each step generates files recording the changes during this simulated time step which are used to analyze the values afterwards. This decoupling of the two environments also supports a distributed approach where each environment can be executed on a dedicated computer.

4. HIL Framework

This section is describing a testbed environment that uses a software simulation of the power grid and a hardware-in-the-loop realization of the data network. The testbed environment is called Smart Cyber-Grid Security Lab or shorter SmartSecLab. The SmartSecLab allows cyber-security analysis by enabling the integration of data network hardware-in-the-loop components (e.g. real network switches, routers, etc.) together with the power grid simulation in a coherent facility for analyzing cyber-attacks.

The SmartSecLab platform is based on the SMB [5], a flexible software tool that allows loose interconnection of various building blocks in the general security simulation environment. The SMB allows creation of stacked proxies that allow connection of different modules (see Figure 3). The SMB is integrated with a power grid simulation tool called DIgSILENT PowerFactory [6] for power grid simulations. The DataLab proxy (DL) are testbed modules that are on one side connected to the SMB, thus also to the grid simulator, and on the other side they communicate with the grid controller located in the Data Network lab. The Data Network lab can be realized using real networking switches and routers or it can be emulated.

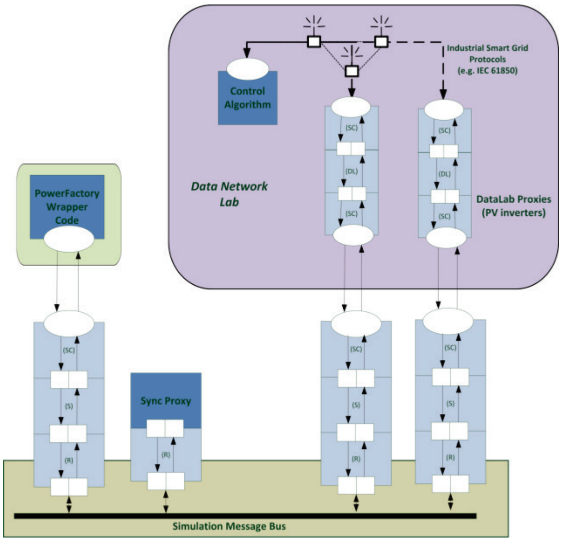

Figure 3. Realization of the SmartSecLab using the SMB framework.

5. Case Study on a Low-Voltage Grid

In this section we show an example by instantiating the building blocks on top of the co-simulation environment and show how impact of a cyber-attack can be analyzed.

The power grid is realized with a simulation based on the IEEE low voltage reference grid [7]. The topology of the feeder is a radial distribution and the network is connected to the medium voltage system through one transformer in a substation.

The developed communication network (Figure 4) is modelled to meet the introduced structure of the power grid. Each load in the power grid model is represented by a household in the data network model. The households are grouped into streets in the same manner as the loads are grouped in the power grid model. A central control station is responsible to route the control commands (e.g. price update messages) through the communication network to the households.

Figure 4. Omnet++ model of the communication network

In the power grid there are 55 loads. Their power consumption is modelled by a time series for the period of one day.

The considered attacker in this instantiation is capable of interfering with the transmitted messages in the communication network. He performs a MITM attack on the exchanged price messages between substation control center and the smart meter in the houses. By this, he is in the position to influence the behavior of the smart meter. Coincidentally, the attacker learned that a price threshold exists in the power grid and as prices announced by the substation fall below this value, all smart meter attach additional load to the grid (see Figure 5).

Figure 5. Attack profile example

Further, we show how such attack patter on of the load profiles can influence the bus voltage. In Figure 6, it can be see that the attack causes voltage drops on a voltage bus. The mmeasured voltages drops can be subsequently mapped to the impact level and describe effects for quality of supply. Impact levels can be used for further risk assessment.

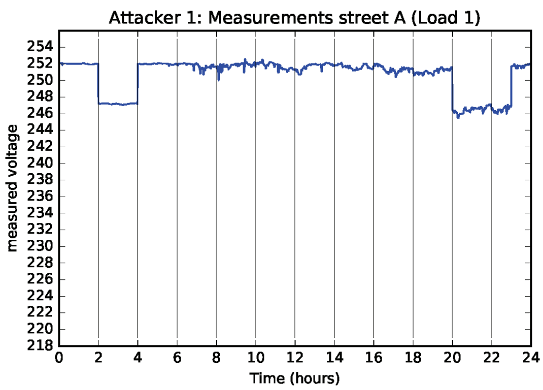

Figure 6. Effect of the cyber-attack on a bus voltage

Acknowledgements

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INTEGRA

Integrated Smart Grid reference architecture of local intelligent distribution grids and virtual power plants

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Abstract – INTEGRA explores how influential a safe and stable system operation in the presence of a large number of mutually interdependent and smart grid services can be organized taking into account the European energy markets. Against the background of different frameworks of policy and regulation it is necessary to reconcile the requirements of various markets with local network conditions. Results are available as a largely standardized Smart Grid Reference Architecture and a "unifying" instance, the "Flexibility operator". Thus, a concrete basis for the necessary discussions and next steps set up and strengthened the strategic positioning of Austria at the European level.

1. Introduction

INTEGRA addresses a central issue in the implementation of smart grid approaches: How can safe and stable operations of intelligent medium and low voltage networks be organized, taking into account a variety of influences of mutual and interdependent smart grid services and at least the actual regulations of European Energy markets? Objective is to prepare the target system of the Smart Grid Model Region Salzburg (SGMS), and to guarantee a homogeneous and efficient operation of the power system (market AND network requirements) on the basis of a single Smart Grid Reference Architecture. INTEGRA develops an internationally visible Smart Grid Reference Architecture, which allows to bring the requirements of the common European market and the nationally authorized, individual schemes in the market system in line, considering a special focus on security and privacy policies by design.
Another goal of INTEGRA is the "missing link" in the form of a toolbox (e.g., interfaces, software modules, ...), to develop the relationships between the different smart grid applications and to provide them for the market. With it the integrated application of smart grid functionality will be enabled, as soon as the relevant applications are feasible from an economic perspective. Technically, the project defines and develops among other things a Flexibility Operator (FlexOP) which was also tested as a proof of concept in SGMS. Thus, organizational and technical interaction of the grid and market-specific processes of the smart grid are made possible. The findings of this project and the transnational cooperation will strengthen the strategic position of Austria in standardization bodies and in the debate at the European level in the aforementioned subjects. Clear recommendations for policy and regulation as well as for the standardization work are derived.

2. Conclusions

2.1 SGAM based Smart Grid modelling and reference architecture

As part of the INTEGRA project, a concept for the model based on the development of smart grid systems has been realized. Moreover, this concept was applied in the

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modeling of a reference architecture. Particularly noteworthy is that this reference architecture demonstrates the integration of the US "NIST Logical Reference Model" and the European "Smart Grid Architecture Model". In INTEGRA, the best of both worlds has been combined. A significant contribution of SGAM is the context (the reference system) for the display of smart grid system architectures. The NIST LRM is characterized by a specific reference architecture with an integrated and expandable security concept. The integration of these two concepts in both the SGAM Toolbox as well as in the modeled system bridges the gap between conceptual activities of standardization and practical application in projects. In addition, it points to a path of a holistic development system: it allows bridging the boundaries between domain experts on the one hand and technology experts on the other side. This approach is a feasible way towards "domain-specific systems engineering" which allows to see smart grids as a whole - which in turn is an essential prerequisite for the implementation of Security by Design.

The approach in its current form provides promising concepts, and it could attract attention in the community. It can be concluded that the implemented design is a step in the right direction, but many more are needed. In addition to a stronger integration of different standardization activities (for example NIST and SGCG), on the side of applicability there are still improvements to be made. Further work on these issues is necessary to refine the concepts presented and to assist with current tools. Moreover, it was visible in this project that besides the technical interface between "Grid" and "ICT" there is also a gap in the human interface between "domain experts" and "technology experts" which has to be closed.

Developed as part of the INTEGRA project concepts, especially the architecture modeling and the developed reference architecture model are already further developed in subsequent projects. The modeling approach will be further researched and developed in the Josef-Ressel Centre at FH Salzburg. Since 2015 SIEMENS CT Munich is a partner at JRZ, where an explicit focus is put on this issue. In addition to the theme of "applicability" the investigation of architectural models based on KPIs is being prioritized.

The developed reference architecture is also further used. In the project "RASSA Architecture" on this basis on a generalized Austrian reference architecture is worked. Here the deficits identified in this project will as a first step be addressed and will then be carried out on the basis of the Austrian "domain model .AT" an instantiation for Austria.

Based on the findings of the INTEGRA project different recommendations can be given. In addition to specific recommendations for the integration of different standardization activities as well as individual technical recommendations (extension of SGAM concepts to dependability aspects, integration of interfaces with power system analysis tools, ...) a recommendation on education and training has been made. Here training offers in tertiary education are required, making it possible to build a bridge between domain and discipline experts. For example, in the form of ICT Master courses for experienced energy experts or energy master courses for experienced ICT experts. Moreover, it would be desirable to place more emphasis on systems thinking (keyword "Systems Engineering") in various configurations to connect the human interface between ICT and energy.

2.2 Coordinated Voltage Regulation

A purely technical comparison of the studied control strategies without considering economic aspects is of limited use, because the solutions examined differ significantly in CAPEX and OPEX. The results of this case study cannot be generalized, nevertheless, some lessons can be learned from the case study:

‡ 7KH QHHG IRU FRQWURO LQ WKH C both PV-reactive-power-control as well as on-load-tap-changer- (OLTC) regulation over the entire considered medium voltage network is very low. If wide-area-control in primary substations optimizes the voltage level across the medium voltage network, the coordinated operation with Q (U) control is only active in a very few low-voltage networks. This is a result of the significantly higher degrees of freedom of the coordinated control.

‡ $ FRPELQHG YROWDJH UHJXODWLRQ -voltage and low-voltage-level does not necessarily lead to a significant increase of the reactive power flows in the grid.

‡ 7KH UHDFWLYH SRZHU FRQWURO D in voltage level has a positive influence on the voltage situation on the other voltage level. This means that both, a reactive power control in the LV shows a positive impact on the voltage in the MV, as well as a reactive power control in the MV has positive effects on the voltage in the LV.

‡ 7KH VLPXODWLRQ UHVXOWV in- GR QR crease in the network losses by a cross-level voltage regulation.

‡ ,I WKH LQWHJUDWLRQ RI SKRWRYRe ously distributed over the entire medium voltage network, a very high density of PV systems can be achieved.

‡ $ FRV3KL 3 FRQWURO OHDGV WR power flows than a Q (U) control. In the case study network, the same voltage-decreasing effect can be achieved with a Q (U) control when less reactive power flows were necessary.

‡ $GYHUVH LQWHUDFWLRQV EHWZHHQ XQFRRUGLQDWHG UHDFWLYH power control and tap changer control were analyzed in a stability study. The result of this study was that adverse interactions can be largely avoided by a sensible parameterization of all control components which adapted to the respective network parameters. One way to exclude unwanted interactions can be the use of coordinated control approaches.

2.3 Flexibility Operator

In INTEGRA a market-based approach for the coordination of market and network called Flexibility Operator (short FlexOP) was developed. This approach was designed based on the traffic light model and in accordance with a specially designed regional flexibility market, which could allow a future market-oriented distribution network operation.

The basic applicability of the approach has been demonstrated by simulative Proof-of-Concepts. A clear explanation of the tasks and operation of Flexibility Operators can be accessed http://www.siemens.at/flexop on the website.

Based on the proof-of-concepts a FlexOP and subsequently a prototypical Flexibility Operator platform were implemented in the context of an intelligent secondary substation. For testing the prototypes were combined with the Smart Grid Co-simulation framework mosaic. This coupling allows the test of the FlexOp in different network scenarios and applications with a variety of system elements. Even in the case of the Flexibility Operator platform the applicability of the approach has been successfully demonstrated. The functionality of the Flexibility Operator platform will be further developed in subsequent projects with other forms of interference and other market models and will be tested in the field. Also there are plans to extend the approach to smart contracts and block chains for a better verification of the compliance of the negotiated contracts.

2.4 Building Energy Agent

The Building Energy Agent (BEA) is a key component in an intelligent building, it is based on supply- and load-forecasting to optimize the energy use in buildings. On the other hand the BEA raises flexibility potentials, forwards them to the FlexOP and realizes flexibility requirements from FlexOP by adjusting the current energy use plans.

For the proof-of-concept considered in the project, these properties of BEA were simulated and tested in a laboratory environment. Another goal of the project was also to complete the BEA which is used in the field with requirements developed in INTEGRA.

These changes have been very challenging, even when a suitable software base in the form of OpenMUC of Fraunhofer ISE was found. The planned improvements and enhancements were implemented. Moreover, some extensions to start preparing for the already launched follow-up project "LEAFS" have been implemented. The completion of this work and a detailed field test will be conducted in this follow-up project.

2.5 Economic evaluation and conditions

The economic evaluation of the use of a flexible operator in combination with virtual-power-plants (VPP) strategies in the case study Köstendorf showed that the cost benchmark of an implementation for an observation period of 50 years was a few euros euros or in an ideal case a few hundred euros.

From the technical side equalizing effects of load and generation in the regional existing network infrastructure were observed and due to the existing planning approaches network restrictions therefore only occurred in very few cases. This resulted in a lower utilization of the FlexOP-concept and correspondingly in low profit margins due to few interventions and little amounts of lost energy that would have been traded by VPPs.

To achieve cost parity compared to reactive power control the loss of income on the tertiary control energy market caused by the flexibility operator must have been much higher. However, these market price developments have not been foreseeable. These results are of course linked to the case study and cannot be generalized.

A local active power limitation seems to be the most cost effective solution for PV integration in the considered case study. When an appropriate and cost-effective communication- and controller-infrastructure (driven by other applications, for example smart metering or DSM) is available in the future, the use of Flexibility Operator concepts can possibly avoid active power limitation for small producers and loads.

Future research should focus on larger loads and buildings (for example the flagship project of the Seestadt Aspern) and possible economies of scale.

Based on a position paper the following positions on Network State Estimation, Re-Dispatch, the provisioning of network services and the establishment of regional market platforms are noted:

‡ $SSURSULDWH QHWZRUN DQDO\VLV combination with state estimation in the low-voltage-level can avoid network restrictions by scheduling changes through the market players. The frequency of occurrence of local network restrictions caused by decentralized virtual power plants is a decision criterion for the use of state estimation. At the moment state estimation is only required in selected network areas because of alternative solutions (for example reactive

power control of inverters). Nevertheless, state estimation currently provides a very good cost/benefit ratio for the grid integration of decentralized generators. The future potential of state estimation solutions is limited because it is difficult to estimate future price developments on the energy markets.

‡ $ “Dispatch” in the distribution network is indeed conceivable in principle but many questions remain unanswered. This mainly concerns the relationship of costs and benefits of such a method and the question of the possible allocation of costs. In individual cases this can currently be solved by individual contracts and recourse to the experiences in the transmission networks.

‡ $ IXWXUH PDUNHW PRGHO XVLQJ H[LVWLQJ GHFHQWUDOL]HG power reserves and flexibility on the producer and consumer side has to pass necessary schedule changes to the parties concerned (for example, balancing groups) in time. The temporal resolution of the data transmitted must be adapted to the current market conditions.

‡ ,Q JHQHUDO WKH HVWDEOLVKPHQW RI VPDOO PDUNHW VHJPHQWV and traded services is difficult, especially with regard to market liquidity and existing risks for the players.

Acknowledgements

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Optimization of multi-carrier energy systems using an FMI-based co-simulation approach

Edmund Widl

Abstract This paper presents a software prototype for the model-based design of multi-carrier energy systems. Using a tool-coupling approach based on the Functional Mock-up Interface (FMI) speci cation, a modular and exible framework has been implemented that enables a detailed analysis and optimization process. The implementation of this software prototype is discussed and its applicability is demonstrated with the help of a use case.

Keywords multi-carrier energy systems analysis and optimization co-simulation Functional Mock-up Interface (FMI)
Di erential Evolution

1 Introduction

Innovations in today's energy systems are mainly driven by the need of reducing their carbon footprint and the integration of decentralized renewable energy sources. A transition towards multi-carrier energy systems is expected to help within this context, as the integration of di erent energy domains promises the exploitation of hitherto unused synergies.

However, traditional simulation tools and models are typically focusing on only one respective energy domain. They are thus not capable of properly describing multi-carrier energy systems in detail (including their controls), which is an important prerequisite for a suitable design process and optimized operation. Tool coupling approaches (co-simulation) provide a promising alternative, facilitating the detailed assessment and optimization of the interactions between the various domains for an in-depth evaluation of the actual synergy potentials.

This paper presents a prototype implementation of such a tool coupling approach, relying on established methods and tools where available and extending the state-of-the-art where needed. Furthermore, the applicability of the Functional Mock-up Interface (FMI) speci cation within this context is demonstrated, which facilitates modularity and exibility with regard to the utilized models and tools.

The remainder of this article is structured as follows. Section 2 discusses the co-simulation environment used in this work. The integration of an optimization algorithm into the co-simulation environment is explained in Section 3. Section 4 presents the application of the software prototype to an example comprising a hybrid thermal-electrical energy system. Finally, Section 5 summarizes the ndings and closes with an outlook.

2 Co-Simulation of Multi-Domain Energy Systems

Within the context of multi-domain energy systems, the deployment of a tool coupling approach enables domain experts (e.g., thermal, electrical and controls) to use the most appropriate tools for their respective domain. This enables an adequate and precise representation of not only the individual domains but also the complete system.

Within the context of this work, the FUMOLA [1] environment has been used [6]. FUMOLA is speci cally designed to support the features o ered by the Functional Mock-up Interface (FMI) speci cation [1], which de nes a standardized API and model description for

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1 See http://fumola.sourceforge.net/

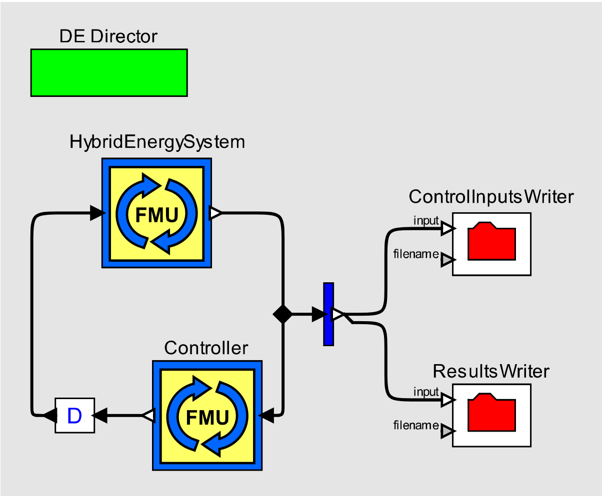

Fig. 1 Graphical representation of a co-simulation model.

both co-simulation and model exchange. FMI has been selected as it is a non-proprietary, industrial strength specification, developed by both academia and industry.

FUMOLA is developed on top of the Ptolemy II simulation environment [2], utilizing the FMI++ library[2] for handling FMI-based co-simulation components. Ptolemy II's focus on the simulation of concurrent processes as well as its capabilities regarding hierarchical and heterogeneous modeling make it an ideal foundation for a co-simulation environment. By enhancing it with the high-level FMI-based utilities of the FMI++ library, FUMOLA provides a state-of-the-art co-simulation framework that is applicable to a wide variety of applications.

Fig. 1 shows the graphical representation of a co-simulation model as seen by a modeler using Ptolemy II's graphical user interface. It depicts a typical closed-loop control system model as used for the example presented in Section 4. For details explaining the functionality of the individual blocks in this model please refer to [5].

3 Optimization of Multi-Domain Co-Simulation Models

Given a system layout with certain degrees of freedom and a design criterion represented by a scalar objective function, the goal is to determine the set of values for these degrees of freedom that minimize the objective function. For energy systems, degrees of freedom could typically be related to the sizing of components (e.g., storage capacities or power ratings) or controller set-points (e.g., gains or thresholds). The objective function maps certain technical and/or economical aspects of the overall system to a numerical scalar value, with smaller values indicating a more desirable performance of the system than higher values. In the case of multi-carrier energy systems, objective functions typically relate aspects of the overall system that are traditionally treated by different engineering domains. Furthermore, objective functions may evaluate effects that result from dynamic interactions between the subsystems, especially synergies between production, consumption and storage and their impact on network operation.

Even though co-simulation approaches are very well suited to evaluate such objective functions for a given system design, their application in the context of design optimization is more challenging. This is mostly due to fact that in general no closed (semi-)analytical representation of the overall system is available, which in turn prevents a closed (semi-)analytical representation of the objective function (or its derivatives). However, even though this prevents the straightforward deployment of many optimization algorithms, it is possible to use metaheuristics that rely solely on the evaluation of the objective function itself.

In the context of this work, the Differential Evolution method [4] has been applied. This method optimizes a problem by maintaining a population of candidate solutions and creating new candidate solutions by combining existing ones according to a simple procedure. At each iteration, the candidate solution associated to the smallest value for the objective function is kept. In this way the optimization problem is treated as a black box that merely provides a measure of quality given a candidate solution, without the need of computing derivatives.

Implementation of the Optimization Prototype

The implementation for the prototype presented here is based on openly available MATLAB code[3], containing the algorithm in its full functionality and incorporating bounds, inequality, and equality constraints. In order to adapt this code for the use within a co-simulation environment, the following changes have been made:

- The base class ObjFunCoSimBase has been introduced to handle all interactions between the Differential Evolution algorithm and the co-simulation environment. To run an optimization, a class has to be derived that implements the details specific to the co-simulation environment and the system model, referred to as simulation handler class.
- Instances of the simulation handler class have to set up co-simulation runs according to the parameters

[2] See http://fmipp.sourceforge.net/

[3] See http://www1.icsi.berkeley.edu/~storn/code.html

provided by the optimization algorithm (method setup_all_cosim_tasks), start the simulations and retrieve the results (method retrieve_cosim_task_results).

- The call to a simple objective function has been replaced by a call to the method objfun of the simulation handler class.
- Plotting of the results is an optional feature of the simulation handler class, done via a call to the class method plotter.
- In the optimizer code, the for-loops used for iterating the candidate solutions have been split up. A first for-loop checks for boundary conditions, then the simulation handler class is called (returning the results for all candidates) and finally a second for-loop evaluates the results.

Figure 2 depicts a sequence diagram of the optimization procedure. The optimization algorithm (Optimizer) interacts with the co-simulation environment via an instance of the simulation handler class (ObjFunCoSim). When calling the method objfun(...), the simulation handler class translates the optimizer's input, i.e., the parameters of the candidates, into setups for individual co-simulation runs and executes them (ideally in parallel). The figure only depicts two instances of FUMOLA (sim1 and sim2) that are executed in order to illustrate that the simulations (can) run in parallel, in a real application the number of (parallel) simulation task corresponds to the number of candidates. After all co-simulation runs are finished, the simulation handler collects the results and evaluates the objective function for each. Finally, the optimizer evaluates these results.

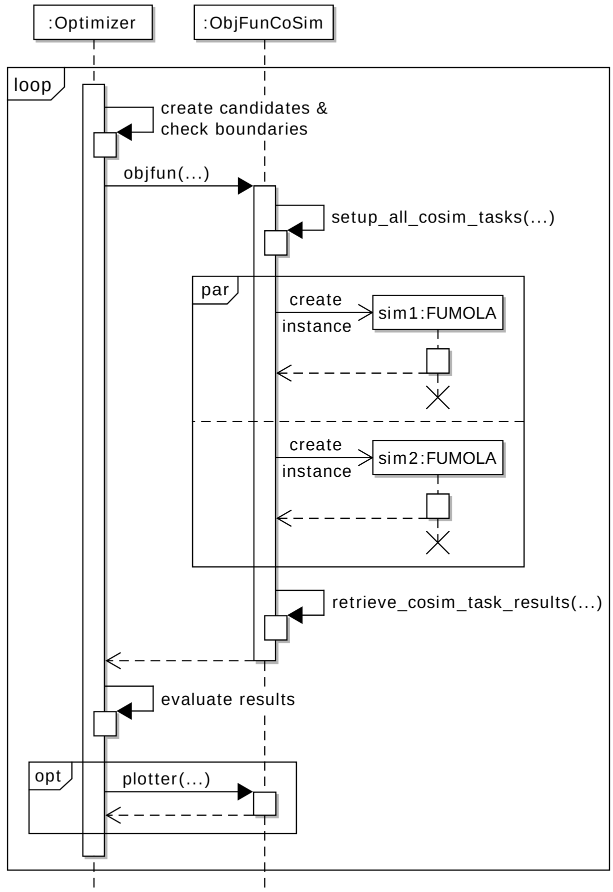

Fig. 2 Sequence diagram of the optimization procedure.

4 Example Application: Optimization of a Hybrid Thermal-Electrical Network

An example use case comprising a hybrid thermal-electrical energy system has been used to demonstrate the applicability of the software prototype described above. It demonstrates the applicability of FMI-based co-simulation approaches and their potential benefits for optimizing the design of multi-carrier energy systems.

System Layout

A schematic view of the system layout is shown in Figure 3, with arrows indicating the allowed flows of energy. The modeling of both the thermal and the electrical side relies mostly on power and heat flow balances, ensuring that the demand of the loads is met by the various energy sources. The thermal side comprises a boiler feeding into a buffer, which is connected to the thermal loads. Alternatively, a heat pump can be used to heat the buffer. For the buffer a simple capacitor model is used, linked to a hysteresis controller that signals whether the buffer needs heating in order to keep the temperature in a predefined range. The main source of electricity to meet the demand of the electrical loads is the external grid, but there is also a PV system and a battery available. Similar to the thermal storage, a capacitor model is used for the battery. Realistic profiles are used for the demand of thermal and electrical loads and the production of the PV system. With the profiles used for this work, the system resembles a medium-size commercial site with offices and workshops.

The boiler, the heat pump, and the battery are operated with the help of an energy management system (EMS). The EMS aims at two goals:

1. Use local electricity generation from renewable energy sources to operate the heat pump and reduce the utilization of the boiler. Whenever there is an overproduction of PV, i.e., when the PV production is higher than the local electrical consumption, or when the battery is sufficiently charged to power the heat pump, the EMS prioritizes the heat pump over the boiler.

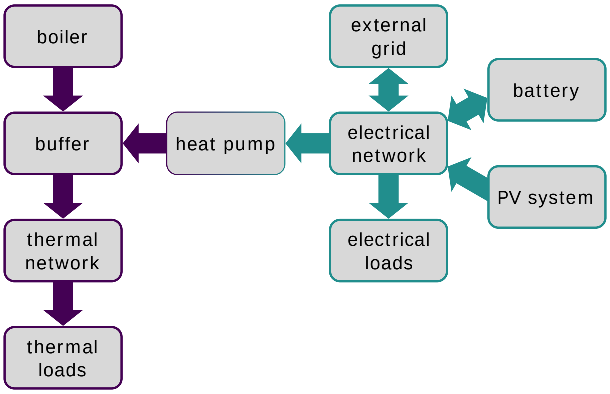

Fig. 3 Schematic view of the energy system.

2. Charge the battery whenever there is either PV overproduction and no need to operate the heat pump (no signal from the buffer's hysteresis controller) or enough PV overproduction to have a surplus even if the heat pump is running.

Model Implementation

The FUMOLA co-simulation environment introduced in Section 2 allows to use the most convenient tools and modeling approaches for different parts of the overall system. For the example at hand, the energy system model can be easily represented with the help of a simple set of algebraic and differential equations (including the buffer's hysteresis controller). Modelica [3] has been used for modeling and the resulting model has been exported as an FMU for Model Exchange. For the EMS, which follows a rule-based concept, a different implementation approach has been chosen. The EMS was programmed using a procedural language (C/C++) and with the help of the FMI++ library the resulting executable has been wrapped as an FMU for Co-Simulation.

Figure 1 shows the graphical representation of the combined model that has been used for the design optimization.

Objective Function Definition

For the example at hand an object function evaluating only the technical perspective of the system has been chosen, neglecting economical aspects. The design goal is to maximize the exploitation of the local renewable electricity production, in order to reduce boiler operation by using the heat pump. The degrees of freedom in the system layout are the heat pump size, i.e., its electrical power consumption P_{hp} when turned on, and the battery size, i.e., the amount of electrical energy E_{bat} stored in the battery when fully charged.

As a measure for the heat pump's effect on the system, its impact on the energy produced by the boiler E_{boiler} is considered, which should become as small as possible. Its value is calculated from the boiler's thermal power output $P_{boiler}(t)$:

$$E_{boiler} = \int_0^T dt\, P_{boiler}(t) \rightarrow \min \qquad (1)$$

At the same time, the battery's utilization ε_{bat} should be maximized. As a measure for the utilization, the integral of the charging power $P_{charge}(t)$, normalized with the amount of electrical energy E_{bat} stored in the battery when fully charged, is used:

$$\varepsilon_{bat} = \frac{1}{E_{bat}} \int_0^T dt\, P_{charge}(t) \rightarrow \max \qquad (2)$$

Furthermore, for a given heat pump size P_{hp} the battery size E_{bat} should not be too small, in order to match the discharge power of the battery needed for operating the heat pump (cp. EMS design goal 1) to the battery's capacity. In practice this can be achieved by requiring the numerical value of E_{bat} to be greater than or equal to the numerical value of P_{hp}.

For the purpose of defining an objective function Equations 1 and 2 are not suitable. Using only Equation 1 results in unrealistically large heat pump and battery sizes, as this would allow to store all surplus PV production (especially during the summer time) and use it for the operation of the heat pump later on. Using only Equation 2 results in unrealistically small battery sizes, as this would artificially increase the measure of the battery's utilization.

Ideally, an objective function should penalize too large heat pump sizes, because the necessary battery size would result in a poor battery utilization. At the same time, the objective function should penalize too small battery sizes, as this would result in impractical heat pump sizes. To achieve this goal, Equations 1 and 2 can be combined to construct the following objective function:

$$\frac{E_{boiler}}{\varepsilon_{bat}^{k}} \rightarrow \min \qquad (3)$$

The parameter k determines whether the emphasis of the objective function is more towards E_{boiler} ($k \rightarrow 0$) or ε_{bat} ($k \rightarrow \infty$). Due to its definition, the objective function's value increases for both small battery sizes (increase in E_{boiler}) and very large heat pump sizes (decrease in ε_{bat}).

Optimization Results

Figures 4 and 5 show the results for a typical optimization run (using $k = 1$). It used 15 iterations with a

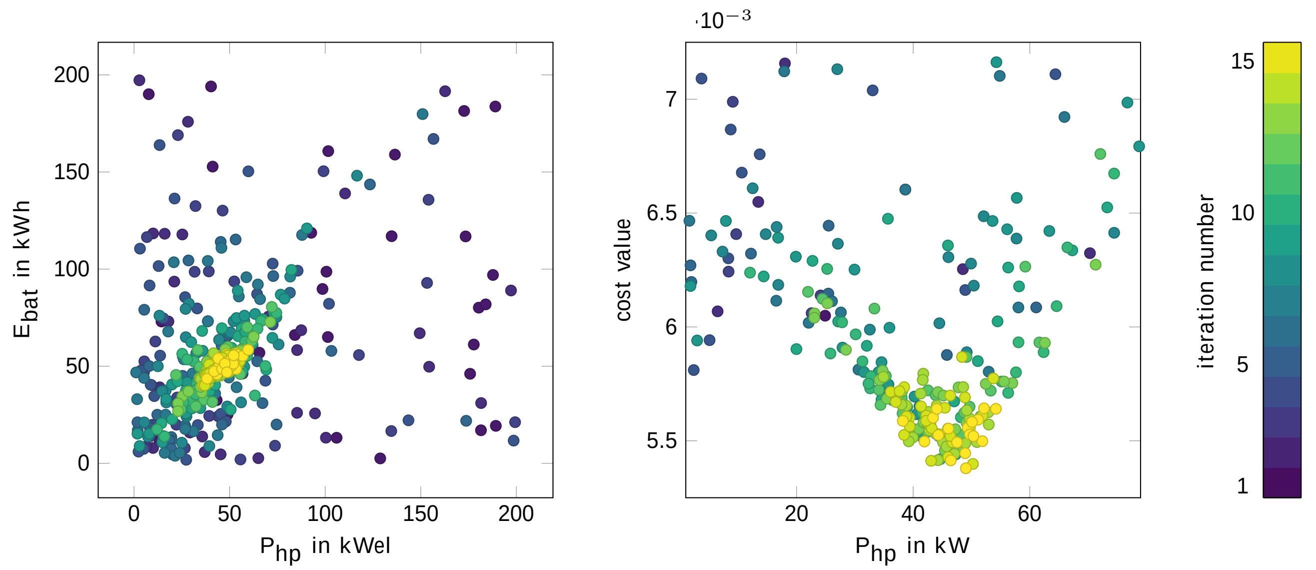

Fig. 4 Example of population evolution in the parameter plane (left) and evaluation of cost-function for P_{hp} (right).

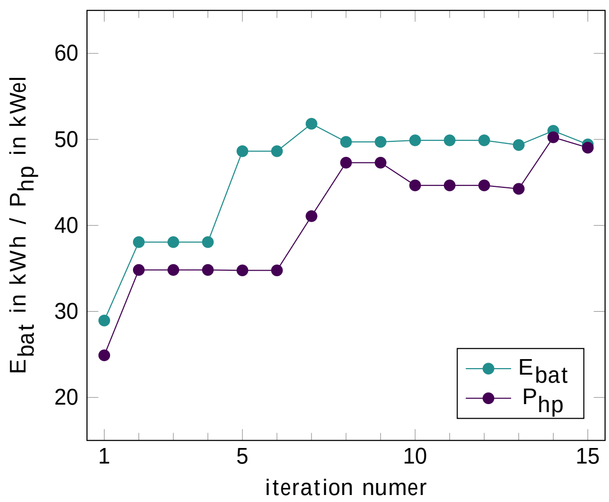

Fig. 5 Example of optimization parameter evolution.

candidate population size of 30, with each candidate associated to a full-year simulation run of the corresponding system layout. The computation of the objective function was parallelized by distributing the individual co-simulation runs among 5 client nodes (batch processing). The whole optimization procedure took roughly 25-30 minutes, using 6 computing nodes (1 master node and 5 client nodes).

Figure 4 shows on the left a scatter plot depicting the candidate population evolution in the search space. The color indicates to which iteration a candidate belongs, with darker colors indicating lower iteration numbers. The convergence of the candidate population towards the vicinity can be clearly recognized. The right side of the gure shows the evaluation of the objective function in dependence of the candidates' value for P_{hp}, depicting the convergence of the candidate population towards smaller values of the objective function.

Figure 5 shows the convergence of the optimization parameters. After 15 iterations the best candidate solution found has a heat pump size of P_{hp} = 49 kWel and a battery size of E_{bat} = 49:4 kWh. With this con- guration it is possible to substitute 27% of the energy produced by the boiler by operating the heat pump instead, using only locally produced electricity.

Figure 6 depicts optimization results in dependence on the parameter k. Each dot corresponds to the resulting value for P_{hp}, averaged over 15 optimization runs with di erent random seeds (15 iterations with a candidate population size of 30 each). The gray band indicates the RMS of this average value. As expected, for small values of k the optimization favors large heat pump sizes (and battery sizes), for k = 0 the optimization basically yields the largest value allowed within the prede ned search interval. Conversely, for large values of k the optimization favors small values of P_{hp}. In the interval k 2 [0:4; 1:1] the optimization procedure yields basically the same results in all cases, meaning that the objective function is well de ned in this interval. For larger values the RMS increases drastically, indicating that the objective function exhibits several pronounced local minima and causing the optimization procedure to give inconsistent results.

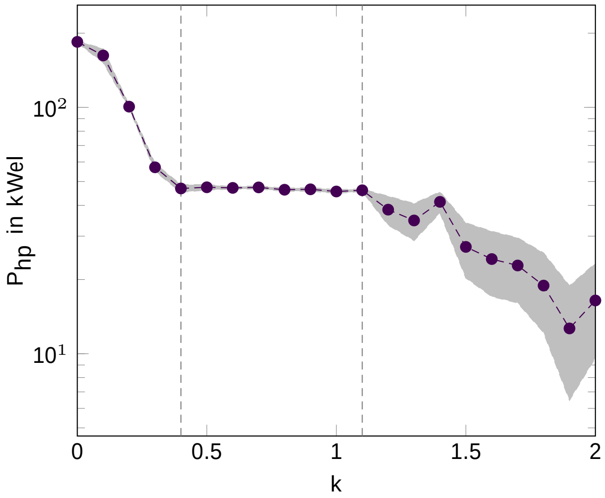

Fig. 6 Dependence of optimization result on paramter k.

5 Conclusions and Outlook

The work presented in this paper demonstrates the feasibility of utilizing FMI-based co-simulation approaches for optimizing the design of multi-carrier energy systems. Building upon the FUMOLA co-simulation environment and an openly available implementation of the Di erential Evolution optimization method, a software prototype has been successfully developed. The feasibility of this approach in general|and the software prototype in particular|for the design optimization of multi-carrier energy systems has been demonstrated with the help of a simple but representative use case. The software prototype will be made available as part of the FUMOLA environment.

Future developments will aim in two directions. On the one hand, the prototype will be extended to allow the use of other metaheuristic optimization algorithms. On the other hand, optimization methods based on numerical derivatives will be studied.

Acknowledgments

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$EVWUDFW This publication compares three di erent distributed energy management algorithms. All algorithms are evaluated regarding quality of energy management and communication requirements. In addition, their scalability and behaviour at communication limitations are analysed. Furthermore, recommendations for the use of the di erent algorithms are given. The rst algorithm is COHDA. It has a fully distributed approach without any central unit. Secondly, the well known algorithm PowerMatcher, which performs market based supply demand matching, is analysed. Thirdl y, a round-based and privacy preserving algorithm called PrivADE is evaluated. All algorithms are simulated in the ns3-based simulation environment SiENA.

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Energy management in the domestic area will become a vital part in the future power grid. This comprises Demand Side Management (DSM) and the management of supply units like micro Combined Heat and Power Plants (CHPs). To handle the possibly high number of households and devices, di erent Energy Management Algorithms (EMAs) were developed. Their functionalities vary considerably and they partially pursue different goals. Speci cally EMAs were developed for day ahead scheduling of CHP or Heat Pump (HP). Other EMAs were made for frequency response by using Battery Storages (BSs) or Electric Vehicles (EVs). A third EMA application is intra-day load balancing with lower real time requirements than frequency response EMAs.

The convergence of the aforementioned day ahead scheduling algorithms is not time-critical because they can be executed beforehand. This leads to low restriction regarding convergence times and therefore low communication requirements. In contrast, frequency control algorithms have to react within very low delays (often less than 1 second) and very high reliability. All information that is needed is the grid-frequency which is inherently available through the power grid. An additional communication network would be redundant. The only kind of algorithms which should be analysed in perspective of communication requirements is the third group of EMA applications. Because, in contrast to day-ahead and frequency response EMAs, the behaviour of intra-day EMAs often depends on the communication network. So, the publication is focusing on requirements of this intra-day EMAs.

For these intra-day EMAs, various possibilities to manage households and their energy devices exist. A simple way is a central control unit, which controls each device directly. This method is called Direct Load Control (DLC). A more common and in the public more accepted way is an indirect management, e.g. by price incentives. For this indirect method, di erent EMAs were published in recent years. In this paper, three different algorithms are simulated and evaluated regarding communication requirements. The rst algorithm is COHDA [3]. Originally, it was developed for day ahead scheduling of controllable power supply. How-

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ever, COHDA was adapted in this paper to handle intra-day energy management of di erent devices. The second algorithm is PowerMatcher. It was rst published by Kok in 2005 [5] and is mainly used for DSM in households. However, the concept of PowerMatcher can be also used for energy generating units. Additionally, we present PrivADE [1]. PrivADE is a round-based approach with homomorphic encryption to preserve users privacy.

There are already several evaluations that analyse communication requirements for smart grid applications. Saad [6] focuses on scheduling algorithms using game theory. He suggests Power-line Communication (PLC) or wireless technologies, but does not compare di erent algorithms. He highlights that the area of communications in smart grid systems is still in its infancy. Conejo [2] describes the importance to use a bidirectional communication, but does not analyse the requirements in detail. Samadi [7] also proposes a two-way communication. He compares the required amount of messages by his game theoretic approach to a price anticipating system. However, he does not compare their abilities with regard to energy management functions. So it remains unclear, if his game theoretic approach is advisable in all scenarios. Yan [13] describes challenges and requirements on communication in a smart grid. He gives a good motivation for communication in smart grids. However, he only provides an overview about required latency without focusing a concrete scenario.

Another overview is given by the US department of energy [10]. They categorise smart grid functionalities and give an overview of communication requirements. For demand response they estimate the required bandwidth between $14\,\mathrm{kbit\,s}^{1}$ and $100\,\mathrm{kbit\,s}^{1}$ as well as the latencies ranging from 500 ms up to several minutes. However, the functionalities that could be enabled with these communication properties are not described.

To enable a better overview, this paper focuses on required data amount and time for convergence of EMAs. This is simulated with households and their devices as controllable units in concrete scenarios. Especially scaling properties and behaviour with bandwidth limitations and high communication delay is analysed.

This publication is structured as follows. In section 2 the algorithms COHDA, PowerMatcher, and PrivADE are described. Afterwards, the simulation environment and the scenario is shown in section 3. In section 4, simulation results of the algorithms are shown and the communication requirements analysed. Finally, the algorithms are compared and recommendations for different scenarios will be given.

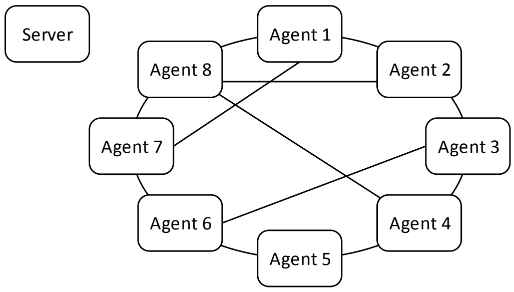

Fig. 1 COHDA - small-world overlay network example (= 0:5)

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The communication requirements depend largely on the EMA itself. Several algorithms with di erent functionalities were published in recent years. In this section, the algorithms COHDA, PowerMatcher and PrivADE are introduced shortly to illustrate their functionalities.

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COHDA is a heuristic for multi agent systems [3]. Including our adaptation for the motivating use case of intra-day energy management in the present contribution, the algorithmic approach in COHDA ca be described as follows: Each agent represents a household h 2 H. All households are connected by an overlay network and have identi cations that are well-ordered. For best performance, the overlay network should be realized as a Watts-Strogatz small-world model [12] (see Fig. 1). Each household h has a predicted energy consumption C_h for QSw@Õì ™cð < H Ð

$_i$. Afterwards, the goal value, solution candidate and the working memory is sent to all neighbours in the overlay network.

3. A household i that receives a packet with a working memory $_r$ and a solution candidate $_r$, rstly updates the energy consumptions in its own working memory ($_i$! ^0_i). If it has been updated ($_i$ 6= ^0_i):
   - If the amount of households in ^0_i is higher than the amount in $_i$ and $_r$ (jH $'_i$j > jH $_i$j^j H $'_i$j > jH $_r$j), the best own consumption C_i will be selected (minimum e(; C_i + P $_{C_h 2 \; 'nC_i}$ C_h)), and ^0_i is set as a new solution candidate $_i$.
   - If the set of households in the received solution candidate is equal to the set in the own solution candidate (H $_r$ = H $_i$):
     (a) If the received $_r$ is better than the own $_i$ (e(; P $_{C_h 2 \; r}$ C_h) < e(; P $_{C_h 2 \; i}$ C_h)), or $_r$ is equal to the own $_i$ (e(; P $_{C_h 2 \; r}$ C_h) = e(; P $_{C_h 2 \; i}$ C_h)) but has a solution creator with a higher identi cation, replace $_i$ by $_r$.
     (b) Find the own consumption C_i that minimise e(; C_i + P $_{C_h 2 \; i nC_i}$ C_h) and store C_i into $_i$. If $_i$ has a lower error value than $_i$ (e(; P $_{C_h 2 \; i}$ C_h) < e(; P $_{C_h 2 \; i}$ C_h)) replace $_i$ by $_i$.
4. When either $_i$ or $_i$ have been modi ed in one of the previous steps, the household sends a new packet with the goal value, solution candidate and working memory to all neighbours in the overlay network.

When COHDA is converged, the predicted energy consumption can be set. Further information about COHDA is available in the Hinrichs publication [3].

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PowerMatcher is a common method for supply demand matching. It was rst published by Kok in 2005 [5]. In PowerMatcher, households send a bid to an auctioneer, which has information about the goal consumption and chooses a price depending on the accumulated bids. In the next sections, the methodology of creating bids and the execution of PowerMatcher is described in more detail.

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Each adaptable device is represented by a device-agent. Every device-agent has to create a bid-curve, which depends on the environmental conditions. Example: a device agent for a HP adapts its bid-curve depending on the load level of the hot water tank (see Fig. 2). When the load level is high, the HP has not to run necessarily.

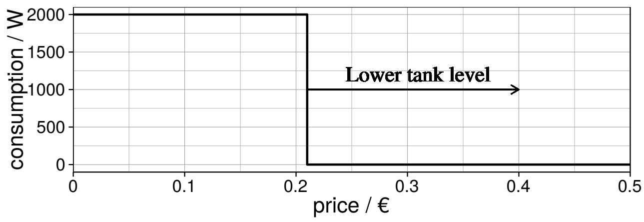

Fig. 2 Bid-curve of a heat pump

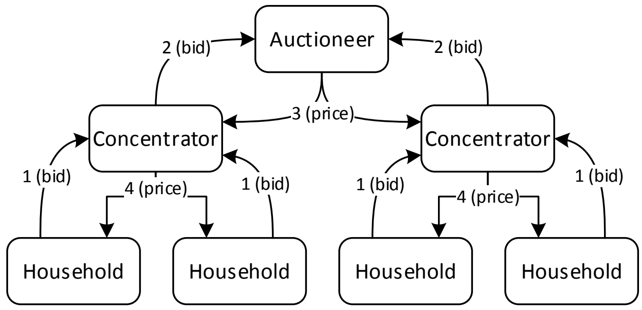

Fig. 3 Overlay network and steps during execution of PowerMatcher

In case of bid-curves for BSs or other continuously manageable devices, the bid-curve has no jump discontinuities. However, bid-curves are always monotonically decreasing functions. If the price increases, the consumption stays constant or will be lowered.

The bid of Fig. 2 can be represented by the coordinates f(0 :21€; 2 kW), (0:21€; 0 kW) g. Values between the coordinates, are calculated by linear interpolation. Thus, continuous decreasing bids can be realised with only two coordinates too. The most bids of exible devices have just two or four coordinates. That leads to a very small amount of data.

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The execution of PowerMatcher consists basically of four steps, these steps are shown in Fig. 3 and described in the following:

1. Each device agent creates a bid. Each household aggregate these bids and send them to a concentrator.
2. All concentrators receive bids from di erent households. They aggregate these bids and send the result to another participant called the auctioneer.
3. The auctioneer calculates the price, where the bid-curve matches the total goal consumption . This price is then sent back to the concentrators.
4. All concentrators receive the price and forward this to each household. The households set their devices to the corresponding consumption value.

PrivADE is a Privacy-Preserving Algorithm for Distributed Energy Management [1]. It is round-based and distinguishes adaptable loads that can be managed ne granular (BS and EV), and switchable loads which can only be turned on or o (CHP, HP and heating rod). The households and the server are part of an overlay communication network that is arranged as a ring (see Fig. 4). The server knows the goal consumption and tries to match the total consumption to this goal.

In the rst round, all necessary data is gathered. Therefore, the server creates a data packet with several counters and sends it through the ring. Each household that receives this package adds its values to the corresponding counters. For example adds its total energy consumption to the corresponding counter. This is done using homomorphic encryption.

After the rst round, the server has information about the total consumption C (e.g. 28000W), the amount of switchable devices with certain consumptions (e.g. two devices with 1000W and one with 10000W can be turned on) and the possibilities of adaptable devices to increase (e.g. = 4000W by A = 5 households) or decrease the consumption (e.g. = 3000W by B = 2 households). So the server decide, which device-categories (e.g. all devices with 1000W) to switch, for allow achieving the goal consumption (e.g. = 32500W) with the adaptable devices. So the server sends another packet through the ring with the devices to switch and a consumption share for the adaptable households (e.g. $\frac{32\,500\,W \quad 28\,000\,W \quad 2\;1000\,W}{5}$ = 500 W). Each household that receives this package adds, if appropriate, its adaptation and send the package to the next. If all adaptable households can ful l their adaptation share, PrivADE has been converged.

If a household cannot ful l its share (e.g. one household can only adapt to 300 W) the remaining households have to adjust their adaptations (e.g. additional $\frac{2500\,W \quad 4\;500\,W \quad 300\,W}{5 \quad 1}$ = 50 W). This requires another round. So the number of rounds can increase till maximum jHj in the worst case.

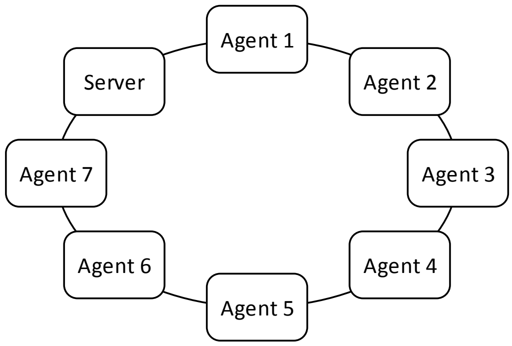

Fig. 4 Ring overlay communication network of PrivADE

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SiENA contains a large data basis of energy consumption curves for the most relevant household appliances (stoves, o ce devices, washing machines, fridges, etc.). Market penetrations are speci ed by values of the German federal statistic o ce [8]. For realistic simulations, the simulator chooses appropriate activation times for the di erent devices. A simulated consumption and the German standard load pro le (H0) match fairly well. This is shown in Fig. 5. Therefore, it can be assumed that the simulated energy consumptions are well grounded.

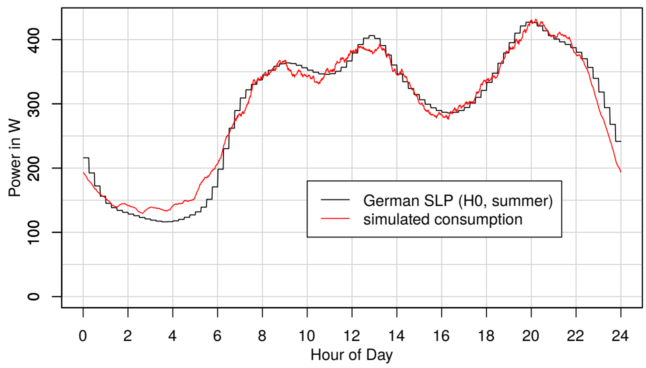

Fig. 5 Comparison of simulation and Standard Load Pro le (SLP) for households

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To simulate the behaviour of the introduced algorithms, a lot of probabilities and surrounding conditions have to be considered. In the following subsections, the capabilities of our simulation environment called SiENA [9] and the scenario for our experiments are described. SiENA is integrated in the network simulator ns-3. This enables to simulate simultaneously the communication behaviour and the energy consumption.

In addition to the devices commonly used today, devices like CHPs and HPs can be simulated. Therefore, the heat demand according to the standard VDI4655 has been implemented [11]. In addition, EVs and BSs can be simulated. All these future devices have high potential for load shifting and load adaptation. The selection of controllable devices depends on the scenario, which is described in the next section.

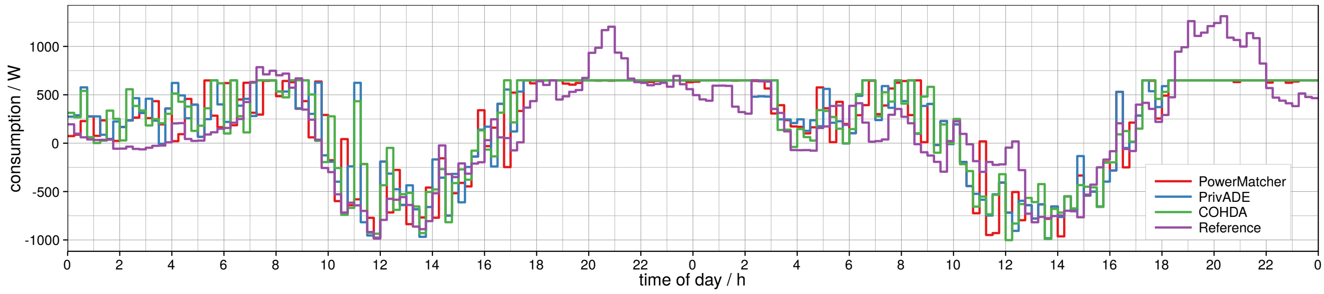

Fig. 6 Energy consumption of 50 households controlled by di eren t al horithms

6 F H Q D U L R

Many scenarios exist that allow a useful energy management, e.g. load shaping and peak clipping (see Fig. 7). Load shaping can be used to adjust the energy consumption to uctuations in generation. A uctuating generation can be caused for example by renewable energy sources like photovoltaic systems or wind turbines. In our scenario, we assume a distribution grid supplies 50 households and a substation not allowing a higher total power consumption than 32.5 kW. So, algorithms for peak clipping are needed. However, simulations have shown that increasing the energy consumption before the peak can allow a better ability to reduce consumptions during the peak. So, the goal of the algorithms is to increase or decrease the peak demand to 650 W per household. This goal is typical for load shaping.

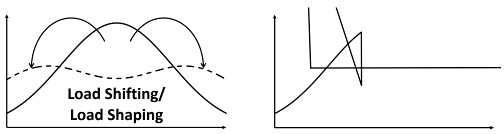

Fig. 7 Goals of energy management

In the scenario each household has probabilities for owning controllable devices. The probability to own a CHP or a HP is 25% each. Both devices are controllable if the corresponding heat storage is lled above 30%. 20% of households own an EV which is manageable if its load level is at least 90%. Further, 30% of the households own a BS. They have no special conditions for being controllable. Fig. 6 shows two exemplary days managed by each introduced energy management algorithm. It can be seen that all algorithms have similar capabilities to clip the peaks. The quality ratings according to the methodology of [4] are shown in Table 1 and con rm this observation.

Table 1 Quality ranking of di erent algorithms in percent (higher values correspond to a better result)

	COHDA	PowerMatcher	PrivADE
Peak Clipping	28	27	28
Load Shaping	25	23	25

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Independent of the EMA overlay network, the communication technology has a physical topology. Therefore, a tree was selected, which can be found in wired internet connections like Digital Subscriber Line (DSL). Each household is represented by a leaf and upper level nodes represent network elements such as switches or routers. The maximum number of leafs for a node is ten and the graph has a maximum height of ve, meaning the worst case path size from leaf to leaf is ten in case of more than 80 leafs. In case of more than 160 leaf nodes, the root has more than two connections (see Fig. 8).

Fig. 8 Topology of a tree network with 182 nodes

The topology ends with households, meaning that no in-house communication is simulated. All leaf nodes (households and servers) have a 20 ms latency and a bandwidth of 5 Mbit s ^{1}. All other nodes (routers) have 2 ms processing delay and a data rate of 1 Gbit s^{1}.

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In this section, simulation results are described and discussed. The scenario of the previous section is used. Table 2 shows an overview of the simulation parameters. The algorithms use the UDP-Protocol for communication. All data amounts include the 30 bit MAC header.

Table 2 Overview of simulation parameters for the subsections 4.2 and 4.3

simulated objects:	50 households and their appliances
exible devices:	CHPs, HPs, BSs and EVs
simulation period:	varies depending on simulation complexity from 7 days up to 1 month
interval:	15 minutes
communication parameters:	leaf bandwidth 5 Mbit s $^{-1}$, router bandwidth 1 Gbit s $^{-1}$, delay 20 ms

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In this section, the required time for convergence is simulated and analysed. This is very important because the convergence time determines the interval within an algorithm can be executed. The smaller the interval, the faster the reaction of the energy management. Simulation period is one month. The gures in this section illustrate a curve for an exemplary day as well as a box plot for the entire simulation.

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COHDA is a heuristic and its convergence behaviour depends on various conditions. The best case for fast convergence occurs when no household has any adaptable device. So the households only inform the other households about their energy consumption. Another important condition is the overlay network. Because no representative small-world overlay network can be de ned, the best case for an open ring and a star overlay network is described, as clarifying example in the following, before deriving properties of the small-world topology afterwards on this basis.

Fig. 9(a) shows the best case with an open ring overlay network and four households. The number of sequential steps is 2jHj 1. This results to 7 steps in case of four households and 99 in case of 50 households. If another overlay network is used, the amount of sequential steps decrease. In case of a star overlay network, only four sequential steps are required. This is independent on the number of households jHj (see Fig. 9(b)). So the amount of sequential steps depends on the maximum number of hops. The small-world topology used for the overlay network here, has typically a logarithmically growing maximum number of hops. So the real best case in our scenario with the small-world overlay network has a number of sequential steps between 4 and 99. Please note that the convergence time has a linear dependency on the number of sequential steps.

However, simulations show that the worst case does not occur in practice. Convergence times of an exemplary day and a box plot of a one month simulation is shown in Fig. 10. The simulated best case is 3:8 s and the worst case 8:5 s. The median time for convergence is around 4:7 s.

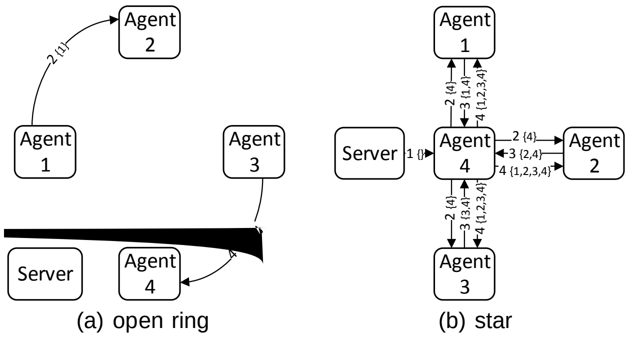

Fig. 9 Messages in the best case with four households and two di erent overlay networks

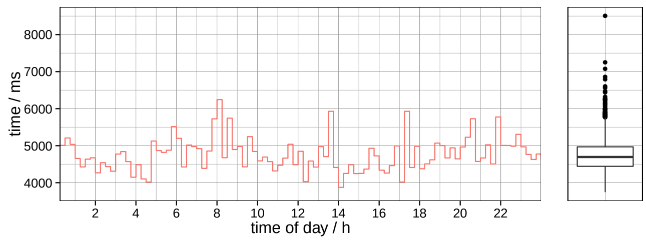

Fig. 10 Time for convergence (COHDA)

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PowerMatcher always performs the same four communication steps to nd a solution. As soon as the algorithm has performed these steps, it can be regarded as converged. The time for convergence is shown in Fig. 11. To prevent a concentrator overload, the households send their bids with an equal distributed time delay between 0 and 100ms. This way the convergence time of PowerMatcher is almost a representation of this delay and an additive for the latency and time for transmission of around 215ms in average.

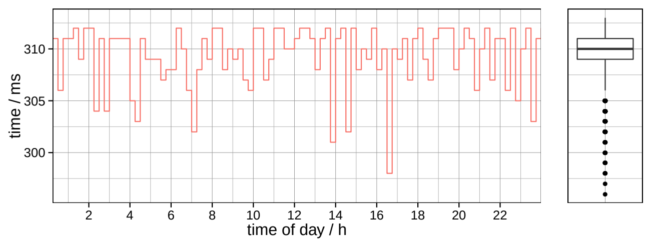

Fig. 11 Time for convergence (PowerMatcher)

PrivADE is a round-based algorithm. The communication is in principle organised unidirectional and no parallel communication steps occur. For this reason the converging times is proportional to the required number of rounds and the amount of households, which is 50. The rst round needs 2:7 s and each additional round approx. 2:4 s. PrivADE needs two to six rounds in the simulated scenario. This results in convergence times from 5:1 s up to 15 s. Fig. 12 shows the convergence times of an exemplary day and a box plot for a simulation with a period of one month.

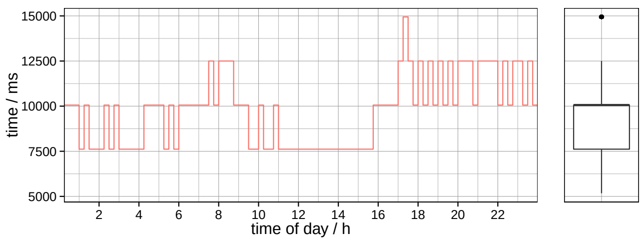

Fig. 12 Time for convergence (PrivADE)

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The convergence times of COHDA and PrivADE algorithm are close to each other in this scenario (4:7 s compared to 9:7 s). PowerMatcher is much faster with times around 0:3 s. All convergence times are below 15 s, which enables an execution in a one minute interval.

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In this section, the data amount of the di erent EMAs is analysed. Simulation period is one month. The gures in this section illustrate a curve for an exemplary day as well as a box plot for one month, which corresponds to the entire simulation.

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Similar to COHDAs time for convergence, its best case for the amount of data can be shown at the example of Figure 9. With the open ring overlay network and four households the message amount is ten. Household 4, that calculates the nal solution candidate, has to exchange 2 messages. Household 3 has to exchange 3, etc. For increasing number of households $|H|$ it results to

$$|M_{best;openring}| = 1 + \sum_{n=1}^{|H|-1} (n+1) = \frac{|H|^2 + |H|}{2} \,. \quad (1)$$

This results in a message amount of 1274 for 50 households. In case of the star overlay network, the number of messages is

$$|M_{best;star}| = 1 + 3|H| \,, \quad (2)$$

which leads to 151 messages for 50 households. The best case in the simulation is 801 messages and thereby between both (see Fig. 13).

The message size varies dependent on the number of households that are considered in the message ($|C|$). The message size can be calculated as follows: 38 Byte + $|C|$ 64 Byte. This results in a maximum message size of 3238 Byte for 50 households.

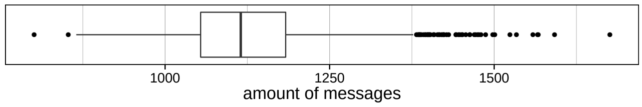

Fig. 13 *Total message amount for convergence (COHDA)*

The simulated amount of data needed to converge is shown in Fig. 14. This data amount varies between 600 kB and above 1600 kB. Fig. 15 shows that the total amount of received data varies considerably in the different households. Household 25 only receives 15:6 kB in average, compared to household 45 that receives 46:5 kB in average. Please note that the amount of transmitted data is basically equal to the received data in COHDA.

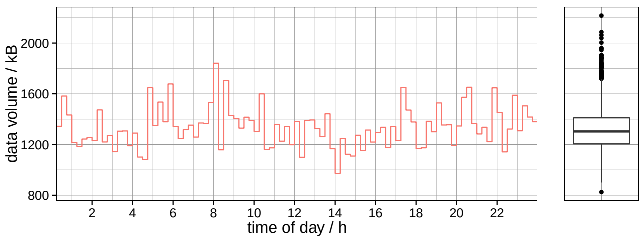

Fig. 14 Data volume needed for converging using the COHDA algorithm (including MAC headers)

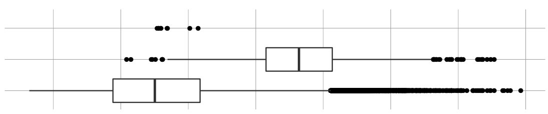

Fig. 15 Amount of received data per household required to converge using the COHDA algorithm

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The more devices are manageable in a household, the more extensive is the bid-curve. This results in a higher data volume. The most complex household bid-curve-message has only 78 Byte, including the MAC header of 30 Byte. This corresponds to six stored coordinates. On the other hand, the smallest bid-message has a size of 38 Byte. In this case, only one tuple containing price and consumption has to be transmitted. If a household contains an adaptable device, at least one more tuple needs to be sent. While a CHP only requires a single additional tuple, a battery storage requires three extra tuples. This is due to the more complex bid-curve. Fig. 16 shows the spread of bid-curve-message sizes. The sum of the total data volume sent by all participants is shown in Fig. 17. Depending on the number of controllable devices, the total data volume varies from 4:7 kB up to 5:6 kB. Especially during the evening when a lot of EVs are at home, a lot of devices are controllable.

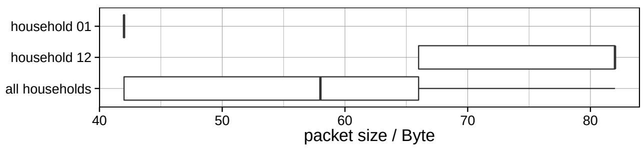

Fig. 16 Bid-curve-message size of all households and the households with the lowest and the highest average package size (including MAC headers)

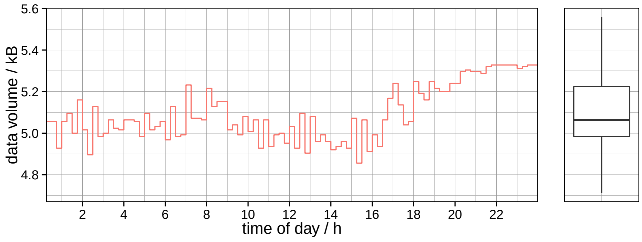

Fig. 17 Data volume needed for converging of PowerMatcher (including MAC headers)

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Analysing the amount of data transferred for convergence using the PrivADE algorithm leads to a similar outcome as for the required convergence time (compare Fig. 12 and Fig. 18). This is due to the round-based approach of PrivADE. The rst round requires approx. 120kB of data. Second or later rounds only need approx. 8 kB. So the total data volume required by PrivADE varies between 128 and 161kB.

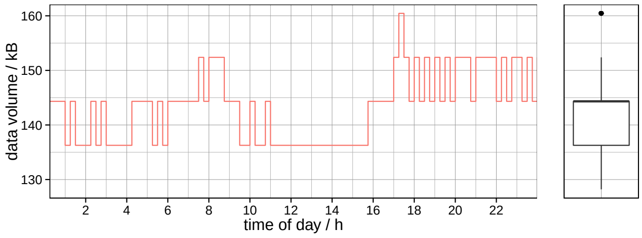

Fig. 18 Data volume needed for converging of PrivADE (including MAC headers)

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Similar to the time required for convergence, the amount of data depends on the selected algorithm as well. While PowerMatcher leads to very low data receptions and transmissions for households, the concentrator has to handle messages from each household in parallel. Using COHDA or PrivADE leads to lower communication requirements on the server side (including concentrator), because they are based on a more distributed approach. Therefore, households need to exchange more data. However, in the considered scenario, the average number of messages is 11 per household for COHDA and 4 for PrivADE, as well as their total data size around 1:5 MB or 144kB. Both algorithms can be handled by most communication technologies. Table 3 gives an overview of the required communication.

Table 3 Average tra c needed for convergence of COHDA, PowerMatcher and PrivADE (including MAC headers)

		COHDA data/count	PowerMatcher data/count	PrivADE data/count
household	rx	26:4 kB/11	38 Byte/1	2805 Byte/4
	tx	26:4 kB/11	55:6 Byte/1	2805 Byte/4
server/ auctioneer	rx	-	374 Byte/1	2805 Byte/4
	tx	38 Byte/1	38 Byte/1	2805 Byte/4
concen-trator	rx	NA	2818 Byte/51	NA
	tx	NA	2274 Byte/51	NA

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In this section the scalability regarding increasing number of households of the di erent algorithms is analysed. Therefore, the required time and data for convergence is evaluated. The number of controllable devices per household remains constant.

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In small-world topologies, the average minimum path length l increases logarithmically with the number of nodes $|H|$ ($l \propto \log|H|$) [12]. The average number of neighbours remains constant at three. As a result, it can be assumed that the average time to reach convergence increases logarithmically with the number of households ($O(\log|H|)$).

The total data volume for convergence increases much faster than the time for convergence. This is due to two additional scaling e ects. Firstly, the number of messages $|M|$, that will be sent simultaneously, increases linearly with the number of households $|H|$, because all households send messages in parallel ($|M| \propto |H|$). Secondly, the average message size m_{size} increases linearly with $|H|$, because information about each household has to be communicated ($m_{size} \propto |H|$). In addition to the time e ect, this results to a data amount scaling behaviour of $O(|H|^2 \log|H|)$.

Simulations that are shown in Fig. 19 con rm both scaling assumptions. This leads to a total data transmission of more than 1 GB in case of 1000 households.

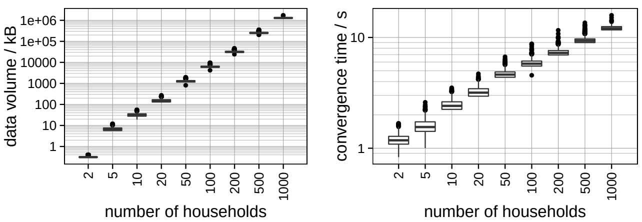

Fig. 19 Time and total data volume needed for convergence by varying the number of households (COHDA)

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For the scaling analysis of PowerMatcher, the number of concentrators is xed to one. Because of the four same steps in PowerMatcher, the algorithm scales independent from the number of households ($O(1)$). Small e ects on the scaling behaviour are due to the network topology: the maximum number of hops increases logarithmically till 80 nodes are reached (see section 3.3). The time of the slowest communication path in each of the four steps (Section 2.2.2) determines the total time. Due to the topology and the random time delay in each household, a slight increase can be expected. The amount of messages $|M|$ increases linearly with the number of households $|H|$ and the amount of concentrators $|C|$ ($|M| = 2|H| + 2|C|$). Due to the fact that there are much more households, than concentrators ($|H| >> N_C$), the increase of messages can be described as $O(|H|)$. Because of an almost constant average message size, the data volume increases also linearly with the number of households ($O(|H|)$).

Simulations with the amount of data and the required convergence time are shown in Fig. 20. The time for convergence increase slightly with the number of households. The average time increases from 226 ms in case of 2 households up to 340 ms in case of 1000 households. This behaviour is expected. The simulations show, that the data volume increases slightly less than linear. This can be explained with the aggregated bid, which is sent from the concentrator to the auctioneer. Its size increases less than linear because some prices in households bids-curves are the same. This is an economy of scale e ect.

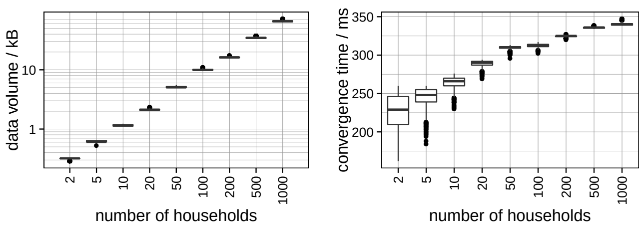

Fig. 20 Time and total data volume needed for convergence by varying the number of households (PowerMatcher)

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In order to analyse the scaling behaviour of PrivADE, rstly the number of required rounds $|R|$ has to be considered. In Fig. 21, it can be seen that the number of rounds increases less than double logarithmic with the amount of households ($O(\log\log|H|)$) in our scenarios.

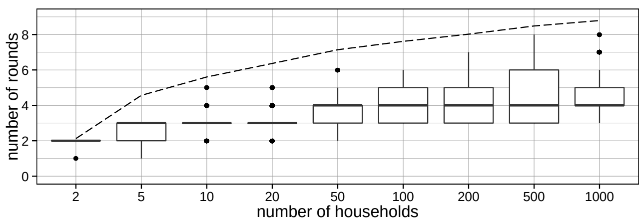

Fig. 21 Required rounds by varying the amount of households (PrivADE). The dashed line represents a curve with a $\log\log|H|$ behaviour.

Due to the fact that each round needs $|H| + 1$ communication steps, the convergence time increases linear with the number of rounds $|R|$ and the number of households $|H|$ ($O(|H| \log\log|H|)$). This leads to convergence times up to 347s in case of 1000 households. The data volume does not increase as fast as the time to converge, because the size of data exchanged in the second and later rounds is smaller than for the rst round. The scaling behaviour of time and data required for convergence is shown in Fig. 22.

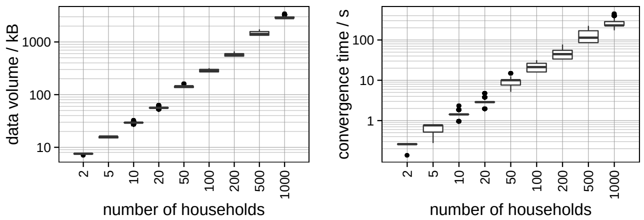

Fig. 22 Time and total data volume needed for convergence by varying the number of households (PrivADE)

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The scaling behaviour of the algorithms regarding increasing numbers of households is di erent. Two aspects have been analysed, the data amount and the time for convergence. Regarding data, PowerMatcher scales linear with the number of households. PrivADE is a bit worse and needs slightly more data with increasing households. COHDA, on the other side, needs much more data. It scales worse than quadratic with the number of households. Table 4 shows an overview of the scaling behaviour. Regarding time for convergence, PowerMatcher achieve the best results again. It converges nearly independent of the number of households. The convergence time of PrivADE increases slightly faster than linear and the time-scalability of COHDA is between PowerMatcher and PrivADE. Fig. 23 shows, that PrivADE and PowerMatcher converge equally fast in case of 2 households. Because of better scalability, Private becomes slower with increasing number of households. From 20 households upwards, the worse scaling of PrivADE allows COHDA to be second best.

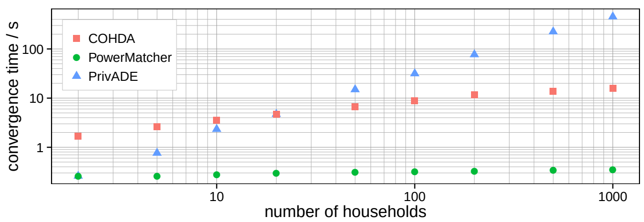

Fig. 23 Convergence times comparison by varying the number of households in our scenario

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In this section, the convergence times of the algorithms are analysed by variation of available bandwidth and latency. Thereby, only bandwidth and latency of the leafs

Table 4 Scalability comparison of COHDA, PowerMatcher and PrivADE in our scenario

	total data amount	convergence time
COHDA	$\mathcal{O}(\|H\|^2 \log \|H\|)$	$\mathcal{O}(\log \|H\|)$
PowerMatcher	$\mathcal{O}(\|H\|)$	$\mathcal{O}(1)$
PrivADE	$< O(\|H\| \log\log \|H\|)$	$\sim O(\|H\| \log\log \|H\|)$

(see topology in Fig. 8) are limited. These leafs represent households, servers, concentrators and the auctioneer. The bandwidth and latencies between routers remain una ected (1 Gbit s^{1} and 2 ms).

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In the considered scenario the minimum data rate per household is 50 kbit s ^{1}, when using the COHDA algorithm. In case of lower bandwidths, the algorithm does not converge reliably within the 15 minutes interval. This is independent of the latency. The convergence time in dependency of the data rate and the latency is shown in Fig. 24. High latencies become relevant at higher data rates. For example a latency of 200 ms, compared to 2 ms, slows down the convergence by approx. 7 s at high data rates.

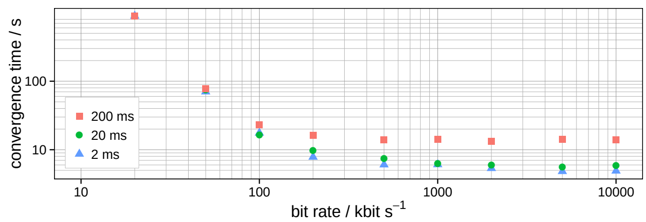

Fig. 24 Maximum time for convergence of COHDA by varying the bandwidth and the latency

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In PowerMatcher, a latency of 200 ms slows down the convergence by 1:6 s. This is due to the four steps of PowerMatcher, where each step needs the sum of all component delays that are within the communication path. This corresponds to two times the latency of the leafs (200 ms) plus up to six times the latency of the routers (2 ms) at each of the four steps. These 1:6 s are negligible when considering that one minute is the nest interval that is taken into account.

Regarding low data rates, PowerMatcher shows fairly robust results too. Fig. 25 shows, that 100 bit s ^{1} are already su cient to reach convergence in 500 s, which is well within the 15 minute interval.

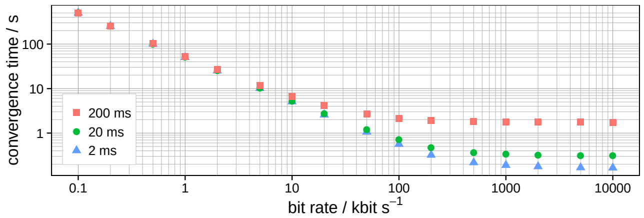

Fig. 25 Maximum time for convergence of PowerMatcher by varying the bandwidth and the latency

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In contrast to COHDA and PowerMatcher, the in uence of large delays of household d_h and the server d_s is very high on PrivADE because it requires $|H| + 1$ sequential communication steps per round. This leads to a total convergence deceleration of $t_d = 2 (d_s + \sum_{h \in H} d_h)$ alone through the leaf delay. This time is 20:4 s each round in case of a 200 ms leaf delay. In our scenario the maximum number of rounds is six, which leads to a total time delay of 122.4 s. Thus, an interval of one or two minutes is prohibited, even in case of very high bandwidths.

The bandwidth limitation cause a further time delay of $t_b = (|H| + 1) \frac{5438\,\text{Byte}}{b}$. The 5438 Byte is the data amount, that have to be send sequential in six rounds.

In sum, the convergence time of PrivADE composing the addition of t_d, t_b and the time for transmission trough the higher layers of the physical topology, which is very low. In our scenario, PrivADE can be executed reliably with bandwidths down to 5 $\text{kbit}\,\text{s}^{-1}$.

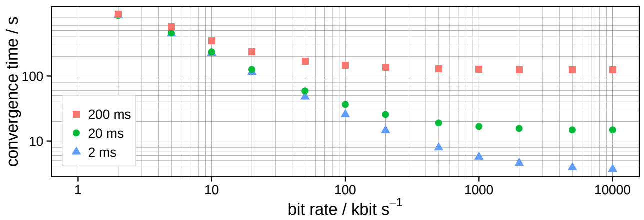

Fig. 26 Maximum time for convergence of PrivADE by varying the bandwidth and the latency

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The in uence of communication limitations on the considered algorithms vary signi cantly. While COHDA is prone to bandwidth limitations, higher latencies does not have a large impact. PrivADE shows the exact opposite behaviour. A latency of 200 ms leads to a total convergence deceleration of approx. 100 s. A lower bandwidth on the other side has no great in uence.

In general the e ect on PowerMatcher is not as high as the e ect on both other algorithms. All in all, PowerMatcher can be used with bandwidths as low as 100 $\text{bit}\,\text{s}^{-1}$, PrivADE requires at least 2 $\text{kbit}\,\text{s}^{-1}$ and COHDA a minimum of approx. 30 $\text{kbit}\,\text{s}^{-1}$.

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The energy management, convergence times, data requirements, scalability and behaviour on communication limits have been analysed for COHDA, PowerMatcher and PrivADE. Regarding energy management, all algorithms have a similar ability to reduce consumption peaks or shape the load.

Regarding communication costs, PowerMatcher has the fewest requirements. It requires few data, so a limited bandwidth has low in uence. Due to only four sequential communication steps, high latencies has limited in uence too. Furthermore, PowerMatcher has the best scalability. However, in case of a shared communication medium, an individual time delay for each household should be considered. Otherwise, all households send messages at the same time. This leads to data collisions and can cause a temporary network overload. Due to the fact, that the concentrator is a part of each communication step, a performance upgrade of this node could improve the scalability characteristics even more. Furthermore, it is also possible to use more concentrators to split the load. However, PowerMatcher needs the auctioneer as a central unit and at least one concentrator.

COHDA needs the server only for an initial information about the goal consumption. The households then nd a solution totally distributed. This is advantageous because no infrastructure has to be provided by the energy manager. In COHDA, each household is only aware of its own objective. The objectives of the other households are unknown, so many messages have to be transmitted to nd a good solution. This leads to high parallel communication requirements and moderate scalability. However, for a limited number of households and communication technologies with the ability to handle a high data volume in parallel (e.g. DSL), COHDA can be well suited. Another advantage of COHDA is, that a convergence is possible, even if messages are lost or a node failure occur.

COHDA and PowerMatcher have in common, that parts of private data is disclosed. To preserve privacy fully, it is necessary that no participant knows any consumption values of any other household. This is the strength of PrivADE. It is using homomorphic encryption and is based on rounds. In this way only the server holds values of the households. However, these values are aggregated and no information about an individual household can be gained. Due to the round-based approach a large amount of sequential communication steps are necessary. On the one hand, this leads to convergence times which are strongly dependent on the latency of each household. On the other hand, there are no parallel communication steps, which limits the load of the total network. Therefore, a use of PrivADE is suitable for technologies with a shared medium like wireless communication or PLC.

Table 5 shows an overview of recommendations for the di erent algorithms.

Table 5 Recommendations for COHDA, PowerMatcher and PrivADE

COHDA	needs a network that enables high parallel communication, insensitive to high latencies, robust against node failures, moderate scalability, server only necessary for initiation
Power-Matcher	low bandwidth and latency requirements to the communication network, fast convergence, good scalability, auctioneer and at least one concentrator necessary
PrivADE	requires communication network with low latencies, good for shared medium technologies, moderate scalability, privacy preserving, one server necessary

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Energy Management will become more and more important in the future. All three analysed algorithms are highly suitable to solve the emerging problems of our scenarios. However, the requirements on the underlying communication system vary signi cantl y. If a high parallel communication network is available and a central unit is undesirable, COHDA can be recommended. If only a technology without ability of parallel communication is available and privacy is a concern, PrivADE is the best solution. However, PrivADE requires a communication technology without high latencies. If only fast convergence is required and a central unit is feasible, PowerMatcher will be the best choice. PowerMatcher has a good scalability and thus can handle very high number of households. This only requires an appropriate number of concentrators.

In future work scenarios with other communication technologies like PLC or mobile communication networks will be analysed. Furthermore, the e ects of packet loss and node failures will be evaluated.

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Energy management on a residential level can provide supplementary load shifting flexibility for upcoming smart grids, supporting increased energy efficiency by aligning load with surplus energy generated from renewables. This paper presents results from the EIT Digital Project HEGRID, in which a multi-commodity test-bed has been evaluated in Karlsruhe, Germany. The system architecture is based on the EF-Pi framework (Energy Flexibility Platform and Interface) and integrates different energy carriers (natural gas, electricity, heat). We present the device driver architecture, user interface, simulation capabilities, and energy management through drivers of device categories. Our experiments validate this multi-commodity scenario and its components in a real device test-bed and provide lessons learned from a prototype implementation of the entire stack, thus decoupling hardware-specific devices through software drivers from energy management.

.H ZRUGV Energy Management · Hybrid Energy · Multi-Commodity · Power Generation Economics · Smart Homes

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With the growing percentage of electrical energy from renewable energy sources, solutions for managing and integrating hybrid energy approaches [6, 14, 15], which utilize more than one energy source to decrease generation dependability, are becoming more and more popular in order to ensure stable and constant power supply. In this paper, we present a prototype which instead of focusing on the level of generation, puts the vision to the management and optimization of multi-commodity (electricity, gas, and thermal energy) within residential households, as introduced in related work [7, 8]. We present the results of the EIT Digital[1] HEGRID (Hybrid Energy Grid Management) which focuses on hybrid energy management on the consumer side with innovative ICT concepts.

Most other energy management systems on the market or under development consider single commodities only. Even if multi-commodity management is supported, it is usually divided into separate approaches for each commodity. For example, HomeOS [2] provides a PC-like abstraction for home technology. It provides common APIs for applications to conduct tasks involving multiple devices. Current applications developed on this system are electricity oriented and are used to implement functionality of home automation. As another approach, the Organic Smart Home (OSH) is based on the observer/controller architecture. OSH optimizes the schedule of appliances so as to minimize energy costs for residents [1]. The platform has been further developed to support multi-commodity scenarios and optimization of energy usage powered by evolutionary algorithms [7, 8]. Further work has presented an intelli-

[1] https://www.eitdigital.eu

gent home energy management algorithm for demand response applications [9]. The algorithm generates decisions for sending signals to change the appliance status by combining load priority and customers' preference settings. In essence, it implements the generation of heat and electricity by using a single commodity only (electricity) through turning on or off power switches of different appliances. A scenario, in which a general system and a mathematical model for energy management in multi-commodity energy systems are built, is available as well [10]. Its objective is to minimize the electricity exchanged with the grid connection. The closest related work to the test-bed described in this paper is another test-bed of the HEGRID project [12], which developed an optimization approach based on dynamic programming and the Energy Flexibility Platform and Interface (EF-Pi).

Parts of the following results have been compiled into internal research reports, restricted to EIT community [5, 3, 4]. In this paper, the work is published for thefirst time.

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In this paper, we utilize the EF-Pi framework [13] for the implementation and evaluation of a real device multi-commodity energy management scenario. EF-Pi connects energy devices to demand side management concepts. These concepts are implemented in form of so called energy apps, provided by demand side managers (e. g. energy retailers). The term app is not related to mobile apps, one could name it service, module or software package. EF-Pi acts as a middleware system for smart buildings in our scenario. The optimization scenario assumes a residential customer and an energy retailer selling gas and electricity to this customer. Our scenario comprises a multi-commodity device in form of a micro combined heat and power unit (μCHP) with additional electrical heating, as a bivalent domestic heating system. In such a scenario heat can be generated by gas or by electricity. Furthermore, heating by gas produces electricity at the same time, which may be sold back to the grid in case that electricity production exceeds demand. Demand side management is integrated in form of algorithms provided by the energy retailer's app. The optimization approach is based on static or dynamic prices for multiple commodities, provided by the retailer in the form of a real time tariff. The management algorithms have been specifically extended to support multiple commodities in order to be applicable to our scenarios.

The real device test-bed is provided by the Energy Smart Home Lab at the Karlsruhe Institute of Technology (KIT). It offers a running and testing environment for the prototype. This lab is a two bedroom apartment of 60 m^2. In addition to basic measurable and controllable household appliances, like dish washer and washing machine, the lab is also equipped with PV panels, batteries, a charging station for electric vehicles, etc. Particularly, a μCHP is also available in the lab. With natural gas fueling its Otto engine, the μCHP with a water storage of 750 liters is able to produce electricity and heat simultaneously. In order to enhance its functionality, the water storage of the μCHP is extended with an electrically driven heating coil as an alternative actuator to produce heat. As for the hardware installation, the μCHP provided by KIT's Energy Smart Home Lab, named Dachs, is a product of the German company Senertec, and the heating coil is a product of the German company Eltra. Due to the hybrid energy features, the μCHPis bivalent and plays a key role in our hybrid energy management scenario. Figure 1 represents a physical model of the μCHP. It shows the different kinds of energy transitions possible (e. g. electricity to heat). These different energy transitions reveal capabilities of the μCHP to leverage the hybrid energy potential. Furthermore, not only flows of energy but also flows of water are indicated.

Fig. 1 The physical model of the bivalent μCHP *[4].*

Instead of directly utilizing expensive and maintenance-intensive real hardware, a simulation environment is needed in order to pre-test the performance of the optimization solutions. This simulation environment should correctly reflect the behavior of the μCHP and hybrid energy demand in the household. Therefore, the simulation environment as outlined in Figure 2 has been created, which can approximately simulate the real environment of the household in our prototype. This simulation model consists of three main parts: a μCHP simulation, an energy app, and a building model.

The μCHP driver provides the core functionality for observation and control of real μCHPs. It can not only reflect the behavior of the μCHP but is also capable of running in a simulation mode. It hides the technical

Fig. 2 The model of the simulation environment [cf. 4]: The μCHP driver represents the buffer storage. Possible generation loads are communicated to the central energy app. A building model is used for heat demand simulation, corresponding needs are communicated to the energy app. Heat and demand matching is performed by the app.

details of the μCHP and provides a common interface for energy apps. The driver stores states of the μCHP for forecasting purposes. Furthermore, it can do simple forecasts itself based on the day before.

The energy app contains an optimization component, which integrates price models and a cost model. It collects newest states periodically from the μCHP driver and receives simulated hybrid energy demand from the building model. Taking all those factors into consideration, the energy app is able to exploit energy flexibility (e. g. flexible loads or storage availability) and make optimized decisions for the selection of the best energy carrier to satisfy the demand for heat, or to intelligentlycontrol the battery .

In the simulation environment, the building model simulates the energy demand within the household. In order to make the simulation more realistic, we used demand profiles from the Energy Smart Home Lab. Based on these profiles, the building model provides simulated heat and electricity demand in the household to the energy management app during the cost-optimized hybrid energy management scenario. Note that the drivers implemented within the EF-Pi framework provide a form of categorical device abstraction. The energy app is only aware of these drivers and the communicated information of the devices through these drivers. Thus, our work investigates the practicality of such a decoupling in our implementation.

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The prototype is based on the EF-Pi framework, a middleware platform for smart grid integration of decentralized energy resources. Within the EF-Pi framework,

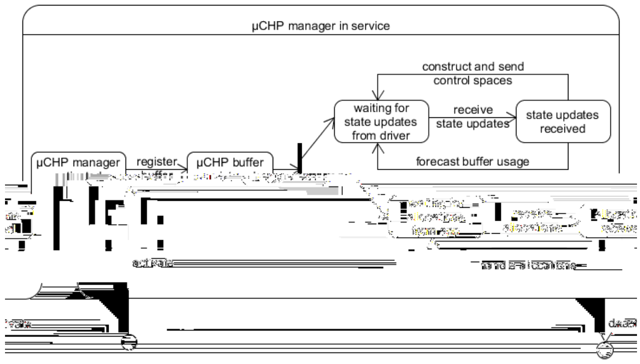

Fig. 3 The state machine diagram of the μCHP manager.

an appliance's energy flexibility is expressed in a generic structure, called control space. Devices are classified according to their characteristics of offering energy flexibility, and are cast into one of four kinds of control spaces: uncontrollable, time shiftable, buffer/storage, and unconstrained. A buffer control space, which is used for the presented work, consists of buffer leakage function, fill level information, power values for the gas burner, power values for the heating coil, minimum/maximum runtimes and charging behavior profiles. By modeling all sorts of appliances in generic control spaces, energy apps can be developed against a collection of the control space categories, and without explicit knowledge about particular devices. As a response to receiving control spaces from appliances, energy apps optimize schedules of appliances and send so called allocations to the appliances. Similar to control spaces, allocations are also generic structures, generated by energy apps to interact with different appliances. Allocations respect the constraints expressed in control spaces and indicate how the energy flexibility is to be exploited [cf. 13].

As the μCHP has a water storage, it can act as a buffer to store thermal energy by heating water. The Otto engine and the heating coil, as mentioned in the last section, are two actuators that can charge the heat buffer by using different energy carriers. The driver interface of a buffer includes the state of charge of the buffer, current running mode, leakage function, actuator behaviors, and others. Furthermore, the driver collects current states of the μCHP and compiles control spaces for the energy app. It receives and translates allocations from the energy app and further passes specific instructions on to the device. Internally, the driver consists of a driver class and a manager class. The state machine diagram of the μCHP manager class is displayed in Figure 3.

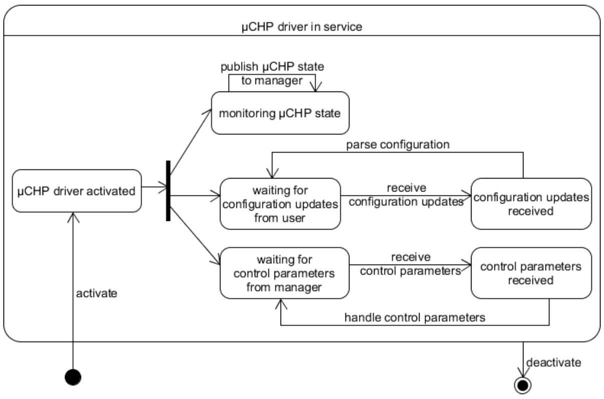

Fig. 4 The state machine diagram of the μCHP driver.

With the two aforementioned actuators (Otto engine and heating coil), the μCHP can operate in one of the following running modes:

- Idle mode
- Otto engine activated mode
- Heating coil activated mode
- Otto engine and heating coil activated mode
- Otto engine activated for legionella protection mode

With the aim of minimizing costs of procurement of energy carriers, the energy app determines the specific running mode of the μCHP. However, as a legionella protection mechanism, the device can start itself automatically if necessary. The energy app should be aware of the mode in time and adapt its optimization model accordingly.

Figure 4 shows the state machine diagram of the μCHP driver class. The specific running mode determined by the energy app is sent by the manager class as control parameters to the driver class. The driver class keeps monitoring the μCHP by periodically reporting the newest state of the device to the energy app and waiting for the target running mode from the energy app. Under the premise of satisfying the current operational constraints, e. g., the Otto engine has to run ten minutes without interruption once started up, the driver would turn to the required running mode after getting a control parameter from the manager class.

Visualization of real time device states is done via a lightweight widget-based user interface as shown in Figure 5. It presents the temperature of different parts as well as detailed real-time operational parameters of the μCHP both in reality and in simulation.

Fig. 5 The user interface of the μCHP [3].

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The implementation of the prototype of our hybrid energy management system currently runs on an off-the-shelf x86-computer which is connected to the Home Area Network. Based on positive simulation results, testing on real hardware was promising and the drivers and observation user interface have been tested with real hardware successfully [5]. Due to the fact that all devices are off-the-shelf products, the developed prototype implementation can be considered ready for commercial utilization. The combination of simulation functionality and real hardware enables powerful hardware-in-the-loop evaluations. The EF-Pi ecosystem provides several different resource apps for the simulation of devices. Based on the hybrid scenario described and further simulated components the following results have been generated, using both simulated as well as real devices.

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The energy management app observes the system state by processing the retailer tariff and messages coming from all device drivers that are present in the scenario. The retailer tariff is considered to be communicated outside the EF-Pi framework, possibly through proprietary prototcols, since our scenario foresees energy management applications to be developed by the retailers, therefore making it possible to encode any desirable tariff. In contrast, the device messages are exclusively using the EF-Pi messaging protocols. A complete system state is composed by initial device registration messages and updated over time as devices signal new information, such as control spaces or updated forecasts.

The decision problem that the energy management application faces is essentially an allocation or scheduling problem with uncertainty. The app uses the system state and available forecasts indicating demand of heat and future electricity load, and computes an allocation. In our experiments, the application receives heat and electricity demand through uncontrollable EF-Pi drivers. Similarly, the PV solar generation and its forecasts are communicated as uncontrollable. In addition, the μCHP and the battery are represented as a buffer driver. Both the μCHP and the battery have several running modes that can be controlled by allocations. The initial registration messages describe the available run modes and corresponding energy consumption and state-of-charge effects (i. e., charging or discharging the heat or battery storage). The energy management application complements the forecasts of demand with forecasts of the demand of controllable devices by projecting the energy consumption and state-of-charge effects of the current run mode into the future. If no allocations are being sent, the devices simply switch run modes according to their pre-programmed behavior. In case of the battery, it remains idle. In case of the μCHP, it switches into legionella protection mode if the temperature (communicated as state of charge in the driver) drops below a critical threshold for a certain period of time. Albeit this behavior is not known or communicated explicitly to the energy management app, the run mode specific state transitions are dependent on the state of charge and imply the default behavior.

For the purpose of the demonstration in this article, the management application preforms a heuristic optimization of the allocation problem under two external tariffs from the retailer. Both tariffs use a static gas price of 0.60 Euro/m^3, since gas can easily be stored and may thus be less likely to fluctuate, especially on the short term. In addition, the first tariff comprises a static electricity tariff of 0.22 Euro/kWh for consumption and no reimbursement of feed-in, while the second tariff employs a time-dependent dynamic price signal for both consumption and feed-in of electricity. The dynamic price signal has been derived from imbalance market data, since the purpose of energy management by the retailer is supposed to aid in the balancing of the future smart grid. More precisely, the dynamic price signal is taken from 2014 data of the Dutch imbalance market operated by TenneT [11], and rescaled to the average of 22 Euro cents per kWh. In line with the imbalance market, these prices are assumed to correspond to 15 minute intervals.

*Fig. **6** Comparison of overall consumption costs between different scenarios. Du to the feed-in tariff, overall costs could be negative (profits). Graphs for static pricing are overlapping.*

The remainder of this section presents simulation results of energy management against the simulated μCHP driver, which has been validated against a real μCHP device as described in the previous section. To this end, we first present the comparison of the end-effect of energy management on costs under two energy tariffs. Subsequently, we proceed to present plots that elucidate the behavioral effect of energy management, and which explain how and when the gains have been achieved.

The empirical results comprise four scenario runs of approximately the same length. The cost comparison is depicted in Figure 6. Each label shows one of the two tariffs, which differ by and are labeled by the electricity pricing rule (static or dynamic), and either indicates planning to imply that the energy management has sent allocations, or no planning, indicating that it has only observed the system state without interference with the default behavior. Negative consumption costs indicate reimbursement for feed-in of electricity.

The first observation is that the dynamic price tariff comes out fortunate for the consumer, whether or not energy management is applied. This is largely due to the fact that feed-in in the static case has not been reimbursed. Second, energy management does not lead to significant savings under static pricing. Our experiment corresponds to a winter day, starting at 9:00, hence PV generation does not exceed demand, which eliminates the only way of saving in this scenario. However, under dynamic electricity prices, both the battery and the heating coil can be used in times of negative or very low

Fig. 7 Runmode changes of the μCHP's Otto engine, under intelligent management and static prices.

Fig. 8 Runmode changes of the μCHP's heating element, un-der intelligent management and dynamic prices. Black shaded area indicates the actual runtime.

prices to reduce costs. Since the cause of negative prices in the imbalance market is over-production (e. g., due to the national actual PV generation exceeding forecasted supply), the residential flexibility in this case aids the balancing of the envisioned smart grid. At the same time, the local increase of load charges the battery or the heat buffer of the μCHP and thereby prepares for later savings by deferring the time at which the heat needs to be topped up by the gas-driven Otto engine or discharging the battery to meet local electricity demand.

The demand response induced by energy management can be inspected in detail by studying the running modes over time, as allocated and observed by the energy management application. The reference scenario does not show any runmode changes for the battery or heat coil, and only shows periodical forced activation of the legionella protection for the μCHP. Since there are no incentives for demand response under static prices, the behavior is equivalent, except for μCHP run mode changes now not being forced by the device, but being allocated by the management application. The following plots therefore focus on the energy management allocations under dynamic prices, which are most illustrative. For reference, the energy price has been overlayed in gray to aid in the interpretation of the behavior.

Figure 7 shows the behavior of the μCHP's Otto engine. Since the simulation is started near the legionella protection limit of the heat buffer, the energy management initially allocates the activation of the heat buffer, and then reverts to recommending idle mode. The device has a minimum running time of 30 minutes, which has not been communicated and evaluated in the prototype implementation, which explains the discrepancy between allocation and observation following the brief activation impulse by the energy management app.

The behavior of the heat coil is shown in Figure 8. At the times of negative prices the energy management application sends and observes activation of the heat coil. In line with the hardware device's parameters, the heat coil can be cycled quickly. Due to an interaction of the messaging protocol and the hardware driver, the device must be reactivated regularly to stay in operational on mode, which explains the apparent black bar in the activation times.

Fig. 9 Runmode changes of battery under intelligent management and dynamic prices.

Finally, Figure 9 illustrates the charging and discharging behavior of the battery. The demand response behavior follows the intuition that the battery charges in times of negative prices and discharges as soon and as long as possible thereafter.

Overall, these results show that intelligent energy management is possible through the device driver abstraction of the EF-Pi framework. The management heuristic has been able to perform cost-savings as long as profitable incentives are provided by the external tariff, here in the form of a dynamic price signal. Practical limitations of hardware control, especially regarding minimum runtimes, require careful calibration of the drivers. In addition, system state aggregation and aggregate forecasts projecting current run modes into the future are common functionalities that were implemented in our energy management application but would be a valuable part of any energy management framework.

This article provides an overview of a residential multi-commodity energy management scenario, and its prototype implementation with a decoupled stack of energy management against EF-Pi device driver categories, abstracting simulated and real hardware devices. By executing integration tests we have shown the practicality of such a driver-based decoupling of energy management and hardware control, using flexibility categories provided by EF-Pi. Potential future work may further strengthen these results with a complementary quantitative evaluation. Due to the restriction of real-time execution in the prototype, the results have so-far been of limited duration. Nonetheless, the preliminary results we obtained have shown a qualitative improvement of consumption behavior, leading to reduced costs in the evaluated multi-commodity scenario under dynamic pricing. This indicates that flexible residential customers may be incentivised to activate their flexibility if energy retailers offer innovative dynamic tariffs. Developing such tariffs and integrating them into the unified framework is an essential and promising future extension of this work.

FNQRZOHGJHPHQWV We gratefully acknowledge the finan-cial support from the European Commission in Horizon 2020 and EIT Digital, which provided the environment for com-posingthis paper.

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Non-Intrusive Load Monitoring (NILM) is a technology offering methods to identify appliances in homes based on their consumption characteristics and the total household demand. Recently, many different novel NILM approaches were introduced, tested on real-world data and evaluated with a common evaluation metric. However, the fair comparison between different NILM approaches even with the usage of the same evaluation metric is nearly impossible due to incomplete or missing problem definitions. Each NILM approach typically is evaluated under different test scenarios. Test results are thus influenced by the considered appliances, the number of used appliances, the device type representing the appliance and the pre-processing stages denoising the consumption data. This paper introduces a novel complexity measure of aggregated consumption data providing an assessment of the problem complexity affected by the used appliances, the appliance characteristics and the appliance usage over time. We tested our load disaggregation complexity on different real-world datasets and with different state-of-the-art NILM approaches. The introduced disaggregation complexity measures are able to classify the disaggregation problem based on the used appliance set and the considered measurement noise.

. H \ Z R U G V Complexity Measure,Time series, Non-Intrusive Load Monitoring, Load Disaggregation

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The power draw of households are composed by aggregated power profiles of appliances. By knowing the IPVTFIPMET P FS ESB P FS DPOTVN U PO O PTT CMF UP E TBHHSFHB B M BODF DPN POFOUT E TBHHSFHBU PO PS OPO BT G STUM OUSPEVDF

Up to now many different techniques and algorithms were published to solve the problem to disaggregate load profiles. A comprehensive overview of the state-of-the-art is presented in [2, 3]. To be able to improve the state-of-the-art of load disaggregation, it is necessary to compare different approaches in a fair way. A comparison between algorithms is possible with facts such as how many features are used or on which sampling frequency is the algorithm able to work. Also algorithm comparisons with qualitative measures such as accuracy, F-score or Hamming distance are widely used and applicable. But an algorithm comparison lacks of the ability to compare the results on problem level even if the same dataset was used. Unfortunately, a fair comparison between different algorithms on problem level is not possible due to the fact that recent approaches depend on different conditions and features such as the sampling frequency, the number of observed appliances, the appliance type, signal preprocessing and the set of used appliance features. In particular, the detected and used appliance power states for classification can complicate the load disaggregation process due to erroneous power states and similarities between power states. The choice of power states and accordingly, the choice of appliance characteristics is highly affecting the load disaggregation process which was also stated by the initial work of Hart in [1]. Therefore, there is the need of a common quantitative measure for NILM which is algorithm independent and considers data assumptions as well as data pre-processing. The problem itself has to be made comparable which is created by the used appliances in a house, their appliance characteristics and their usage over time. The measure should make it possible to provide the possibility of a quantitative rating of the disaggregation problem with its model and processing assumptions.

A possibility to make the load disaggregation problem comparable is to describe the complexity of the problem as a time series of aggregated power loads. To describe the complexity of time series different complexity measure were proposed, for example entropy-based complexity measures [4, 5, 6]. These measures are used for different applications such as DNA [7, 8] sequences or EEG [9, 10, 11] signals. In contrast to these applications the problem hardness of load disaggregation is difficult

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H I UW VWULD

[1] The terms NILM and load disaggregation are used in the same context and are replaceable throughout this paper

to describe with these measures due to the high variety of different appliances, their different ways to consume energy and their high time-variant behavior introduced by the users. The load disaggregation problem is thus highly time-variant and model dependent. It is therefore necessary to involve appliances, their characteristics as well as the time dependent behavior into the evaluation of a possible complexity measure.

In this paper, we propose an approach to make the disaggregation problem of aggregated power demands comparable by introducing two novel load disaggregation complexity measures. To the best of our knowledge, this is the first approach summarizing the disaggregation problem as a complexity value created by statistical characteristics of the appliance set and the time series. A similar approach was introduced in [12] stressing fundamental limits of NILM. The authors derive an upper bound on the probability to distinguish scenarios for NILM algorithms to guarantee on when NILM is impossible without using privacy ensuring approaches, like the one presented in [13]. The work in [12] differs from our approach as we try to make the problem of superimposed loads comparable with the used appliance characteristics not considering a specific NILM modelling approach. In addition, Pöchacker in [14] presents a measure based on the proficiency of power values for the load disaggregation problem which can be interpreted as a complexity measure for load disaggregation. He models the problem as an information theoretical problem in which the power states are interpreted as the accessible channel for the transmission of a set of possible device states. With this assumptions, he computed the entropy, the mutual information and proficiency of synthetically generated and real-world based power values. The work in [14] is different from to the presented approach since we are considering model and measurement uncertainties and trying to reflect real world effects and challenges to be handled by a load disaggregator.

The two proposed disaggregation complexity merits are evaluated on real-world data and compared to the disaggregation results of state-of-the-art NILM algorithms.

The remainder of this paper is organized as follows: Section 2 identifies difficulties of load disaggregation and discusses complexity influencing factors for NILM. With this knowledge an appliance set complexity and a time series complexity are defined in Section 3. Section 4 specifies the used appliance datasets, the way to extract possible power states out of measurement data and the load disaggregation approaches used. Section 5 presents three case studies to review the complexity measures according to their suitability and meaningfulness for description of load disaggregation problems. Section 7 concludes the paper.

2. Complexity of the Power Draw makes Hardness for Disaggregation

The input for a load disaggregation process, as sketched in Figure 1, is the (households) power draw $P(t)$ that is generated by the usage of devices. The output of the load disaggregation allows to conclude about the device states and usages scenarios. Some characteristics of the single devices must be known by the load disaggregator, in many cases it is power or energy consumption values. For supervised disaggregation approaches the characteristics are known *a priori* or entered by experts. The more advanced unsupervised disaggregation algorithms extract the needed feature from the power draw, remember it and can so learn by themselves. A specific

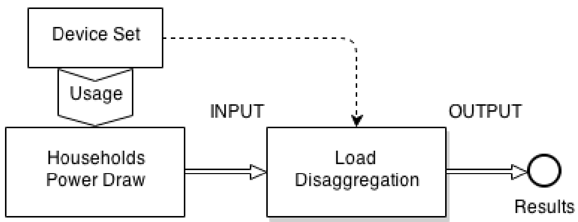

Fig. 1: The shape of the power draw is of high relevance for the success of load disaggregation. The complexity of the input should be assessed independent from the performance of disaggregation.

power draw can be simple or hard to disaggregate, depending on the way of *usage* of the same set of devices. In other words power draws comply differently with the disaggregation algorithms. We claim a clear distinction of the hardness of the problem and the performance of load disaggregation.

The general assumption for NILM is that the appliance or device set is known through its main characteristics, e.g., the power consumption. The specific severity depends upon the approach of the specific disaggregation algorithm. The aim is now to define a complexity measure that describes load disaggregation problems by a comparable quantity. The complexity measure should be independent from the used load disaggregation approach and describe the problem of aggregated power loads.

A power draw is the superimposition of the appliance power profiles over time as

$$P(t) = p_1(t) + p_2(t) + \cdots + p_N(t) \text{ for } t \in \{1, T\} \qquad (1)$$

where N represents the number of used appliances. The problem of load disaggregation is to gain single appliance power consumption components $p_n(t)$ out of the total households power draw $P(t)$. Each power profile p_N is described by the consumed energy, by the appliance power states (e.g.: on/off appliance, multi-state appliance) and the appliance usage (e.g.: fridge with periodic usage, TV with common usage times) over time. A complexity measure of load disaggregation has to be able to represent this fact. General facts influencing the hardness of a load disaggregation problem are as follows:

1. The complexity of aggregated loads is increasing with increased number of appliances due to higher probability of ambiguous power draws.
2. The higher the switching frequency of devices (like in the case of periodic performing appliances such as a fridge), the more complex is a device set.
3. Appliances with several operation states (i.e., multi-state appliances instead of simple on/off appliances) make a device set more complex.
4. The higher the similarity between appliance features, the more complex is the problem. Examples are devices with similar power values or consumption shapes.
5. Additional noise and measurement uncertainty, unknown or not considered appliances interfere with the household power draw and increase the complexity of the problem. The presence of noise typically increases the number of possible interpretations of a power draw.

A power draw can be generally interpreted as a stream of symbols. The Shannon entropy [15], which corresponds the averaged information of all possible streams, can be calculated if the symbol occurrence probabilities are known (or can be assumed). The set of possible symbols is then defined by the power values (or other attributes) of single devices and their possible combinations, respectively. Entropy reflects the difficulties in NILM related to the number of involved appliances and their likelihood in the power draw. Also noise could be included in a continuous formulation of Shannon's entropy. But there is the problem that entropy states about average information of all possible streams or the so called typical sequences. So far it is unknown whether load profiles are typical sequences in that sense. Furthermore, the difficulties for NILM due to very similar or equal power values for different states are not reflected in the entropy concept. Complexity measures based on statistical averaged information are therefore not sufficient.

Computational complexity theory can be used to describe the way and complexity to find the best solution. The theory of computational complexity is widely applied to quantify the difficulty or hardness of computational problems. It is used to answer whether a (type of) problem is solvable at all or how the calculation time scales with the problems size. In that sense load disaggregation is shown to be NP hard by Hart [1]. In general, the term complexity characterizes systems with a non-trivial number of parts with non-trivial relations [16]. In other words, complexity can indicate a high number of non-linear interactions between the involved entities. In the context of appliances and their aggregated power demand, the complexity of the disaggregation problem is the interaction of different appliances with each other in which each appliance has different characteristics and is used in different ways by users.

The approach of Kolmogorov Complexity[15] follows the idea to describe the complexity of a stream by the length of the shortest possible program that can generate this specific stream. It is especially helpful for loop-like structures as in the day, week and annual circles of power profiles. In this context the device usage is interpreted as a program that is producing the stream. The disaggregation algorithm would be somehow an "inverting" program. A periodic device profile would be simple in this sense, still many NILM approaches have difficulties in its disaggregation. The average Kolmogorov complexity of all possible streams approaches the Shannon Information as shown by [15, 17]. Still Kolmogorov complexity is more a theoretical concept and there is currently no general method to estimate it. It can be well approached in practice but it remains the uncertainty about existence of a shorter (undiscovered) solution. The specification of load disaggregation problems requires a complexity measure that is calculable like the Shannon entropy.

As the Shannon Entropy and the Kolmogorov Complexity fails to entirely describe the difficulty of a load disaggregation problem, we introduce a new complexity measure in the next chapter which aims for following requirements:

1. Describes the load disaggregation problem and should not be dependent on the load disaggregation approach.
2. Includes appliance descriptions as number of states and the similarities between appliances and states.
3. Should be applicable to time series to describe the influence of appliance usage affecting the used NILM approach.
4. Should be easy and understandable as standard complexity theories.
5. Must not be a general complexity merit. It is an application dependent complexity measure to make load disaggregation problems comparable without considering the load disaggregator.

3. Novel Complexity Measure for Load Disaggregation

In this work we follow the idea that all possible power values of an aggregated household power draw are combinations of possible power states of appliances. This requires the load disaggregator to find the best matching combination of power states with the measured power value. The measured power value is influenced by noise and should be approximated as good as possible enabling the load disaggregator to decide which appliances are running. The general idea of the novel complexity measures is to relate an observed power value to all possible power state combination under the influence of measurement noise as well as erroneous appliance modelling.

3.1 Appliance Set Complexity

One of the major factors influencing the complexity of aggregated power profiles, is the set of possible power values. The more complex the appliance model and their operational states are, the more complex is the problem to disaggregate them. In general, the appliance set is composed by N different appliances. With the knowledge of the appliance set and power states of each appliance, the first step is to compute the number of possible aggregated power values M. In case of two-state devices there are 2^N possible combinations. In general there are

$$M = 2^{N_2} 3^{N_3} \cdots = \prod_{Z=2}^{Z_{max}} Z^{Nz} \tag{2}$$

different possible power values, where N_2 is the number of appliances with two states, N_3 with three states and so forth. For the calculation of all possible aggregated power values P_i repetitions of the same value are possible, for instance if a water kettle and a coffee machine consume the same power. Exceptions are the zero Watts (0W) power state (all off) and the all-on-state P_M which is the highest possible power value. The vector P is the set of all possible (aggregated) power values P_i for a set of appliances, where i is defined as $i \in [1, M]$.

In its simplest form a NILM device observes a power value and compares it to all possible values P_i given by the device set. As long as there is one single matching power value in the set the task is solved straight forward. The problem is harder if either are two or multiple matching values or if the value is not in the set at all. For the disaggregation complexity measure we reason that it should contain something like a multiplicity or occupation number of the possible power values to reflect its multiple occurrence. While it does not occur in ideal NILM problems it is likely in reality that a measured power value does not match exactly to any of the M aggregated power values. Therefore, we propose to represent the possible power values by a probability distribution function instead of a single value. It is possible to estimate for a power value, which would not be explainable in the discrete set, the probability for being caused by a respective nearby power state. This approach covers also uncertainties caused by adjacent power values which hardly can be distinguished, e.g. through insufficient measurement accuracy in the NILM device. A simple measure for the similarity of two distributions is the overlapping coefficient

$$\mathrm{OVL}(f_1, f_2) = \int_x \min(f_1(x), f_2(x))\mathrm{d}x \tag{3}$$

which gives the intersection area of the two distribution curves f_1 and f_2 as stated in [18].

For a load disaggregation complexity measure C we propose to estimate the similarity of one power value distribution to all the other possible aggregated power valued distributions. The possible power values are expected between 0 and P_M. By use of the overlapping coefficient the disaggregation complexity measure for the power state P_k is defined as

$$\begin{aligned} C_k &= \sum_{j=1}^{M} \mathrm{OVL}(f_{P_k}, f_{P_j}) \\ &= \sum_{j=1}^{M} \int_0^{P_M} \min(f_{P_k}(p), f_{P_j}(p))\mathrm{d}p \quad . \end{aligned} \tag{4}$$

C_k is the disaggregation complexity of the power value P_k within the set of M power state combinations. The parameter k determines the chosen reference power state combination, where $k \in [1, M]$. In case the exact distribution of the power values are not known, it is reasonable to assume a normal-distributed probability density function (PDF) $\mathcal{N}(\mu, \sigma)$. The mean value $\mu = P_k$ represents the mean observed power value and the variance σ expresses measurement and model uncertainties. The variance σ is highly influencing the result of C_k. This represents also the reality because inaccurate power measurement or errors in the appliance modelling process are highly affecting the load disaggregation process. The higher the possible fluctuations of power values, the higher the changes of wrong detected appliances due to similarities and uncertainties.

Figure 2 sketches an example how to estimate the disaggregation complexity. For a given set of three on-off devices with nominal power of 10, 20 and 35 Watts we estimate the complexity for the power value P_k of 30 that represents the case when device one and

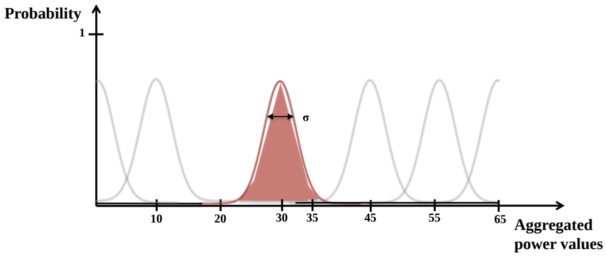

Fig. 2: A sketch of the different PDFs for each power value produced by the combination of all available power demands of an appliance set. The appliance set consists of three on-off appliances with demands of 10, 20 and 35W.

two are turned on. The set has $M = 8$ possible power values in total. Each power state is represented by the same normal distributed PDF. The final disaggregation complexity value is then the sum of all overlapping areas A_M. The largest three areas A_1, A_2 and A_3 for this case are labeled in Figure 2. The introduced disaggregation complexity C can be interpreted as a similarity factor of power states in the appliance set.

To evaluate the complexity of an appliance set, it is now possible to apply the introduced disaggregation complexity for each possible combined power value. This yields information which power values and therefore appliance state combinations are more complex than others. Accordingly, a disaggregation complexity C of 1 means that at least one solution or appliance state is equal to the wanted power value. But it can also mean that two power value distributions match with similarity 0.5. The disaggregation complexity $C = 2$ means that in the case of two appliances each of them have indistinguishable power demand. Exceptions are the all-off power state (0W) and the maximum power demand P_M. Through to bounds of the complexity computation by $[0, P_M]$ these states show a value of $C = 0.5$. The values of C depend as well on the chosen variance σ of the PDF. The variance σ can be considered as a adjacency or similarity factor between power state combinations as well as a noise and uncertainty factor affecting the power draw. The higher the value of σ, the higher is the probability of intersections between power values. This means the higher σ the higher is the appliance set complexity.

Finally, a whole appliance set is characterized by its power states complexity spectrum that shows the complexity value for each of the aggregated power state values. The power states complexity spectrum shows at which regions confusions of states and therefore wrong appliance detections are more likely.

3.2 Time Series Complexity of Aggregated Power Profiles

The introduced disaggregation complexity C considers the appliance set and similarity of possible power states but does not refer to a specific aggregated power profile. Therefore, we introduce the time series disaggregation complexity C_{total} which is basically a weighted average of the complexities of the power values within a time series. It considers the appliance set implicitly through the disaggregation complexity. The usage of the different appliances is reflected by the power values in the profile. We define the time series disaggregation complexity of an aggregated power draw as

$$C_{total} = \frac{1}{T}\sum_{t=1}^{T} C_t = \frac{1}{T}\sum_{t=1}^{T}\sum_{k=1}^{M} \mathrm{OVL}(f_{P_t}, f_{P_k}) \quad , \qquad (5)$$

where T represents the number of observed power samples. This disaggregation complexity C_{total} describes the averaged complexity of observed power values within all possible appliance state combinations for the whole observation time. Calculation of C_{total} requires knowledge of the respective appliance set, i.e., their number of states, the power values and their distribution (or reasonable assumptions about it). The complexity C_{total} provides feedback at which point in time a complex power state combination is occurring. This is based on the observed power value and the possible power state combinations.

4. Evaluation Settings

4.1 Real World Dataset

To test the proposed complexity measures on different test cases, we performed our complexity study on three different datasets. The first choice was the open REDD dataset [19]. We have chosen three different houses with 6 appliances having a significant affect on the households power demand [20] from the dataset. Furthermore, we used the open dataset GREEND [21] which documents an appliance level measurement campaign in Austria and Italy. As in the case of the REDD dataset, we used 3 houses with 6 different appliances. Finally, we also selected the ECO-Dataset [22] for our evaluations. It contains electricity consumption and occupancy data from 9 Swiss houses. 3 houses with 6 different appliances were chosen. Table 1 lists the appliances for each house and dataset. For evaluation we have chosen the whole observation time for the REDD dataset and two weeks from the GREEND and ECO-dataset. This condition is valid through the rest of the paper if not mentioned differently.

Dataset	House	Appliance Type	Detected Power (submetered)	Detected Power (aggregated)
REDD	*1*	oven, fridge, dishwasher, microwave, stove, washer dryer	[1680 2478], [200 420], [50 210 410 890 1115], [55 110 270 300 620 1405 1505], [260 710 1440], [2705]	[55], [200], [250], [410], [710], [890], [1078], [1368], [1620], [17425], [2270], [2504], [2670]
REDD	*2*	kitchen outlet 1, lighting, stove, microwave, kitchen outlet 2, fridge	[130 210 770], [123], [410], [40 1718 1850], [1050], [160 420]	[90], [145], [245], [310], [410], [600], [770], [937], [1060], [1752], [1885]
REDD	*3*	fridge, dishwasher, washer dryer, microwave, bathroom gfi, kitchen outlet	[100 400], [210 525 730], [2265], [120 540 1698], [860 960 1285 1605], [40 365 900 1220 1520]	[70], [120], [205], [270], [370], [535], [730], [960], [1274], [1676], [1835], [2197], [2367], [2630]
ECO	*1*	fridge, dryer, coffee machine, kettle, washing machine, PC	[40], [250 440 785], [50 1225], [1800], [90 180 250 365 21688], [72]	[105], [245], [335], [545], [900], [1232], [1800], [2170]
ECO	*2*	diswasher, fridge, entertainment (stereo system and TV), Freezer, water kettle, dimmable lamp	[120 2132], [70], [55 175], [50 310], [50 1840], [80 185]	[110], [190], [280], [510], [18689], [2108]
ECO	*3*	fridge, kitchen appliances (coffee machine, bread baking machine and toaster), lamp, freezer, entertainment (stereo and TV), microwave	[100], [67 190 280 445 650 785 1065 1545], [130], [100 175 280], [120], [40 1365 1485]	[80], [135], [195], [265], [435], [668], [841], [1007], [1185], [1386], [1565]
GREEND	*1*	coffee machine, washing machine, fridge, dishwasher, water kettle, vacuum cleaner	[60 148 470 570 1225 1265], [70 155 210 260 423 1898], [55 140 240], [40 1900], [1790], [1220]	[110], [239], [448], [540], [1267], [18967]
GREEND	*2*	fridge, dishwasher, water kettle, washing machine, dryer, bedside light	[80], [80 1725], [850], [90 173 1910], [1580], [60]	[92], [182], [845], [1583], [1775], [1900]
GREEND	*3*	TV, washing machine, dryer, dishwasher, kitchenware, coffee machine	[110 235 285 360], [125 245 358 1998 2100], [70 160 2358 2550], [70 2002], [120 1235], [55 125 540 882 1047 1220 1630]	[110], [295], [530], [863], [1043], [1230], [1635], [1920], [2093], [2355], [2554], [2830]

Table 1: List of datasets (REDD, ECO-dataset, GREEND) with 6 chosen appliances and their appliance power states detected for submetered power draws and the aggregated power draw.

4.2 Identification of Appliance Power States

To be able to compute the two complexity measures, the set of all possible (or at least occurred) power states is required. If meta data provides this information, it could be used, but for most datasets this information is either not provided or not in the desired extent. Accordingly, the most obvious approach would be to use expert knowledge to identify the appliance states and their power demand. But this process is time consuming and erroneous. Therefore, an automatic state detection algorithm is required. In this paper we used an automatic state detection described in [23] and state results provided by NILMTK [24]. NILMTK is an open-source toolkit to evaluate the accuracy of NILM approaches. At first, we concentrate on the state detection provided in [23]. It automatically detects the most common power states in any used power draw. The state detection can be done from submetered measurement data or from the aggregated power measurements. For both scenarios different outputs are produced in which the submetered measurements can produce multi-state power states of appliances. Consequently, similarities between appliances and their power states are possible. In contrast the aggregated power measurement data is producing a set of power states without any information of appliances and their number of states. It is only detecting different power states and not different appliances. Considering this input case, no similarities between appliances are possible. The algorithm tries to find a unique set of power states. However, we want to clarify that the use of this detection approach is not necessary for the calculation of the complexity values. The complexity values can be applied to any detection approach providing a set of appliance power states in which the appliances are described as on/off or multi-state appliances. Therefore, the second used approach of this paper is provided by NILMTK. In detail, this toolkit is an open-source Python toolkit[2] providing two implemented load disaggregation approaches: combinatorial optimisation (CO)

[2] https://github.com/nilmtk/nilmtk

and factorial hidden Markov model (FHMM). The CO approach is based on the seminal work of Hart [1] and the FHMM approach is based on extension of the works [25] and [26]. These two algorithms provide appliance model information such as power states used by the algorithm. This state information from NILMTK is used by our complexity measures. All other case studies and their corresponding appliance states are created by the algorithm proposed in [23].
The results are listed in Table 1. The detected states for NILMTK are provided in Table 3.

4.3 Load Disaggregation Algorithms

The proposed complexity values should describe the hardness to disaggregate power draws. To get an idea how meaningful the proposed complexity approaches are, the results should be compared to the results of an appropriate and suitable load disaggregation approach. This comparison should give a quantitative feedback if the complexity value is meaningful according to the used load disaggregation algorithm. We claim that the load disaggregation approach needs to have the same inputs as described in Section 2 to be able to provide meaningful results. Therefore, we used the approach of [27] and the approaches provided from NILMTK [24].
In [27], the approach is based on Particle Filtering (PF) and used appliance models created by Hidden Markov Models (HMM)s. The aggregated power draw is modelled by an Factorial Hidden Markov Model (FHMM). For the evaluation the PF is parametrized as in [27] in which the number of used particles, as most important parameter, is set to 1000 particles.
As mentioned in the previous section, NILMTK provides two implemented load disaggregation approaches. One approach is based on combinatorial optimization and the other approach is based on FHMM.

5. Case Study

5.1 Appliance Set Complexity for Different Datasets and Different Sets of Power States

As described in the previous sections, the appliance set complexity is aiming to describe the complexity of the used appliance set without considering the appliance usage over time. Therefore, the most relevant parameter are the used power values for each appliance power state and the value[3] $\sigma = 5W$ representing measurement and model uncertainties. These power states are identified for each appliance using the algorithm presented in Section 4.2.

Dataset	House	submetered		aggregated	
		max	*mean*	*max*	*mean*
REDD	*1*	16.91	7.88	2.28	1.48
REDD	*2*	6.170	2.62	2.32	1.33
REDD	*3*	21.39	8.69	1.98	1.32
ECO	*1*	6.65	2.88	2.67	1.36
ECO	*2*	12.06	4.75	1.44	1.04
ECO	*3*	16.62	6.53	1.59	1.15
GREEND	*1*	18.20	7.17	2.01	1.19
GREEND	*2*	4.46	2.18	1.36	1.07
GREEND	*3*	48.36	24.43	1.87	1.18

Table 2: List of mean and maximum of the appliance set complexity for each house and dataset

In this case study the appliance set complexity is tested on the appliance set based on aggregated power readings and on submetered power readings from Table 1. As input for the complexity computation a vector of all possible power state combinations of the appliance set is used. The results are presented in Table 2 using the mean and the maximum value of the appliance complexity. The complexity values for submetered data are higher and therefore more complex than for the aggregated power readings. As reason we claim that similarities between appliances are getting lost in the case of aggregated loads due to the inability to distinguish between appliances. With aggregated power readings it is only possible to distinguish between different power states. This also leads to the fact that the problem complexity for the same house of a dataset differs between appliance sets created by the aggregated or the submetered power data. This strengthens the need of a complexity measure due to different preprocessing stages of power data. However, appliances produced by submetered data are affected by power state similarities and have therefore a higher appliance set complexity. We also provide Figure[4] 3 which presents the appliance set complexity for each dataset over all possible power state combinations. It is based on the appliance states produced by the submetered power readings. The plot shows for each possible power state combination the appliance set complexity. The color white means that the appliance set complexity is zero because this power value is not producible by a combination of saved power states for a certain dataset and house. The appliance set complexity starts from green (low complexity), blue (medium complexity) and ends at red (high complexity). The colors are normalized according to the dataset with

[3] $\sigma = 5W$ is valid for the whole paper and was empirically identified as sufficient

[4] For readability please consider coloured prints

Dataset	**House**	**Appliance Type**	**Detected Power (CO)**	**Detected Power (FHMM)**
REDD	*1*	washer dryer, microwave, light, socket, fridge, light	[0 452 2779], [0 71 1518], [0 65 98], [0 82 282], [0 193 459], [0 23 70]	[0 668], [0 4 998], [0 67], [0 2 90], [0 6 200], [0 22 54]
REDD	*2*	microwave, sockets, sockets, light, fridge, dishwasher	[0 45 1839], [0 14 775], [0 285 1058], [0 29 146], [0 162 428], [0 209 1198]	[0 10 1730], [0 5 721], [0 1 1052], [0 9 132], [0 6 165], [0 2 1198]

Table 3: List of detected power states for NILMTK with CO and FHMM

Fig. 3: Colormap of the appliance set complexity for the REDD, ECO and GREEND houses over all possible power combinations.

the maximum occurred appliance set complexity. Figure 3 shows which dataset and house is more complex according to the used power states presented in Table 1. For example, house 2 of the GREEND dataset has a very low appliance set complexity while house 3 of the same dataset has a very high and tight appliance set complexity.

5.2 Time Series Complexity for Different Datasets and Different Sets of Power States

The appliance set complexity gives feedback about the complexity of the used appliances by comparing their power states and appliance structure. For the load disaggregation problem another important factor is the influence of the appliance usage over time. This considers how and when appliances are operated which could be for example user driven (e.g., coffee machine, TV) or periodically activated (e.g., fridge). The proposed time series complexity considers this circumstances in its computation. For the evaluation of this complexity measure the time series of all houses and datasets for an observation window of half day are considered. The input for the complexity computation are the measurement samples which are combinations of possible power states affected by noise. In contrast, the appliance set complexity considers power state combination without noise as input for the complexity computation. As for appliance set complexity, appliances based on aggregated and submetered power data are used. In Table 4 the mean and the maximum of the time series complexity for all houses and datasets are presented. The time series complexity is highly affected by the appliance usage. We claim that even complex appliance sets as the house 3 of the GREEND dataset can have a low time series complexity when the appliances are sparsely used over time. Thus, the appliance set complexity and the time series complexity do not necessarily correlate. A snippet of a time series of house 3 of the ECO dataset with corresponding complexity values for each measurement sample is presented in Figure 4. The colors white and green means low complexity, blue means medium complexity and red means high complexity. The coloring is normalized to maximum occurred complexity value for the considered observation time and measurement samples. Comparing the colormap with the time series shows that overlapping behavior results in an increased and high complexity value while high power values do not necessarily results in a high complexity.

Fig. 4: Time snippet of the power readings for house 3 (ECO dataset) with a colormap of the time series complexity per sample

Dataset	House	submetered		aggregated	
		max	*mean*	*max*	*mean*
REDD	*1*	13.79	1.04	1.62	0.50
REDD	*2*	5.39	0.54	2.32	0.11
REDD	*3*	17.54	1.07	1.98	0.35
ECO	*1*	3.71	0.95	2.62	0.15
ECO	*2*	11.99	2.86	1.11	0.19
ECO	*3*	14.77	4.91	1.57	0.41
GREEND	*1*	7.77	0.89	1.06	0.12
GREEND	*2*	4.305	0.91	1.35	0.50
GREEND	*3*	45.01	3.67	1.81	0.04

Table 4: List of mean and maximum of the time series complexity for each house and dataset

Dataset	House	Appliance States
REDD	1	[1690 2455], [190] [210 410 880 1110], [60 1533], [260 710 1440] [2712]
REDD	2	[770], [145], [410], [1875], [1050], [160]
REDD	3	[120], [210] [2255], [130 1740], [960 1290 1610], [360 900]
ECO	1	[40], [780], [50 1205], [1795], [80], [90]
ECO	2	[120 2060 2170], [70], [55 178], [50], [1845], [160]
ECO	3	[100], [55 1085 1520], [130], [100], [120], [1330 1567]
GREEND	1	[50 1270], [55 1840], [50 140], [40 1900], [1790], [1220]
GREEND	2	[80], [80 1730], [850], [90 160 1910], [1580], [60]
GREEND	3	[60], [72 2020], [160 2415], [70], [1230], [1030]

Table 5: Appliance set used by the load disaggregation approach.

5.3 Load Disaggregation of Complexity Marked Power Readings

In this case study the results of the complexity measures are compared with the results of a NILM approach on the same power data. The aim is not to evaluate the used disaggregation approach. This evaluation should give a feedback about the suitability and meaningfulness of the proposed complexity measures. As described in Section 4 we used the load disaggregation algorithm from [27] which is able to handle on/off and multi-state appliances and the NILMTK framework of [24].

5.3.1 Evaluation based on the approach of [27]

Table 5 shows the appliance set and models identified by the submetered measurements. We assume the availability of ground truth data for the evaluation as reason to use the submetered data and not the aggregated power readings. The appliance set detected in Table 5 compared to the listed ones in Table 1 are different because the appliance state identification algorithm from Section 4 was considering only the most common appliance power states. We defined power states as most common appliance power states if a detected power state occurred as often as 15% of the maximum occurred power state. We used power readings of a whole day to calculate the time-series complexity. The load disaggregation algorithm is evaluated according to the real and estimated energy per kWh on appliance level and to the aggregated power readings. The results for each house and dataset for all used appliances are shown in Table 6.

Less complex time series, like in REDD house 2, are easier to disaggregate than more complex time series, as for instance ECO house 2. Similar power states as for example in house 1 and 2 in the ECO dataset are highly affecting the load disaggregation result. In the

Dataset	House	App. 1 *real/est.*	App. 2 *real/est.*	App. 3 *real/est.*	App. 4 *real/est.*	App. 5 *real/est.*	App. 6 *real/est.*	**Total** *real/est.*	**AC** *mean/max*	**TC** *mean/max*
REDD	1	0.13/0.22	1.27/0.98	0.31/0.43	0.53/0.21	0.003/0.32	0.0/0.06	2.23/2.21	2.97/9.06	0.41/4.64
REDD	2	0.19/0.13	0.82/0.99	0.05/0.28	0.29/0.05	0.24/0.20	1.67/1.44	3.26/3.01	2.01/4.69	0.23/1.27
REDD	3	1.08/0.94	0.16/0.25	0.70/0.78	0.20/0.29	0.69/0.87	0.33/0.34	3.17/3.46	1.69/3.78	0.40/4.09
ECO	1	0.54/0.35	0.001/0.04	0.23/0.26	0.0002/0.02	0.002/0.34	0.49/0.26	1.27/1.27	1.469/2.69	0.84/2.59
ECO	2	0.0/0.05	0.53/0.61	0.86/0.067	0.71/0.54	0.30/0.31	0.01/0.82	2.39/2.40	2.72/5.83	0.758/3.038
ECO	3	0.66/1.18	0.48/0.32	0.073/1.55	4.18/1.26	0.54/1.46	0.42/0.48	6.30/6.25	2.34/6.45	0.54/2.66
GREEND	1	0.11/0.29	0.0/0.10	1.20/0.32	0.01/0.41	0.0/0.03	0.0/0.081	1.32/1.24	2.57/6.04	1.08/5.15
GREEND	2	0.55/0.43	0.81/0.04	0.0/0.03	0.0/0.04	0.19/0.82	0.0/0.196	1.56/1.55	1.07/1.27	1.002/3.023
GREEND	3	2.59/0.49	0.93/0.94	1.94/1.60	0.65/0.58	0.08/1.50	0.19/1.40	6.37/6.48	1.73/4.01	0.42/2.15

Table 6: List of the load disaggregation result (real and estimated) on appliance level and in total for all houses and datasets. For comparison also the appliance set complexity (AC) and time-series complexity (TC) are shown.

case of similar power states the algorithm is not able to distinguish between appliances with similar power states which is supporting the need of a common complexity measure for load disaggregation. By using a different power state identification setting also the appliance set complexity compared to the previous case studies is different. This also strengthens our assumption to have a complexity measure handling the set of appliance power states independent from the used load disaggregation algorithm.

5.3.2 Evaluation based on NILMTK

For the evaluation with NILMTK we used the appliance sets of Table 3 for house 1 and 2 for one week. We evaluated the results with NILMTK by presenting the achieved F-measures. Moreover, we calculated the appliance set and time series complexity. The results are presented in Tabel 7. Evaluating the F-measure for the different load disaggregation approaches (CO and FHMM) for the different houses, the more advanced approach based on FHMM achieved better results independent from the achieved complexity measure. The time series complexity for both houses are nearly the same. This shows that the measures describe the problem based on occurring power states but do not evaluate the used load disaggregation approach. Therefore, creating a relation between the load disaggregation result and the complexity measures is not directly possible.

6. Discussion

In the previous section different case studies were presented to evaluated usefulness of the proposed complexity measures. For example in the case study for the appliance set complexity the complexity is highly dependent on the used appliance set. The number of devices several states and similar states between appliances are affecting the load disaggregation complexity strongly. Thus, we claim that the preprocessing stage has an important effect on the problem complexity and accordingly also on the result of the used load disaggregation process. This fact is also valid for the time-series complexity. The time series complexity is highly affected by the appliance usage. We claim that even complex appliance sets as the house 3 of the GREEND dataset can have a low time series complexity due their appliance usage over time. Thus, the appliance set complexity and the time series complexity do not correlate between each other. For example a high appliance set complexity can lead to a low or a high time series complexity. We also show that the proposed complexity measures can classify the complexity of a load disaggregation problem but do not evaluate the used load disaggregation approach. The result of the load disaggregation approach cannot be estimated by our proposed approach but gives an indication which problem is more complex (see Section 5.3.1). In addition, it has to be considererd that different approaches need different inputs and therefore produce also different load disaggregation results (see Section 5.3.2). In this case, the complexity measures do not make the problem comparable because the used power states are algorithm dependent. To show which algorithm is performing better, the input of the data should be same. Finally, also the influence of σ has to be discussed. The choice of σ represents the noise influence and modelling errors of the used power states. The higher the value, the more complicated is the problem to disaggregate loads. The choice of σ has to be chosen carefully based on experiments and on ground truth informations. In this work, the choice of σ was determined on empirical analysis of known state detection algorithms and expert knowledge.

7. Conclusion

This paper defined two complexity measures for the problem of load disaggregation which deals with the task

Dataset	House	App. 1 *real/est.*	App. 2 *real/est.*	App. 3 *real/est.*	App. 4 *real/est.*	App. 5 *real/est.*	App. 6 *real/est.*	AC *OC/FHMM*	TC *OC/FHMM*
REDD	1	0.13/0.2	0.05/0.3	0.42/0.78	0.56/0.99	0.52/0.63	0.55/0.33	3.87/4.89	3.46/3.62
REDD	2	0.29/0.22	0.51/0.51	0.09/0.14	0.36/0.38	0.59/0.88	0.06/0.32	3.61/10.4	1.81/2.76

Table 7: Results of NILMTK for the complexity measures AC and TC in comparison with the load disaggregation results

to break down the aggregated power draw of appliance to the appliance components. Appliance characteristics and smart algorithms are used to solve this task. One important aspect is the distinction between the disaggregation approach itself and the problem of aggregated power profiles. Beside clear performance measures for NILM algorithms it needs a clear definition to specify the hardness or complexity of a specific aggregated load profile. This makes a fair comparison of different NILM approaches possible with respect to the complexity of the used load disaggregation problem. To overcome the lack to compare load disaggregation problems we introduced two novel complexity measures to assess the complexity of a load disaggregation problem based on the used appliance sets. With the proposed complexity measures the used appliance sets and the aggregated power readings are evaluated for their complexity. To evaluate how the disaggregation complexity measures are reflecting load disaggregation problems in reality, we performed the complexity calculation and load disaggregation with state-of-the-art NILM approaches on different datasets and time-series. Our evaluations show that our disaggregation complexity measure is able to assess the hardness of an appliance dataset as well as a specific time series. We want to emphasize that the presented complexities are relative and not absolute measures for the problem complexity. Knowing the disaggregation complexity is not sufficient to determine the performance of the load disaggregator as the performance to disaggregate loads depends on the disaggregation algorithm itself. The presented measure gives meaningful results for load disaggregation problems with one feature, i.e. the active power representing each power state of an appliance.

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Workshop:
Tools & Methods in Smart Grid Research

Friday, September 30th, 11:00 – 15:30

Organizing committee
Prof. Dr. Sebastian Lehnhoff (OFFIS, Germany)
Dr.-Ing. Astrid Nieße (OFFIS, Germany)

Talks

Rapid Control Prototyping for Networked Smart Grid Systems
Dr. Mario Faschang, AIT, Austria

In this talk a seamless development process for Smart Grid control systems will be presented, which starts with the first line of code and ends with an operating controller in the field. In order to reduce the risk of a malfunctioning controller, high value is given to the evaluation of the control system through simulation of the controlled distribution grid, co-simulation of communication and distribution grid, and controller hardware-in-the-loop evaluation.

The Organic Smart Home – An Organic Computing Architecture for Energy Management and Smart Grids
Dipl.-Wi.-Ing. Ingo Mauser, KIT, Germany

The presentation demonstrates how concepts from Organic Computing may support the controlled self-organization of the future smart grid. We propose a generic hierarchical architecture–the extended Observer/Controller Architecture–as a framework for various energy management systems. This architecture reflects the physical grid structures as well as user goals and enables adaptive responses to changing objectives as well as disturbances in the system. We developed the Organic Smart Home based on the generic architecture as a prototypical building energy management system that supports the optimization of all relevant energy carriers in buildings. Various simulations and evaluations in the KIT Energy Smart Home Lab and the FZI House of Living Labs show the applicability of the proposed architecture to the domains of energy management in smart grids.

SGAE: Development of distributed Smart Grid algorithms using mosaik and MAS
Dr.-Ing Astrid Nieße, OFFIS, Germany

The development of (distributed) Smart Grid algorithms heavily relies on simulation of large scale scenarios of the controlled components. Although a large body of research emerged on distributed Smart Grid algorithms, a sound methodological engineering approach is often missing. With the iterative process model Smart Grid Algorithm Engineering (SGAE) a process model has been introduced to achieve both: sound research and application relevant results.

At OFFIS, we use mosaik to compose simulation models when developing and evaluating distributed algorithms for the control of DER in different use cases. In this talk, an overview on SGAE and mosaik is given using a practical example from ongoing work on the development of multi-agent based distributed DER control.

Program Overview

Thursday, September 29th

Time	Title, Presenter
8:30	Registration, Get Together, Coffee
9:00	Welcome - Friederich Kupzog, Wilfried Elmenreich, Ronald Bieber Conference Chairs
9:15	Keynote: **Power Line Communications for the Smart Grid: Status and Future -** Andrea M. Tonello, Alpen-Adria Universität
	Session 1: Simulation and Validation of Networked Smart Grid Systems **Chaired by Sebastian Lehnhoff**
9:50	Incremental Development of a Co-Simulation Setup for testing a Generation Unit Controller for Reactive Power Provision Jorge Velasquez, OFFIS
10:10	OpenGridMap: Towards Automatic Power Grid Simulation Model Generation from Crowdsourced Data Jose Rivera, Technische Universität München
10:30	Coffee
	Session 2: Scheduling of Flexibility **Chaired by Friederich Kupzog**
11:00	Demand-Response Optimized Heatpump Control for Service Sector Buildings Edith Birrer, Lucerne University of Applied Sciences and Arts
11:20	Distributed demand side management using electric boilers Lorenzo Nespoli, SUPSI
11:40	Impacts of Domestic Electric Water Heater Parameters on Demand Response Tobias Lübkert, Hamburg University of Technology
12:00	Targeting Customers for an Optimized Energy Procurement – A Cost Segmentation Based on Smart Meter Load Profiles Simon Albrecht, Hochschule Fresenius – University of Applied Sciences
12:20	PhD Workshop Flashlight talks Part I
12:30	Lunch
	Poster Session: Networking with ongoing research projects in DACH+ Region
14:00	Poster Flashlight Talks (conference room)
14:20	Interactive Poster Session (catering area)
15:30	Coffee
	Session 3: Advanced Technologies for Distribution Grids **Chaired by Silvia Santini**
16:00	GridBox Pilot Project Results Alain Brenzikofer, Supercomputing Systems
16:20	A Framework for Disturbance Analysis in Smart Grids by Fault Injection Igor Kaitovic, ALaRI, University of Lugano
16:40	Providing primary frequency control with residential-scale photovoltaic-battery systems Sandro Schopfer, ETH Zurich
17:00	Provisioning, Deployment, and Operation of Smart Grid Applications on Substation Level Stephan Cejka, AIT
17:30	End of Day 1

Friday, September 30th

Time	Title, Presenter	
9:00	Keynote: **Predictive Energy Management for sustainable Cities with Watson IoT -** Marcus Kottinger, IBM	
	Session 4: Power Grid Automation & Protocols **Chaired by Thorsten Staake**	
9:40	Message-oriented Machine-to-Machine Communication in Smart Grids – An Approach for and Experiences from Mapping IEC 61850 and CIM to XMPP - Richard Kuntschke, Siemens AG	
10:00	Accurate Clock Synchronization for Power Systems Protection Devices over Packet Switched Networks - Andreas Aichhorn, Sprecher Automation GmbH	
10:20	PhD Workshop Flashlight talks Part II	
10:30	Coffee	
	Session 5: Privacy - Chaired by Günther Eibl	**Workshop: Tools & Methods in Smart Grid Research, Part I**
11:00	Preserving Privacy in Distributed Energy Management - Daniel Brettschneider, University of Applied Sciences Osnabrück	
11:20	Differential Privacy for Real Smart Metering Data - Günther Eibl, Salzburg University of Applied Sciences	
	Session 6: Electric Vehicles **Chaired by Wilfried Elmenreich**	
11:40	Coordinated Charge Management for Battery Electric Vehicles - Arne Groß, Fraunhofer Institute for Solar Energy Systems	
12:00	Ensembles of Context and Form for Repurposing Electric Vehicle Batteries – An Exploratory Study - Markus Monhof, WWU Muenster – ERCIS	
12:20	PhD Workshop Flashlight talks Part III	
12:30	Lunch	
	Session 7: Forecasting and State Estimation Approaches - Chaired by Hartmut Schmeck	**Workshop: Tools & Methods in Smart Grid Research, Part II**
14:00	Analysis and Model-Based Predictions of Solar PV and Battery Adoption in Germany: An Agent-Based Approach - Hermann de Meer, University of Passau	
14:20	Photovoltaic power forecasting using simple data-driven models without weather data - Jorge Ángel González Ordiano, Karlsruhe Institute of Technology	
14:40	Evaluation of Network State Estimators for Adaptive Power-Balancing Controller in a Microgrid scenario - Mislav Findrik, AIT	
15:00	Hybrid simulation and energy market based optimization of cement plants - Peter Bazan, Friedrich-Alexander-Universität Erlangen-Nürnberg	
15:20	Roundup	
15:30	Start to Excursion	
16:00	Visit to Carinthia’s largest Energy provider **KELAG** and guided tour through control centre of **KNG Kärnten Netz GmbH**	
17:30	End of Day 2	