Energy Informatics

Current and Future Research Directions

Energy informatics (EI) is a young and dynamic research area. Recent developments have boosted its relevance. This article provides an overview over the current state of EI research and shows directions for future research in this area. The featured literature survey is geared to the two major EI research themes: smart energy-saving systems and smart grids.

DOI 10.1007/s12599-013-0304-2

The Authors

Dr. Christoph Goebel (✉)
Prof. Dr. Hans-Arno Jacobsen
Victor del Razo, M.Sc.
Mag. (FH) Christoph Doblander
Dipl.-Ing. Jose Rivera
Technical University Munich
Munich
Germany
christoph.goebel@tum.de

Dipl-Inform. Wirt Jens Ilg
Dr. Christoph Flath
Prof. Dr. Hartmut Schmeck
Prof. Dr. Christof Weinhardt
Dipl-Inform. Daniel Pathmaperuma
Karlsruhe Institute of Technology (KIT)
Karlsruhe
Germany

Prof. Dr. Dr. h. c. Hans-Jürgen Appelrath
Prof. Dr. Michael Sonnenschein
Prof. Dr. Sebastian Lehnhoff
Prof. Dr. Oliver Kramer
University of Oldenburg
Oldenburg
Germany
and
OFFIS
Oldenburg
Germany

Prof. Dr. Thorsten Staake
University of Bamberg
Bamberg
Germany

Prof. Dr. Elgar Fleisch
Federal Institute of Technology Zurich
Zurich
Switzerland
and
University of St. Gallen
St. Gallen
Switzerland

Prof. Dr. Dirk Neumann
University of Freiburg
Freiburg
Germany

Prof. Dr. Jens Strüker
Fresenius University of Applied Sciences
Idstein
Germany

Dr. Koray Erek
Prof. Dr. Rüdiger Zarnekow
Technical University Berlin
Berlin
Germany

Dr. Holger Ziekow
AGT International
Darmstadt
Germany

Prof. Dr. Jörg Lässig
University of Applied Sciences Zittau/Görlitz
Görlitz
Germany

Received: 2013-03-01
Accepted: 2013-09-22
Accepted after two revisions by the editors of the special focus.

This article is also available in German in print and via http://www.wirtschaftsinformatik.de: Goebel C et al. (2014) Energieinformatik. Aktuelle und zukünftige Forschungsschwerpunkte. WIRTSCHAFTSINFORMATIK. doi: 10.1007/s11576-013-0396-9.

1 Introduction

The availability of inexpensive energy from fossil fuels has enabled the impressive growth of wealth and economic prosperity in the developed countries. Our society's undisputed reliance on a dependable energy supply and with it the dependency on politically instable regions, the high externalities of carbon dioxide emissions and mining for fossil fuels, and the risks associated with nuclear power made energy topics a top priority of governments, companies, and consumers alike. For instance, the European Union has set a target to increase energy efficiency and the share of renewable energy sources by 20 %. The German government seeks to cover 35 % of its electricity demand with renewables by 2020 and 80 % by 2050. Other countries have set similar targets. While the individual motives of different governments to achieve these goals and the employed policy instruments vary, the economic incentives to further develop "green technologies" that help to save energy and generate it more sustainably are bound to increase in the coming years.

Increasing numbers of computer science (CS) and information systems (IS) researchers are discovering energy management as a relevant and scientifically

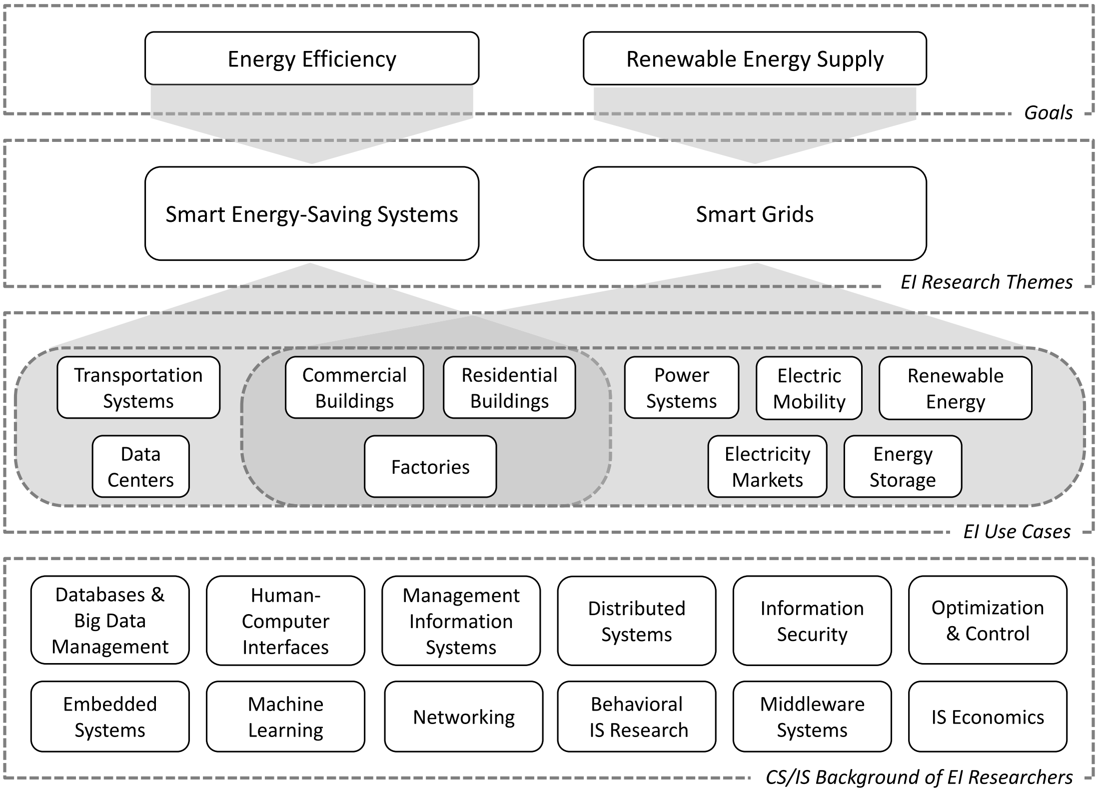

Fig. 1 Scope of energy informatics research

promising research field. Consequently, Energy Informatics (EI) has attracted much scholarly attention recently (Watson et al. 2010). Information and communication technology (ICT) is expected to support the transition to sustainable economies by enabling two developments: (i) the increase of energy efficiency beyond what engineering can do, and, (ii), the efficient integration of renewable sources of energy by making power systems smarter. EI research addresses these high-priority goals by focusing on well-defined research challenges. Solving each of these research challenges contributes to the development of ICT-based systems that will help to achieve sustainable energy supply. EI research can only inform the design of these systems in a satisfactory way if economic considerations are part of their evaluation and if the proposed solutions take existing institutional frameworks, e.g., current electricity market designs, into account.

Figure 1 highlights the scope of EI research. The two overall goals energy efficiency and renewable energy supply drive the development of smart energy-saving systems and smart grids, respectively. In the context of these two higher-level EI research themes, a number of use cases have already emerged, for instance commercial and residential buildings, data centers, and electric mobility. Some of these use cases are relevant for just one research theme, e.g., energy storage for smart grids, others are important in the context of both. Buildings, for instance, usually contain non-deferrable loads as well as deferrable loads serving the same end users. EI deals with both, energy-saving systems and smart grids, at the same time, because there are significant synergies regarding the design of corresponding sensor/actuator infrastructures and software systems: the ability to monitor system states and achieving controllability are key requirements in both areas. Moreover, the relevant use cases and therefore the necessary background knowledge overlap to a large extent.

The box at the bottom of **Fig. 1** contains a selection of CS/IS subcommunities related to EI. Many subcommunity-specific EI venues, mostly conference tracks and specialized workshops, have recently emerged. Genuine EI venues include IEEE SmartGridComm, IEEE Transactions on Smart Grid, ACM e-Energy, and IEEE PES ISGT. In the following sections, we structure research challenges in the area of energy-saving systems and smart grids and review selected work focusing on high-impact EI use cases.

Summarizing the above, we define EI research in terms of common research themes, i.e., smart energy-saving systems and smart grids, and common system goals, i.e., energy efficiency and renewable energy supply. EI researchers contribute to the development of energy-saving systems and smart grids based on their individual background. A central reason why EI is currently evolving into an interdisciplinary research area of its own is that meaningful progress is only possible if related knowledge is exchanged within and across CS/IS subcommunities. This enables the development of common problem abstractions, the reuse of software components, analytical tools, and scenario data for evaluation.

2 Research Challenges

2.1 Smart Energy-Saving Systems

The energy-efficiency of equipment is typically defined as the average amount of work that it is able to do using a certain amount of energy. Over the years, advances in engineering have made appliances and machines of all kinds more energy-efficient and continue to do so. However, this traditional definition of energy-efficiency does not capture the efficiency improvement potential that can be realized by the alignment of service output with end user requirements: Turning off equipment when nobody uses it or adjusting its service level to individual requirements could lead to significant additional energy savings. This additional potential is usually not realized today due to a number of reasons including missing information, the cost of control, and a lack of effective and attractive technical solutions. Even worse, many currently used benchmarking metrics, for example the power usage effectiveness (PUE) metric used in the data center context, do not even reflect energy savings resulting from switching off non-utilized equipment. The role of EI research will therefore consist in closing the information gap and design control mechanisms that reduce energy consumption both effectively and efficiently.

In the following, we refer to a situation where the power consumption of a cyber-physical system is proportional to the output actually required by its end users as *power-proportionality* (Lin et al. 2011). We would like to stress that power-proportionality is only one out of many factors influencing the overall energy-efficiency of a cyber-physical system.

ICT can help to achieve power-proportionality of cyber-physical systems on *three integration levels*.

On the first integration level, ICT enables individuals and organizations to better measure and understand their energy consumption and therefore react accordingly. Challenges for EI research can be divided into three major areas: Developing and evaluating systems and tools that (i) collect and store energy-related data, (ii), attribute energy usage to single devices, people, processes and organizational units, and, (iii), present and contextualize this data in a way that enables energy savings. These challenges are related to the development of event processing systems for sensor data, the optimal design and evaluation of human-computer interfaces, the development of benchmarking schemes, efficient information retrieval and consolidation of data from heterogeneous sources, as well as advancing knowledge about how people and organizations react to various types of information regarding their energy consumption.

The second level for ICT support enables individuals and organizations to control their energy usage more effectively through actuator infrastructures. For instance, such systems can provide building occupants with more sophisticated ways of controlling building services such as heating, cooling, and lighting individually and collectively. Research challenges on this integration level include the design and evaluation of advanced control infrastructures for different cyber-physical systems. This is a non-trivial task since it is usually not possible to maintain service levels for different end users completely independently of one another. For instance, the temperature and illumination of a working space cannot be controlled such that the service level received by each worker residing in the space is exactly equal to the requested individual service level. The same applies to applications running on a shared server infrastructure.

On the third ICT integration level, the energy control loop is closed by advanced ICT systems that are able to automatically align power consumption with actual end use requirements. The challenge for EI research in this domain is to design systems that learn and predict end use and control service delivery such that power consumption is minimized. A good example for such a system is NEST, a learning thermostat (NEST 2012). Many more application areas are conceivable, for instance, the intelligent control of production processes or server operation in data centers (Lin et al. 2011). As a matter of fact, the design of such systems gets more challenging as the physical systems they monitor and control are getting larger and more complex. Whereas NEST was designed for homes with just a few occupants and a single heating and ventilation system, commercial buildings are occupied by large numbers of individuals and feature complex HVAC and lighting.

Innovative energy-saving systems can leverage *existing* ICT. For instance, these systems can enable users to access building control using their smartphones. Existing solutions for indoor localization could be leveraged to facilitate this process so that personal preferences can be processed based on communication policies instead of being explicitly triggered. Modern buildings usually possess many actuators that can be accessed via standardized building bus protocols, such as BAC-Net and KNX (Krioukov et al. 2011). Thus, the cost of putting the described ICT infrastructure in place could turn out to be much lower than expected. Investigating how existing ICT infrastructures could be efficiently combined turns out to be another major EI research challenge.

The decision of people and organizations to deploy advanced energy-saving systems and the long-term success of such systems depend on individual incentives and behavioral dynamics such as learning and feedback among peers. Determining usage incentives and behavioral dynamics can be a challenging research task. For instance, the decision to purchase an intelligent thermostat controller and putting it to effective use is likely to depend on the achievable cost savings as well as on other factors like ease of use and added value. Companies like Amazon and Google might compare the cost savings potential of power-proportional computing to the expected financial impact on conversion rates and customer satisfaction. Thus, EI research focusing on micro-economic and behavioral aspects is likely to play a major role in designing ICT systems for achieving power-proportionality.

To further clarify EI research challenges in the context of smart energy-saving systems, we provide the following selection of concrete research questions:

- How can the power consumption of data centers be reduced by more intelligent resource monitoring and scheduling without affecting service levels?
- What are the micro-economic incentives and disincentives of achieving power-proportionality in different contexts?
- What is the optimal way of presenting personal energy consumption to individuals to achieve long-lasting effect?
- What is the optimal way to store large amounts of sensor data, both from a visualization and control perspective?
- How can we standardize the access to building management solutions such that third-party solution providers can easily develop smart energy-saving applications?

2.2 Smart Grids

The challenge of transitioning to sustainable energy supply is undeniably linked to the large-scale integration of renewable sources of energy. In terms of installed capacity, wind and solar power generation are the fastest growing types of renewable energy sources. Major grid integration challenges result from the variable, uncertain, and non-dispatchable power output of these generators, as well as from their spatial distribution. Long-term targets of sustainable energy production can only be reached if significant electrification of currently fossil fuel-based services occurs alongside renewable integration (McKay 2008). These developments have led to entirely new requirements with respect to the monitoring and control of the electric grid. Experts agree on the leading role that ICT will play in making the integration of renewables and new types of loads into the electric grid possible, which has resulted in a call for smart grids (Appelrath et al. 2012). In particular, ICT is expected to make the full potential of flexible loads accessible and enable the effective demand-side management of large numbers of such loads across multiple time scales (Callaway and Hiskens 2011).

EI research on smart grids investigates how ICT can be leveraged to achieve controllability of electric loads and to realize control systems that leverage the controllability of decentralized suppliers, loads, and energy storage systems for facilitating the integration of renewable resources into power systems. Investigating the controllability of electric loads overlaps with EI research on smart energy-saving systems: In both cases, the goal is to make energy consumption more measurable and controllable via ICT. However, in EI research on smart grids, the goal is to react to the fluctuating supply of renewable energy sources by shifting electric load from times of low supply to times of high supply instead of reducing the overall energy consumption (including non-electrical energy). Thus, the constraints of shifting demand have to be taken into account. These constraints can be highly complex, in particular if systems support the control of flexible loads with a primary use different from grid support.

Realizing systems that are capable of controlling energy resources in smart grids is strongly related to research that has long been a central point on the IS/CS research agenda, namely the efficient coordination of large numbers of independently controlled system components. In today's liberalized market context, generators and loads cannot be expected to automatically strive for the common good (a stable, cost-efficient, and green electric grid) but will instead attempt to maximize their own utility (Ramchurn et al. 2012). Since the electric grid is already operated based on highly sophisticated market mechanisms, EI researchers with a background in economics and market design can contribute to the development of smart grid systems that smoothly interact with existing market structures. They can also help to develop innovative market structures and products that facilitate the market participation of distributed generation, flexible loads, and energy storage. The primary reason why CS/IS can contribute to the design of electricity markets is that electricity trading has to take the physical characteristics of the electric grid into account, which results in highly complex optimization problems. Applying market-based mechanisms to smart grids, in which uncertain supply and flexible demand have to be matched on the distribution grid level, exacerbates the complexity of the corresponding communication, optimization, and control requirements.

From a CS perspective, the ICT backbone of smart grids can be viewed as a large-scale distributed system since it is supposed to enable the communication and coordination of large numbers of distributed generators and loads. The massive scale and reliability constraints of power grids will necessitate highly scalable and dependable systems for data storage, data processing, and communication: Such systems may easily become too complex for centralized communication and optimization schemes. Therefore, distributed systems providing the required services for dispatching large numbers of distributed loads are required to achieve reliability levels similar to today's centralized generation approach. A key enabling factor for the deployment of such a large distributed system is the interoperability of components in regard to international standards.

To further clarify EI research challenges in the context of smart grids, we provide the following selection of concrete research questions:

- Which distributed computation and optimization techniques are applicable to the control of distributed resources in power grids and how do they perform in realistic test cases?
- Which computational methods are best suited for forecasting renewable energy output and demand and how can they leverage higher data volume and frequency?
- How can distributed energy resources like small energy storage and flexible loads be integrated into existing electricity markets?
- Which damage would result from a cyber-attack based on the number of flexible loads that the attacker is able to bring under his control?
- How can we increase the dependability of distributed systems that enable the data exchange between coordinators and energy resources in smart grids?

3 Current Research Directions

3.1 Smart Energy-Saving Systems

EI research focusing on smart energy-saving systems has already addressed a large spectrum of related research questions. On the first ICT integration level, a number of recent publications deal with the challenge to collect, store, and exchange large amounts of energy-related data. sMAP, for instance, is a RESTful web service that allows instruments and other producers of physical information to directly publish their data (Dawson-Haggerty et al. 2010). Another highly relevant topic related to the first ICT integration level that has received a lot of attention so far is the identification of small-scale loads based on aggregated measurements (Weiss et al. 2012). The availability of effective software solutions serving this purpose would allow for obtaining the status of devices as well as highly granular consumption data without having to separately measure the power use of each load. Significant research effort went into designing and evaluating technologies for visualizing energy usage at the end-user level. Examples include the work of Weiss et al. (2010), which evaluates the use of smartphones as energy consumption feedback devices.

Regarding the strategic management of information systems at the organizational level, EI researchers have proposed specific Green IS strategies that enhance firm competitiveness and decrease the environmental footprint of entire organizations (Loeser et al. 2012). To support Green IS strategy implementation, widely used management tools, e.g., the Balanced Scorecard, were adapted to the energy context through integration of energy efficiency and environmental sustainability indicators (Grimm et al. 2012). Another branch of EI research has begun to focus on the behavioral end user impact of smart energy-saving technologies and how positive effects can be reinforced by system design. First research results on the influence of, for instance, social normative feedback (Loock et al. 2011) and the role of goal setting and defaults (Loock et al. 2013) are available.

Several recent publications have started to close the energy control loop and consider possible CS contributions in the area of energy-aware personalized and automatic control of cyber-physical systems. Due to their importance with respect to the fraction of total energy consumption, buildings have been one topical focus. The work of Krioukov et al. (2011), for instance, studies the combined use of web technologies and existing building management systems to achieve personalized lighting control. Although they did not consider automatic decision making on the system side, they measured high energy savings resulting from the ability of people to control lighting directly. Another example for advanced ICT systems in the context of building control is Olken et al. (1998). Feldmeier and Paradiso (2010) investigate personalized HVAC control. They evaluate a prototypical system that measures presence and comfort of building occupants and automatically control the HVAC system based on these measurements. Both Krioukov et al. (2011) and Feldmeier and Paradiso (2010) apply a living lab research method. The work of Aswani et al. (2011) evaluates model predictive control (MPC) for reducing the energy consumption of an HVAC system. Their prototype system leverages sMAP (Dawson-Haggerty et al. 2010) and thus serves as a good example of how different EI prototypes can and should be combined to yield a more comprehensive proof of concept. Initial work on power-proportional data centers has been conducted, for example, by Lin et al. (2011) and Krioukov et al. (2010). These works evaluate different scheduling algorithms for dispatching compute jobs such that the total power consumption of groups of servers over time is reduced. Krioukov et al. (2010) evaluate these algorithms using an experimental test bed, whereas Lin et al. (2011) use several historical work load traces. Hoyer (2011) present a method by which the allocation of computational services to servers can be performed more efficiently with respect to energy consumption. Bodenstein et al. (2012) present an energy-aware scheduling mechanism for compute jobs based on standard optimization techniques and show that it is able to reduce energy consumption by 40 %. The concept of power-proportional computing extends well beyond server scheduling. Creating power-proportional software has been a highly active research area within CS since at least the advent of mobile computing where minimal energy consumption is a key requirement.

3.2 Smart Grids

Most of the EI research that has been conducted in the area of smart grids so far deals with the role of ICT in demand response (DR), usually with a focus on certain types of electric loads (Strüker and van Dinther 2012). Since physical smart grid test beds are not accessible for most EI researchers, they focus on creating new knowledge by applying a model-based research method. Compared to other IS/CS research fields, a lot of data is publicly available, for instance data about electricity demand, market outcomes and prices, renewable energy production, etc. Thus, it is possible to parameterize models and evaluate innovative control methods and systems using actual data (Feueriegel et al. 2012; Goebel 2012; Gottwalt et al. 2011).

DR is a central EI topic since the flexible loads and storage devices that are supposed to adapt their power consumption or supply are spatially distributed and have dynamic individual constraints which limit their ability to perform load shifting. Moreover, the coordination of these resources has to satisfy various constraints related to secure power system operation. In particular, it must not impair power quality or risk failure of grid equipment. Even well-studied optimization problems in the power system context, such as unit commitment and optimal power flow, require significant computational resources. Determining the optimal dispatch of flexible loads and energy storage centrally could thus not be feasible on the required control time-scales. Therefore, EI researchers have begun to investigate the application of distributed optimization techniques to smart grid control problems. Examples include Ma et al. (2013), Ahn et al. (2011), and Gan et al. (2007). Self-organization methods could also help to solve distributed control problems in the smart grid (Anders et al. 2012; Hinrichs et al. 2011).

Irrespective of the coordination or optimization method applied, the ability to forecast key input variables for smart grid control is essential. Depending on the use case, key variables include solar power output, wind power output, power demand, and, in the case of flexible loads, variables describing their primary use, such as vehicle departure times and building occupancy. Therefore, current EI research also extends to the area of forecasting and data mining. For instance, Kramer et al. (2013) propose a system for short-term wind energy prediction. Machine learning methods like support vector regression turn out to be successful time series models for high-dimensional data but further research is needed to assess the applicability of machine learning tools and requirements in the context of smart grids. Flath et al. (2012a, 2012b) use clustering techniques to derive homogeneous consumption groups from smart metering data of household and small business customers.

Apart from solving optimization problems, EI researchers are also interested in the design of information system infrastructure capable of processing data received from potentially millions of physical resources in real-time. Jacobsen and Muthusamy (2011) mention a number of initial requirements that such systems have to satisfy.

If smart grids are to be become a reality, the reliability and security of its ICT infrastructure will be vital. For instance, if DR resources are supposed to replace thermal generators as balancing and contingency reserves, their failure to respond could, in the worst case, lead to blackouts. EI research has, to date, not embraced this topic to the extent necessary. The work of Khurana et al. (2010) provides starting points for meeting this challenge. Strüker and Kerschbaum (2012) present an encryption-based approach to secure the databases of intermediaries who will be responsible for handling large amounts of consumption data collected by smart meters. In certain cases, data privacy in this context could also be preserved by using privacy-preserving data mining (Schlitter and Lässig 2012).

A highly active EI use case in the recent past has been the potential of plug-

Abstract

Christoph Goebel, Hans-Arno Jacobsen, Victor del Razo, Christoph Doblander, Jose Rivera, Jens Ilg, Christoph Flath, Hartmut Schmeck, Christof Weinhardt, Daniel Pathmaperuma, Hans-Jürgen Appelrath, Michael Sonnenschein, Sebastian Lehnhoff, Oliver Kramer, Thorsten Staake, Elgar Fleisch, Dirk Neumann, Jens Strüker, Koray Erek, Rüdiger Zarnekow, Holger Ziekow, Jörg Lässig

Energy Informatics

Current and Future Research Directions

Due to the increasing importance of producing and consuming energy more sustainably, Energy Informatics (EI) has evolved into a thriving research area within the CS/IS community. The article attempts to characterize this young and dynamic field of research by describing current EI research topics and methods and provides an outlook of how the field might evolve in the future. It is shown that two general research questions have received the most attention so far and are likely to dominate the EI research agenda in the coming years: How to leverage information and communication technology (ICT) to (1) improve energy efficiency, and (2) to integrate decentralized renewable energy sources into the power grid. Selected EI streams are reviewed, highlighting how the respective research questions are broken down into specific research projects and how EI researchers have made contributions based on their individual academic background.

Keywords: Renewable energy, Energy efficiency, Power-proportionality, Cyber-physical systems, Smart energy-saving systems, Smart grids, Energy informatics

in electric vehicles for grid support. Published work in this area differs with respect to the control approach used, i.e., either direct or indirect, the models and data used, the goals and constraints of the optimization problem, and finally the analyzed perspective, for instance the system operator's, the utility's, or the PEV owner's perspective. A number of recent papers, including Goebel (2012), Flath et al. (2012a, 2012b), and Schuller et al. (2012), have explored the economic value of controlled PEV charging. These papers benchmark different control strategies with respect to the achievable cost savings. A different set of papers focuses on controlled PEV charging when the objective is to stabilize the power grid, for instance Goebel and Callaway (2013). Work about the actual design of ICT infrastructures that enable controlled PEV charging and related integration aspects is still sparse. Examples include Mültin et al. (2012) who describe a prototypical solution for integrating the control of PEV charging with that of a smart home.

Another use case that EI researchers have begun to explore is the distributed control of loads with intrinsic thermal energy storage. These loads are able to store energy in the form of heat or cold and can be powered electrically. Therefore, the power consumption of loads like HVAC systems, water heaters, and refrigerators can be controlled within certain bounds. The work of Stadler et al. (2009) looks into control methods for load shifting of refrigerators, complemented in Hinrichs et al. (2009) by methods for desynchronization of the power demands of appliances which have reacted to the same control event. Oldewurtel et al. (2011) apply model predictive control to align HVAC operation with spot market prices of electricity. The work of Mathieu and Callaway (2012) is particularly interesting in terms of ICT requirements as it investigates cases where state information is not available in real time.

4 Future Directions and Requirements

As the previous section shows, current EI research is comprised of a number of interdependent streams of research. Most of it either focuses on the potential of ICT to realize smart energy-saving systems or smart grids. For instance, it investigates how PEVs could contribute to a more efficient integration of variable renewable energy sources, or it proposes certain technological and organizational building blocks, such as innovative optimization and control methods. EI research along these lines will certainly continue, as many relevant research questions could not yet be answered in a satisfactory way.

In the future, we expect to see more EI research in two major areas: (1) the explicit quantification of the trade-off between ICT deployment and the achieved benefits in economic and environmental terms, and, (2), the development of more comprehensive ICT solutions and their evaluation based on realistic simulations of cyber-physical systems. As EI researchers are gaining more background knowledge of relevant topics, for example thermal building models and power system operation, they will expand the current spectrum of use cases. Eventually, it will be possible to evaluate innovative ICT system components by co-simulating ICT and physical infrastructure. We therefore predict that future EI research will approach relevant research questions in a more inclusive and comprehensive way, which implies a highly inter-disciplinary approach.

Concerning (1), evaluating economic and environmental trade-offs will be a central theme of future EI research: Smart ICT-based control competes with provisioning more physical capacity. Judging the economic viability of smart grids, in turn, cannot be done without understanding the economics of power systems and markets. EI researchers who plan to focus on this area should thus have a solid background in energy economics. They should, for instance, know the details of contemporary power market design and be able to assess the operational cost of buildings and power systems.

Concerning (2), EI researchers who plan to participate in the design of ICT systems that monitor and control the power supply and demand of the future should be familiar with the underlying machinery and appliances as well as with the behavior of people and organizations interacting with them. Thus, they should either be able to evaluate their proposed solutions in actual testbeds, for instance by following a living labs research approach, or they should be able to use state-of-the-art simulation methods and actual data to evaluate their prototypes. This implies collaborations with researchers from electrical, mechanical, and civil engineering. Evaluation based on simulation also requires large amounts of computational resources, since both the physical components of the cyber-physical system and the actual ICT prototype have to be simulated.

References

Appelrath H-J, Kagermann H, Mayer C (eds) (2012) Future energy grid – migration to the internet of energy. Technical report, National Academy of Science and Engineering

Ahn C, Li C-T, Peng H (2011) Optimal decentralized charging control algorithm for electrified vehicles connected to smart grid. Journal of Power Sources 196(23):10369–10379

Anders G, Hinrichs C, Siefert F, Behrmann P, Reif W, Sonnenschein M (2012) On the influence of inter-agent variation on multi-agent algorithms solving a dynamic task allocation problem under uncertainty. In: Proc of 6th IEEE international conference on self-adaptive and self-organizing systems (SASO), Lyon

Aswani A, Master N, Taneja J, Culler D, Tomlin C (2011) Reducing transient and steady state electricity consumption in HVAC using learning-based model predictive control. Proceedings of the IEEE 100(1):240–253

Bodenstein C, Schryen G, Neumann D (2012) Energy-aware workload management models for operating cost reduction in data centers. European Journal of Operational Research 222(1):157–167

Callaway DS, Hiskens IA (2011) Achieving controllability of electric loads. Proceedings of the IEEE 99(1):184–199

Dawson-Haggerty S, Jiang X, Tolle G, Ortiz J, Culler D (2010) SMAP – a simple measurement and actuation profile for physical information. In: Proc of 8th ACM conference on embedded networked sensor systems (SenSys), Zurich

Feldmeier M, Paradiso JA (2010) Personalized HVAC control system. In: Proc of internet of things (IoT) 2010, Tokyo

Feuerriegel S, Strüker J, Neumann D (2012) Reducing price uncertainty through demand side management. In: Proc of international conference on information systems (ICIS), Orlando

Flath CM, Gottwalt S, Ilg JP (2012a) A revenue management approach for efficient electric vehicle charging. In: Proc of 45th Hawaii international conference on system sciences, Hawaii

Flath CM, Nicolay D, Conte T, van Dinther C, Filipova-Neumann L (2012b) Cluster analysis of smart metering data. Business Information Systems Engineering 4(1):31–39

Gan L, Topcu U, Low S (2007) Optimal decentralized protocols for electric vehicle charging. IEEE Transactions on Power Systems 6(1):1–10

Goebel C (2012) On the business value of ICT-controlled plug-in electric vehicle charging in California. Energy Policy 53:1–10

Goebel C, Callaway DS (2013) Using ICT-controlled plug-in electric vehicles to supply grid regulation in California at different renewable integration levels. IEEE Transactions on Smart Grid 4(2):729–740

Gottwalt S, Ketter W, Block C, Collins J, Weinhardt C (2011) Demand side management – a simulation of household behavior under variable prices. Energy Policy 39(12):8163–8174

Grimm D, Loeser F, Erek K, Zarnekow R (2012) Evaluation von Performance Measurement Systemen zur Konzeption eines geschäftsprozessorientierten Management-Cockpits für IKT-Energieeffizienz. In: Informatik 2012 – Workshop Informatik und Nachhaltigkeitsmanagement, Braunschweig

Hinrichs C, Vogel U, Sonnenschein M (2009) Modelling and evaluation of desynchronization strategies for controllable cooling devices. In: Proc of 6th Vienna international conference on mathematical modelling, Vienna

Hinrichs C, Vogel U, Sonnenschein M (2011) Approaching decentralized demand side management via self-organizing agents. In: Proc of 10th international conference on autonomous agents and multiagent systems (AAMAS), Taipei

Hoyer M (2011) Resource management in virtualized data centers regarding performance and energy aspects. PhD thesis, University of Oldenburg

Jacobsen H-A, Muthusamy V (2011) Green middleware. In: Green IT: technologies and applications. Springer, Berlin, pp 341–361

Khurana H, Hadley M, Lu N, Frincke DA (2010) Smart-grid security issues. IEEE Security and Privacy 8(1):81–85

Kramer O, Gieseke F, Satzger B (2013) Wind energy prediction and monitoring with neural computation. Journal Neurocomputing 109:84–93

Krioukov A, Mohan P, Alspaugh S, Keys L, Culler D, Katz R (2010) NapSAC: design and implementation of a power-proportional web cluster. In: Proc of 1st ACM SIGCOMM workshop on green networking, New Delhi

Krioukov A, Dawson-Haggerty S, Lee L, Culler D (2011) A living laboratory study in personalized automated lighting controls. In: Proc of 3rd ACM workshop on embedded sensing systems for energy-efficiency in buildings (BuildSys), Seattle

Lin M, Wierman A, Andrew LLH, Thereska E (2011) Dynamic right-sizing for power-proportional data centers. In: Proc of 30th IEEE international conference on computer communications (INFOCOM), Shanghai

Loeser F, Erek K, Zarnekow R (2012) Towards a typology of green is strategies: insights from case study research. In: Proc of 32nd international conference on information systems, Orlando

Loock C-M, Staake T, Landwehr J (2011) Green IS design and energy conservation: an empirical investigation of social normative feedback. In: Proc of 31st international conference on information systems (ICIS), Shanghai

Loock C, Staake T, Thiesse F (2013) Motivating energy-efficient behavior with green IS: an investigation of goal setting and the role of defaults. MIS Quarterly 37(4):1313–1332

Ma Z, Callaway DS, Hiskens IA (2013) Decentralized charging control of large populations of plug-in electric vehicles. IEEE Transactions on Control Systems Technology 21(1):67–78

Mathieu JL, Callaway DS (2012) State estimation and control of heterogeneous thermostatically controlled loads for load following. In: Proc of 45th Hawaii international conference on system science (HICSS), Hawaii

McKay D (2008) Sustainable energy without the hot air. UIT, Cambridge

Mültin M, Allerding F, Schmeck H (2012) Integration of electric vehicles in smart homes – an ICT-based solution for V2G scenarios. In: Proc of 2012 IEEE PES innovative smart grid technologies conference, Washington, DC

NEST (2012) NEST – the learning thermostat. http://www.nest.com/. Accessed 2012-01

Oldewurtel F, Ulbig A, Morari M, Andersson G (2011) Building control and storage management with dynamic tariffs for shaping demand response. In: IEEE PES conference on innovative smart grid technologies (ISGT) Europe, Manchester

Olken F, Jacobsen H-A, McParland C, Piette MA, Anderson MF (1998) Object lessons learned from a distributed system for building monitoring and operation. In: Proc of object oriented programming systems languages and applications (OOPSLA), Vancouver

Ramchurn SD, Vytelingum P, Rogers A, Jennings NR (2012) Putting the ‘smarts’ into the smart grid: a grand challenge for artificial intelligence. Communications of the ACM 55(4):86–97

Schlitter N, Lässig J (2012) Distributed privacy preserving classification based on local cluster identifiers. In: Proc of 11th IEEE international conference on trust, security and privacy in computing and communications, Liverpool

Schuller A, Ilg J, van Dinther C (2012) Benchmarking electric vehicle charging control strategies. In: Proc of 2012 IEEE PES innovative smart grid technologies (ISGT), Washington, DC

Stadler M, Krause W, Sonnenschein M, Vogel U (2009) Modelling and evaluation of control schemes for enhancing load shift of electricity demand for cooling devices. Environmental Modelling and Software 24(2):285–295

Strüker J, Kerschbaum F (2012) From a barrier to a bridge: data-privacy in deregulated smart grids. In: Proc of 32nd international conference on information systems (ICIS), Orlando

Strüker J, van Dinther C (2012) Demand response in smart grids: research opportunities for the IS discipline. In: Proc of 18th Americas conference on information systems (AMCIS), Seattle

Watson RT, Boudreau M-C, Chen AJ (2010) Information systems and environmentally sustainable development: energy informatics and new directions for the IS community. MIS Quarterly 34(1):23–38

Weiss M, Loock C-M, Staake T, Mattern F, Fleisch E (2010) Evaluating mobile phones as energy consumption feedback devices. In: Proc of 7th international ICST conference on mobile and ubiquitous systems, Sydney

Weiss M, Staake T, Mattern F (2012) Leveraging smart meter data to recognize home appliances. In: Proc of IEEE pervasive computing and communication (PerCom), Lugano