Power Systems

Anne Beaulieu
Jaap de Wilde
Jacquelien M.A. Scherpen *Editors*

Smart Grids from a Global Perspective

Bridging Old and New Energy Systems

Springer

Power Systems

More information about this series at http://www.springer.com/series/4622

Anne Beaulieu · Jaap de Wilde
Jacquelien M.A. Scherpen
Editors

Smart Grids from a Global Perspective

Bridging Old and New Energy Systems

Springer

Editors
Anne Beaulieu
Faculty of Mathematics and Natural Sciences
University of Groningen
Groningen
The Netherlands

Jaap de Wilde
Department International Relations and Security
University of Groningen
Groningen
The Netherlands

Jacquelien M.A. Scherpen
ENTEG
University of Groningen
Groningen
The Netherlands

ISSN 1612-1287 ISSN 1860-4676 (electronic)
Power Systems
ISBN 978-3-319-28075-2 ISBN 978-3-319-28077-6 (eBook)
DOI 10.1007/978-3-319-28077-6

Library of Congress Control Number: 2015960431

Printed on acid-free paper

This Springer imprint is published by SpringerNature
The registered company is Springer International Publishing AG Switzerland

Foreword

This book represents a bold step toward formulating a number of questions that are crucial to a much-needed redefinition of the electric energy sector of engineering and system science. It should not be surprising to anyone that the initiative for this book came from the Groningen Energy Summer School (GESS), well known in the Netherlands as an institution that greatly values strong links between research and education. If you have not visited this country in person, I recommend that you do so, not only for education and gathering of information, but also for the ambience of the country itself and its relevance to electric energy. You will find yourself, as I did, faced with vast green spaces surrounding relatively small homes. By virtue of an invitation to a Dutch home, I quickly realized that sustainable fields and windmills are higher up in the value chain of the Netherlands than having large homes. This attitude cannot be found everywhere. The Netherlands has long nurtured nature preservation, which shows today in the way people value their environment.

It is also not surprising that several top Dutch schools, many of whose faculty are authors of this book, are very active in research and education sustainability programs. The oldest of them is Groningen where, as an example, a yearly Energy Summer School attracts groups of young unconventional minds meeting on an annual basis to think deeply and openly about evolving objectives of industry, their implications for society as a whole, and their impact on electric energy consumers in particular. I had the privilege of participating in a GESS a few years back. During that time, I reaffirmed my conviction that learning must be a lifelong experience. The GESS experience presented to me many aspects of problems that I had never thought of before. It impressed upon me that there would be much learning ahead if I had the opportunity to proactively interact with such a diverse group in the future. This book is simply another reflection of this deeply ingrained commitment by the Dutch universities to make the world a better place.

However, even as I write these thoughts, I cannot help but think of how challenging must be the entire process of making GESS work. It motivates me to look back at my own career and revisit how I coped with the challenge of going beyond a narrow specialization at different stages in my career. In hindsight (always easy!), I can recognize where I saw the challenge and how I chose my next steps.

As many of the authors in this book, I started with my own discipline-oriented education in electrical engineering and systems science. I was quite content with thinking about electric power systems as complex dynamical systems. Given a new technical problem, like the infamous voltage collapse which took French and Belgian grids into blackouts caused by phenomena previously unstudied, it became quite challenging and rewarding to learn from such legendary engineering leaders, Charles Concordia, John Zaborszky, and Lester Fink, how to look at a real-world problem, pose it mathematically, and design methods for solving it. These people were simply amazing, as they interpreted complex physical problems using clean elegant mathematics. Influenced by each of them, I gradually moved into thinking about electric power grids as complex dynamical systems, whose structures must be defined and used to make the grid work better by means of feedback control. I was working on "smarts" without identifying them with any special names. But, neither new technologies nor perceived needs were ready for their deployment. "Loads" were quite predictable during normal operation, and ICT was viewed more as a liability than as a help to a physical system. Supplying a load reliably had been the golden industry rule, and it was to remain so for years to come. Innovation for efficiency was secondary. So we wrote papers that went largely unused by the industry.

In the early 1990s, the electric utility sector entered the beginning of what was to become a turbulent period to this day. Utilities began the restructuring battle with non-utility-owned generation companies, and customers were assumed to be the only invariant. For all practical purposes, customers were to be captive since there was and still is only one electric connection from users to large energy sources. Needless to say, I began to question my own research direction. I was not formally trained in economics, financial engineering, public policy, or political science. You name the discipline of the day that was to magically transform the industry, and it was not what I knew.

As though none of this had dealt enough bruises to my self-confidence, the "smart grid" wave blinded me during those several years. I watched many people rediscover many known technologies without assessing hidden assumptions that made them work. Storage became the main medicine for all, without having a holistic approach to how to value it relative to, say, a slower-responding resource equipped with model predictive control (MPC) software. But since there was enough extra reserve in the system that deploying lots of expensive storage was not an immediate need, some technically strong companies making large storage such as A123 failed financially.

Currently, we are experimenting with magic new technologies whose inventors are about to save the world. On the other hand, lots of wind power deployed in Germany gets "spilled" and wasted. The grid cannot deliver it to the right customers, and it has become too complex to fix the problem. Instead, we continue to reel out more transmission wires and ruin our beautiful large green fields. Nobody seems to be connecting the dots between new resources, customer needs, and the delivery service to make it all work. I think back to much of the early systems work, including my own, which was published but remained unused because it came before its time. Now, the technologies and needs are here, but we still fail miserably in technology transfer for well-understood functionality. The scary challenge is that many of these "smarts" by themselves do not have value. For example, storage has value in balancing intermittent generation, but the customer can also do this when adjusting its demand using MPC, for example. Technical solutions are non-unique and they must be evaluated in the context of many other factors communicated by the authors of this book.

It is probably safe to say that at the end of the day, the complexity will become so overwhelming that users are going to begin to disconnect from the grid and serve themselves. This is an idea that would have been considered suicidal back in the days of economies of scale, when the bigger power plants routinely meant lowering cost.

All I can say is that it is beginning to look like we are at the point of spiral death of the electric energy sector as we have known it. Everyone is inventing something, convincing government to subsidize its pilot deployment, and, almost as a rule, without supplying any new technologies deployed at scale. This is all done with little understanding of impacts on those who need electricity. Something is obviously wrong with this picture!

As the reader can conclude by now, it remains difficult for me to see that we are so far from posing the problem holistically. Doing this is easier said than done. Fundamentally, we do not have common problem formulations in different disciplines. Communicating differing views of the same complex problem in a way that can be unifying, and that will motivate a multidisciplinary team to solve the actual real-world problem holistically, has remained an elusive holy grail, I believe. This challenge continues to be seen as we attempt to formalize multidisciplinary educational and research programs.

This overall perception of the situation in the field, summarized as a lack of systematic well-defined approaches to multidisciplinary complex problems, brings to focus the major importance of this book. GESS is an emerging living laboratory where methods begin to be molded. It is only by doing it together and listening to each other with open minds and appreciation for the magnitude of the challenge set that we can make progress. Having taken this admirable approach, the authors of this book offer many different aspects of the underlying complex industry evolution. They explicitly question the objectives of industry evolution, keeping customers in the main focus; they are no longer captive predictable loads. Several book chapters make it very clear that our industry evolution is not only about designing economic incentives. It is much more about the sustainability attributes the late Elinor Ostrom envisioned. The key to sustainability is having proactive consumers who understand what can and should be done, ranging from adjustments, to cooperation through distributed aggregation, and/or to using embedded computer applications such as MPC to deal with the uncertainties in a stable way. Customers need to self-manage their own privacy and only exchange what is essential for them to align their characteristics with the characteristics of the others within a complex dynamical system. Fascinating is the concept of a "powerful network" put forward by a group of thinkers. Several authors recognize that it is no longer "one size fits all" but that culture, race, and religion that may jointly determine customers' approach to electric energy. Clearly stressed is that customers do not use watts, but they use heat, light, and computers and drive cars. Not every watt is equally important to all users.

In closing, each chapter in this book is like a breath of fresh air. It is not the sum of the ideas that helps progress in this real chaotic evolution. I can only hope that the GESS continues for years to come. We need hordes of young people with very diverse views spending time together and arriving at the common language needed to formulate the problem holistically. Perhaps it is my biased view, but systems thinking is essential. And it is not about one single method (Foster school of system dynamics; MPC; behavioral science, feedback control, industrial economics), but about being able to zoom out to wrap our hands around this monster problem and zoom back into different aspects of the problem (engineering, economic, social, political, ICT) studied by the discipline experts, and then zoom out again. Some sort of interactive thinking starting with a family of unique single discipline-based formulations and arriving at the holistic multidisciplinary problem formulation is badly needed. We are not quite there yet, but the thinking offered in this book is a big step in the right direction. I encourage young people to make it a routine pilgrimage to GESS where they once in a while step out of their own specialized way of thinking about the problem, and open themselves to learning about other aspects of the problem. And I would say not to get discouraged by what might seem at times an unmanageable roadblock. As I shared briefly with you my own path, this is bound to happen the minute one dares to zoom out into the real world. However, it can be tremendously rewarding. I am heartened by so many young people who, like the authors in this book, think of their work as having a much bigger mission beyond the boundaries of what they know best. I thank the authors for having provided much food for thinking to the readers.

November 2015

Marija Ilic
Carnegie Mellon University
Pittsburgh
PA, USA

Contents

Part I Approaches to Changing Energy Systems

Part II Control and Regulation of Smart Grids: Technical, Legal, Economic, and Social Approaches

Part III Implementing Smart Grids: What Have We Learned?

Introduction—Smart Grids: Design, Analysis and Implementation of a New Socio-technical System

J.H. (Jaap) de Wilde, J. Anne Beaulieu and Jacquelien M.A. Scherpen

Self-Managing And Reliable Transmission electric grids—SMART Grids. According to many sources on the internet, including his own LinkedIn page, Andres Carvallo, "Energy Maven and Smart Grid Godfather", defined the term SMART grid on March 5, 2004" (Carvallo 2015). Johannes Kester (Chap. 12 in this book) found an older source. In a less bombastic manner, Khoi and colleagues defined SMART Grids as:

> The Self-Managing and Reliable Transmission Grid (SMARTGrid) is seen as the future of protection and control systems. It is an automated system of monitoring, control, and protection devices that improves the reliability of the transmission grid by preventing wide-spread break-ups (Khoi et al. 1997).

Beyond Carvallo's bravura and claims to precedence, there are more intriguing aspects to the term SMART Grid. 'Self-Managing' hints at an engine without a driver. Such a techno-fix is expected to help create a sustainable society without addressing questions like 'whose society?' and at 'which levels of welfare and well-being within that society?' This version of smart grids doesn't pause to ask: Will there be equal access for all—in the spirit in which the electricity grid was rolled out in Western countries in the last century—or will smart grids create new social stratification through differential access to energy? Given the way the social is excluded from such definitions, it is not surprising that a number of publications

---

J.H. (Jaap) de Wilde
Faculty of Arts, International Relations and World Politics, University of Groningen,
Groningen, The Netherlands
e-mail: j.h.de.wilde@rug.nl

J.A. Beaulieu (✉)
Energysense, University of Groningen, Groningen, The Netherlands
e-mail: j.a.beaulieu@rug.nl

J.M.A. Scherpen
ENTEG (ENgineering and TEchnology Institute Groningen),
Faculty of Mathematics and Natural Sciences, University of Groningen,
Groningen, The Netherlands
e-mail: j.m.a.scherpen@rug.nl

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_1

on smart grids see the consumers and prosumers as the main obstacles to success. They are externalities and unknown factors in the equation. Not in this book.

In the run up to the preparation of this volume, we have noted again and again how the dominant paradigm in the literature on smart grids insists on the economic road to socialisation: pro- and consumers can be pushed into the desired directions by creating economic incentives. The pro- and consumers are expected to behave like a *homo economicus*, a rationally operating agent who attempts to maximize utility as a consumer and economic profit as a producer. There is also a *homo politicus* and a *homo ethicus*, with corresponding non-economic modes of reasoning, decision-making and behaving. These different dimensions are relevant for families, communities, nations, religions, and societies, and important also for firms, bureaucracies, armies and governments. All are part of complex socio-technical systems, and there is no single stimulus, economic or otherwise, that can bring about change.

If smart grids aim to contribute to a more sustainable production, transportation and use of energy *by design*, its 'self-management', 'reliability' and 'transmission' need to incorporate factors it has ignored so far. This book intends to open a window into that direction by merging a variety of approaches of smart grids. As such it builds on the four-year experience of the interdisciplinary Groningen Energy Summer School, run by the University of Groningen and Globalisation Studies Groningen (GSG). This School unites staff and Ph.D. students from a wide range of academic disciplines in one programme: engineers, lawyers, chemists, sociologists, physicists, philosophers, economists, geographers, psychologists, political scientists, historians, geologists and computer science experts. Over the course of two weeks, they try to incorporate the best of each other's expertise into their own. The Ph.D. students have to present each other's work: a lawyer needs to come to grips with algorithms that run distribution systems, or an engineer needs to understand how speech acts create social realities. This book as a whole represents that practice. The individual chapters, however, reflect the expertise of the authors. Some of them combine various disciplines, but the true transdisciplinary exposure of this book is the added value created by the sum of its parts. To strengthen this we have added Points for Discussion to each chapter, emphasizing the broader context, and helping readers from other fields understand the relevance of a particular kind of expertise for larger questions about smart grids. It is our hope that this book will be an instrument to rethink the boundaries of smart grids as a concept, making it more inclusive and reflexive, and therefore more adequate for shaping a sustainable energy future.

In the course of our discussions, participants often quipped about the relative smartness (or dumbness) of smart grids. Whether the system is seen as smart or not depends on how you define smartness, but also on how the problem that smart grids are meant to solve is defined. While this varies across regions and systems (see Beaulieu, this volume), two main framings of the problem dominate debates about anticipated problems with reliable supply of electricity to consumers, especially households, but also industries. The first focuses on how to incorporate and balance the often fluctuating production of renewable electricity into the grid. The second has to do with managing infrastructures and coping with the increasing electricity demand of societies, in particular peak demand. In both cases the answer is expected to come from ICT, by adding a layer of digital information to the operations of the grid and to the management of supply and demand. These starting points emphasize technology, but do so in relation to an existing infrastructure. Furthermore, the solutions proposed, even the most narrowly technological, always involve a suite of technologies (Shove 2007) rather than a single device. There will be no single 'killer app', but clusters of new technologies and practices. Solutions will necessarily be multiple and heterogeneous, if only because technological change involves the merging of the software of ICT and the hardware of energy infrastructures. The chapters in this book will further more demonstrate how transformations of infrastructures and technologies are intrinsically tied to social, economic, institutional and legal changes of our energy system. Furthermore, these changes will take place in a context where the very nature of 'energy' is shifting. In a near future, we may see transformations as far-reaching as the recent digital revolution, and the very concept of energy may be moving, from the provision of Kw/h to the provision of energy services.

In the first part of this volume, various approaches to changing energy systems are set out. Marco Aiello and Giuliano Andrea Pagani (Chap. 2) focus on energy distribution and the role that information and communication technology (ICT) can play. After a brief overview of the current role of ICT in energy distribution systems, they discuss the consequences of bi-directional energy flows. The electricity meter has to transform in such a way that it can help to predict energy consumption and can deliver a real-time view of both production and consumption anywhere in the distribution grid. They conclude that the current energy systems have to deal with two different constraints. Whereas ICT research and development must deal with a material infrastructure that is highly constrained by physical laws, power systems research and development faces the challenge of having to decentralize its operations and to make room for decision-making by more active end-users.

These decentralized decision refer to the new roles for consumers and prosumers in the grid. The passive and active roles of energy users are analysed by a research team of the Eindhoven University of Technology, led by Geert Verbong (Chap. 3). The authors develop a quadrant with four typical roles: users can be passive or active enablers of potentially sustainable innovation and they can be passive or active 'barriers' to such innovation. There can be organised protest to change or there can be organised grass root innovation projects, and anything in between. They conclude that there is a need for user-centred business models that enable desired roles, for which they sketch out a research agenda.

In Chap. 4, Ellen van der Werff, Goda Perlaviciute and Linda Steg put forth further psychological dimensions to analyse active roles of energy users. Using a review of psychological studies, they identify factors that stimulate so-called 'smart energy behaviour' by individuals and households. Little is known about how different incentives for smart energy behaviour affect each other. Both positive and negative spill-over effects are noted, leading to the 'enabler' or 'barrier' roles discussed in the work of Verbong and colleagues. The processes underlying these effects deserve more attention. Policies stimulating smart energy behaviour need to be aware of people's values, which the authors operationalize in four types: hedonistic, egoistic, altruistic and biospheric sets. The final point in this chapter points to the bridge between psychological and societal dimensions: addressing the biospheric values of individuals appears most effective, provided this is combined with a conducive context, including perceived distributive fairness and trust in the parties involved.

Part 1 ends with Anne Beaulieu's epistemological analysis of smart grids (Chap. 5). Confusion about the nature of new energy systems and the role of smart grids therein is not merely a matter of the developmental stage of the new technologies and their application. Beaulieu discusses the roles of definitions, not by providing an authoritative once-and-for-all definition, but by demonstrating their function in the development of smart grids. "Definitions put forth a reality, foreground and background, include and exclude, assign active and passive roles," she argues. These diverse realities are described in terms of three functions: promissory work, creation of objects and boundary-work. This analysis provides insight in the power of framing inherent in definitions of smart grids, as well as very concrete tools for working across definitions, as is often the case in interdisciplinary work.

In the second part of *Smart Grids in Global Context*, we move from design to control and regulation of smart grids. In seven chapters technical, legal, economic, and societal aspects are discussed. Hassan Farhangi (Chap. 6) kicks off with an analysis of cybersecurity. Smart grids will existentially rely on ICT, and thus get on board the broad agenda of cybersecurity, running from software vulnerabilities for (e.g., hacking or data misuse) to hardware vulnerabilities of its material infrastructure for (e.g., sabotage, bombings or natural hazards). Farhangi moves beyond the general issues by investigating the cyber vulnerabilities in the British Columbia Institute of Technology (BCIT) Smart Microgrid. He analyses it as a potential site for cyber warfare, and concludes that, in face of attack scenarios on critical infrastructure, massive investments in cyber defence are unavoidable.

Part 2 ends with Johannes Kester's Foucauldian approach of the structures and practices that are empowered by the security dimensions of smart grids. "A smart grid is about the delivery *of* power, but there is power *in* and *behind* a smart grid as well," he argues in Chap. 13. He agrees with Farhangi that smart grids are essentially not about electricity but about the infrastructure to deliver it, and, he adds, its owners and operators. Although the smart grid seems to liberalize individual choices about production and consumption, the centralization of information in the energy system may very well move society into an opposite direction. Companies and governments will achieve new powerful positions in the new structures, for better or for worse. The chapters in-between these two analyses of how smart grids will shape vulnerabilities and power (in all sense of the word) further detail the dynamics of control, regulation, privacy and flexibility currently being designed.

Chapter 7, by Bao Nguyen, Desti Alkano and Jacquelien Scherpen, discusses how demand response regulation can be embedded in the market structure of the Universal Smart Energy Framework (USEF). Using distributed model predictive control (MPC) methods, they calculate how the balance between demand and supply can be optimized. Additionally they analyse how innovative storage options like Power-to-Gas can be successfully integrated into the system. With such integration, the electricity grid and the gas grid become physically intertwined. The next step would be to incorporate pricing mechanisms in the system, which are discussed in more detail by Machiel Mulder in Chap. 8.

Mulder focusses first on the present tariff-regulatory frameworks, which were mainly designed to stimulate competition and lower prices for consumers. Environmental and sustainability concerns were not part of the equation. Can they be sufficiently adapted to trigger network operators to make the desired investments to support a shift in the energy sector from a fossil-fuel based to a renewable-based industry? Provided the right circumstances in the wholesale and retail markets, Mulder is optimistic about one form of tariffs: yardstick regulation, a form of price-cap regulation. Experiences in the Netherlands are positive. Productive efficiency can be achieved without negative effects on the performance of the networks.

Energy prices and demand response regulation intend to balance the demand behaviour. But how much unpredictability can the energy system cushion itself? In Chap. 9, Sebastian Trip and Claudio De Persis take on the problem of frequency regulation in power grids in the presence of unknown and uncontrollable generation and demand. They formulate the problem of frequency regulation as an output agreement problem for distribution networks. This is a clear case in which the exchange of information between parts of the grid can lead to new approaches to its control. When the grid also becomes a communication network, new solutions become possible.

Another incentive for studying various aspects of social and technological balancing potentials comes from a game changer in energy transition, which is expected from the massive use of electric vehicles, and electric transportation more generally. Together with distributed renewable energy sources, they add to the balancing problems noticed so far. In Chap. 10 Chris Develder, Matthias Strobbe, Klaas De Craemer and Geert Deconinck investigate demand-response strategies that will be needed to avoid peaks and support balancing in the energy systems. In two case studies they discuss the options for load flattening: the smart grid regulates the charging of electric vehicles, thereby reducing peak demand and moving it away from the present base load peak around 6 pm. The second case shows how the electricity demand of electric vehicles can be used to prevent over-voltage problems caused by irregular electricity supply from renewables. The chapter goes on to investigate three types of algorithms that can be used in these cases: centralized, distributed and aggregate and dispatch algorithms. In terms of scalability and optimality, the distributed algorithms perform best, be it in theory. The authors end by elaborating various simulation tools for further testing.

If Develder and colleagues seek a better interaction between mobility needs and the grid, Lukszo and Park Lee put forth a radical concept, a near fusion of mobility, grid and energy production. They present the 'car as power plant concept that links mobility needs of drivers, the actual immobility of passenger vehicles that are stationary (parked) most of the time, and the need for flexible energy production. They review the feasibility in technical, organisational, economic and social terms of this use of fuel-cell powered cars, which has the potential for create a decentralised and ‘detachable’ energy production system.

Chapters 7–11 show that an optimally functioning electric smart grid profits from optimal data sharing and communication. Compared to the classical grids, the uncertainties in supply and demand are many. The more is instantly known about fluctuations or malfunctions, the more sophisticated the algorithms can become, and thus the higher the reliability of the system. This is clearly in the interest of society. Yet, as always, there is a downside: potential misuse of the data. Farhangi (Chap. 6) mentions the commercial interest in knowing consumer behaviour. Kester (Chap. 13) elaborates the more general problem of a society moving from the spectre of ‘Big Brother is Watching You’ (a centralized tyranny) to the nightmare of ‘Many Little Sisters Are Watching You’—an image developed already in 1997 by Manuel Castells. These new forms of power are hard to control. The least we can do is provide legislation that helps to protect people from misuse.

Jonida Milaj and Jeanne Pia Mifsud Bonnici take up one dimension of this challenge in Chap. 12: how does privacy relate to law enforcement use of smart meter data? They investigate this in the context of the European Union and sketch a sobering overview of the existing shortcomings in European legislation. Simultaneously, the literature on the technical and engineering aspects of smart meters shows how tempting it will be for law enforcement agencies to exploit this source of information. Much can be detected from detailed knowledge of a household’s electricity use, building a clear profile of a suspect, without the suspect’s awareness. But mass surveillance can also be supported by using smart meter data. The EU aims at 80% smart meter use by 2020, but the legal safeguards established thus far by the laws, case law and the doctrine for both service providers and law enforcement authorities do not address the intrusive nature of smart meter data analysis.

In spite of (or should we say: in the face of?) such unsettled aspects of introducing smart grids, many experiments are initiated. Part 3 of this volume takes stock of the lessons learned so far. The authors are reporting field experiences in the Netherlands (Chaps. 14, 15 and 17) and in Denmark (Chap. 16).

Bas van Vliet, Joeri Naus, Robin Smale, and Gert Spaargaren (Chap. 14) present a sociological research agenda to guide existing pilots. They focus on the emerging energy practices in smart energy systems, which they call e-practices. By elaborating Social Practice Theory, they show that existing e-practices at the household level are much harder to change than is often assumed. They are routinized and reflect implicit sets of norms, values and principles which are difficult to address. Specifically relevant is to stop viewing a household as a closed entity or unitary actor. Instead it is “a set of different yet interdependent sub-systems that fulfil specific domestic tasks”, including various human agents. This approach is used to analyse interviews with householders in a trial among 45 Dutch households, energy providers and consumer organisations, and survey and interview data on household involvement in two local energy cooperatives. They conclude that the changes in e-practices that did occur redefined the relationships within and between households and providers. These changes are the outcomes of complex systems, however, and are therefore equally complex to steer, just as expected.

Petra de Boer and Nynke Verhaegh (Chap. 15) report the results of smart grid demonstration projects in The Netherlands, set up by a conglomerate of public and private actors in the energy sectors. They conclude that in these small scale projects, smart grids have been working well in balancing demand and supply in grids with renewable distributed resources. Yet, in line with the previous chapter, they emphasize the basic dependence on the cooperation by consumers and prosumers. On average the motivation of participants in small projects is high. The challenge therefore is to scale up the experiments.

Chapter 16 by Mikkel Baun Kjærgaard, ZhengMa, Emil Holmegaard and Bo Nørregaard Jørgensen, brings us back to the more technical side of bringing smart grids to practice. The first half of the chapter focuses on field tests to improve the capacity of data collection. The second half focuses on the visualization of this data. To this end the research team has set up a *micro-grid living lab* in Vejle (Denmark), aimed at collecting energy data sets covering renewable energy sources, commercial and industrial buildings and their occupants. The project focuses on commercial and industry buildings and involves five companies. Visualisation of the processed data helps to identify domain characterisations, which helps to improve decision support tools, using the merits of instant data collection by smart grids.

Carina Wiekens (Chap. 17) reports on end user research in PowerMatching City II. This is a leading Dutch smart grid project, involving 40 households. As also described in Chap. 15, two energy services were developed jointly with the end users: Smart Cost Savings, and Sustainable Together. This allowed them to build a sustainable community at lowest energy costs. Did they? Well, to some extent. Using self-produced energy appeared to value higher than following the most efficient strategy for saving energy. This seems to contradict a second conclusion that feedback on costs was preferred over feedback on sustainability. Apparently, self-production triggers other values. It also seems that in certain cases, end users "prefer automatic and smart control, even though manual control of appliances felt most rewarding". In face of the major challenge noted in Chap. 15, one of Wiekens' conclusions may be especially crucial to effecting change: "we found that experiences and behaviours were fully dependent on trust between community members, and on trust in both technology (ICT infrastructure and connected appliances) and the participating parties." If this is the case, scaling up smart grid projects to city-levels and transnational levels will put a heavy burden on the societal cohesion of our multicultural societies.

But perhaps it can also work the other way around: discovering the merits of functional cooperation in (partly) distributed smart grids might give end users something else to discuss than their class, gender, age, racial or religious differences. In the end, the global concerns highlighted by the sustainability discourse might overshadow such societal cleavages. Smart grids would then become a project to shape our future, and not only a solution to an infrastructural challenge. Dialogue and collaboration between disciplines are essential. Our hope is that this volume will be a potent tool to develop the variety of knowledge and interaction needed to build this future. The transformational experiences of the authors and participants in the Groningen Energy Summer School reinforce our trust that this is achievable.

Acknowledgements The vision for this book was developed in the course of preparing and running the Groningen Energy Summer School in 2014 and 2015, in which Chris Zuidema, Jaap de Wilde and Anne Beaulieu acted as co-anchor teachers. Bert Wiersema, Margriet Halbersma, Andrea Pagani and Sebastian Trip were precious colleagues and assistants in the preparation and hosting of these events. Each chapter in this book benefited from interactions with participants to the summer school, and this interaction is explicitly signalled at the end of each chapter in the form of 'points for discussion'. The Energy Academy Europe, Globalisation Studies Groningen, the Groningen Energy and Sustainability Programme and the Summer School Office of the University of Groningen also provided material and immaterial support, without which this project would not have come to fruition. The realisation of this volume was also greatly aided by the editorial support of the staff at Springer Publisher and of our editorial assistant Ferry Lounis, whose dedication and attention to detail were invaluable. The material in this book therefore benefitted from myriad contributions and exchanges in the networks created through these events that linked close to 100 staff, participants, contributors and lecturers, and these are gratefully acknowledged by the authors and editors.

References

Carvallo, A.: (2015) https://www.linkedin.com/in/andrescarvallo

Castells, M.: The Power of Identity; The Information Age: Economy, Society and Culture, vol. II. Cambridge, MA; Blackwell (1997)

Khoi, V., Miroslav, M.B., Novosel, D.: Grids get smart protection and control. IEEE Comput. Appl. Power **10**(4), 43 (1997)

Shove, E.: The design of everyday life. Berg Publishers, Oxford (2007)

Part I
Approaches to Changing Energy Systems

How Energy Distribution Will Change: An ICT Perspective

Marco Aiello and Giuliano Andrea Pagani

Abstract The accessibility of small scale renewable sources, the emergence of electric vehicles, and a need for sustainability are fueling a change in the way electricity is produced and consumed. This is happening together with the digitalization of the electric infrastructure, something that is providing for vast amount of data and control opportunities. We overview the current and promised change in the electricity distribution grid from the perspective of Information and Communication Technology, taking the points of the smart meter, the user, the utility, and the ICT service provider.

1 Prologue

Once upon a time there were black boxes hosting electromagnetic motors, installed everywhere. Homes, factories, office buildings had these boxes which would be in almost constant activity, rotating as current went through them, mechanically increasing a Watt counter. Rooted on a patent of 1889 of the Hungarian electrical engineer Ottó Bláthy, these devices have been as pervasive as electricity in homes, offices, and companies. Their design has basically survived a century and they are still widely used worldwide.

The views and opinions expressed in this chapter are those of the authors and do not necessarily reflect the official policy or position of the respective affiliations.

M. Aiello (✉) · G.A. Pagani
University of Groningen, Groningen, The Netherlands
e-mail: m.aiello@rug.nl

G.A. Pagani
e-mail: g.a.pagani@rug.nl

G.A. Pagani
Alliander N.V., Arnhem, The Netherlands

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_2

2 Introduction

Two more or less concurrent events changed the 100 year old way of doing electricity metering and billing. On the one hand, energy flows have become bi-directional. With the introduction of affordable small scale generators, such a PV, small wind turbine, μCHP, the meter had to also account for the energy fed back into the grid and not only coming from it. On the other hand, the meter moved from being a mechanic-analog device—inspected visually monthly or even yearly—to being an electronic meter with the ability to expose via wired or wireless communication channels its state.

Orthogonally, this has meant also the possibility of using the meter differently: not just reading it once a year by physically accessing it and looking at the numbers reported on the meter, Fig. 1. The electric meter gave the possibility of reading remotely the value as frequently as one desires. If some countries, like the Netherlands, pose a legal limitation on the sampling rate (six times a year), in other jurisdictions, these readings can be as frequent as just few a minute. This changes the role of the meter and transforms it into a device that can help predict the energy consumption quite precisely and deliver a real-time view of the consuming/producing situation of any node on the distribution grid.

The evolution underway is depicted in Fig. 2. On top the traditional way of doing analog metering with calendar based visual inspections. In the middle layer, the two trends: on the left, one remarks that current now flows bidirectionally due to the introduction of small scale renewables behind the meters; on the right, the transformation into a digital meter that can stream bits of information via telecommunication channels. On the bottom, the two trends coming together in what can be considered modern infrastructures.

The depicted evolution, today entails much more than just more precise and frequent billing of energy for the end users, this is actually contributing to a revolution in the way energy is produced and distributed. Advanced digital metering infrastructures generate large amounts of data that can be used for gaining insight in the energy use; they can help utilities manage their assets and plan their infrastructure based on the actual usage and not on the peak estimation; a digital meter that is able to react to signals in combination with intelligent equipment at home can open new business opportunities for the utilities and even for new players.

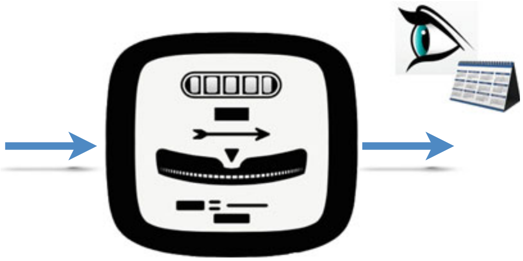


Fig. 1 Traditional analog meter

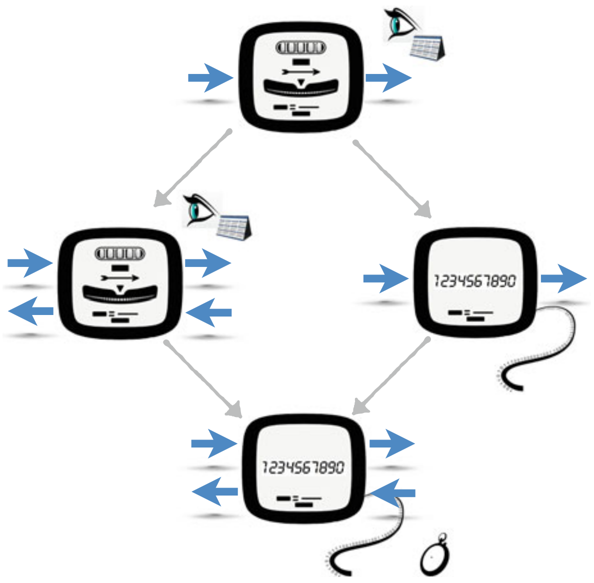


Fig. 2 Evolution of energy metering

Furthermore, it can help users understand how they use energy in order to change their behavior or, at least, account precisely for which action entails which consumption. In this chapter, we look at the current state of affairs in energy distribution from the various views relating to Information and Communication Technology (ICT), our lenses for this will be those of Information and Communication Technology. We leave economic, social, and regulatory perspectives to the other relevant chapters in the book.

3 The Smart Meter View

In some countries, smart meters have been rolled out to all users. Italy was one of the first countries undergoing this massive installation effort and is currently starting the roll out of the second generation of digital meters (Botte et al. 2005). In other countries, due to technical and political reasons, the roll out of the smart meters is partial. For instance, in the Netherlands, a user can refuse to have a meter installed at home on the basis of privacy concerns. Furthermore, the current legislation guarantees that the meter cannot be remotely read more than once every two months.

Smart meters are substituting the traditional analog ones, the pace might vary from country to country, though it appears to be inevitable. From the first million of installations at the beginning of the century, projections currently predict the surpassing of the 1 billion value by 2022 (Navigant Research 2013). Such a shift does not come in isolation. It is just not a matter of substituting one device for another one, it is a matter of putting in place an entire ICT infrastructure.

Smart meters need to communicate their readings with a back-end system on a regular basis. This requires a telecommunication infrastructure and an information system to manage the data. With a reading per month for billing purposes, this can be easily achieved. Though things become interesting when moving to more frequent readings. In fact, to make accurate predictions of energy consumption per unit, it is useful to have historical readings of a meter with the granularity of minutes, if not even smaller time intervals. Such readings may even allow to make accurate recognition of which appliances are running at any given moment (Laughman et al. 2003). In addition, one can make correlations with weather and calendar information so that the load of a customer can be estimated with a fair precision.

From a technical point of view, there are issues of amount of data, speed at which it is generated and has to be transfered, and of its usefulness. Issues that often go together under the heading of *Big Data.* Let's consider each of these individually.

Volume. In Aiello and Pagani (2014), we have estimated what the amount of data that could result from a fully smart energy system for a country like the Netherlands. Considering the number of households, the connected smart energy devices, the generation facilities and the grid itself, one could easily arrive to petabyte (PB) of grid data per year. Table 1 shows the case of a scenario possible in few decades from now where smart meters give a reading every five minutes. Meaning the move from the current bimonthly readings for few gigabyte (GB) of data for the whole country, to PB of information just for the Netherlands alone. Such an estimate is in line with those for other countries. The utility EDF has estimated in its French network 35 millions smart meters and a sampling frequency of 10 min to have a total amount of data of about 120 terabytes/year (dos Santos et al. 2012).

Velocity. The large amount of data is generated in a distributed and independent fashion. This entails the need for its transmission and, in turn, the existence of a

Table 1 Scenario of data generation related to the smart grid for the Netherlands. *Source* Aiello (2014)

Metering	
Metered customers	9,000,000
Installed smart meters	9,000,000
Smart meter sampling period (min)	5
Smart devices	
Electric vehicles	3,950,000
Battery packs	135,000
Intelligent appliances per household	20
Grid infrastructure	
Nodes HV (380/220 kV)	60
Nodes MV/LV	178,221

communication infrastructure. Power line communication is a possibility to go from the smart meter to the first substation and then using other higher bandwidth means to further aggregate the data (Botte et al. 2005). Alternatively, one can use wireless communication directly form the smart meter (Parikh et al. 2010) and then rely on fiber optics for the backbones (Holcomb 2012). Many studies agree that an existing infrastructure such the Internet would not be sufficient to satisfy the bandwidth and, especially, the response time needs an infrastructure based on high frequency sampling of smart meters, while filtering and aggregation and optimization of packet flows might be required based on the telecommunication infrastructure available in each specific case (Kansal and Bose 2012).

Value. Having large amounts of data brings no specific benefit, per se. It is not about the bits of data, but it is about the amount of information that reside in the data and that can give additional value and open new possibilities (Shannon 1964). It is about the use one can make of the information in the data that provides for the added value. As mentioned, precise billing is just the satisfaction of an elementary requirement, the real value has to be searched in the identification of correlations among events that allows one to make reliable predictive models of infrastructure usage and projected energy needs. Being able to predict and, possibly, shift the demand and production of energy can provide for major economic savings and, in some cases, also reduced environmental impact. The reason for this is that energy costs do not grow linearly with the amounts provided and different sources have different environmental impacts (Sims et al. 2003).

Typically, utilities provide a certain amount of energy that is scheduled to cover the base load at a more or less fixed cost. This base load is a function of the estimated load for a given time window and is met by the base-load generating infrastructure (e.g., nuclear and coal-fired plants). The additional demand that is not covered by the base load requires additional energy sources that come at increasing costs. E.g., serving an unpredicted peak much above the common average can cost several orders of magnitude more than the base load energy production. In the traditional energy paradigm, the need to influence the load by a differentiation of the tariff has been already implemented since long time. The solution in place is not dynamic, but simply it makes a broad classification of two time periods: the day-night/weekday-weekend (i.e., peak/off-peak) tariffs. This is done to achieve a better use of the base-load power plants by reducing the load in times of high use, and, in turn, to decrease the use of expensive generating resources and costs of congestion. There is also a technical reason to stimulate the use of base load plants: base load plants are characterized by precise dynamics rules in the variation of their input-output which are rather slow. It is therefore not admissible to shut a coal plant just for few hours since the dynamics of the plant do not allow fast ramp ups and downs of the plant (hours to days for complete shutdown). In plants powered by renewable sources such as sun and wind, the situation is different. The renewable-based plants have still their own dynamics, but they are definitely more difficult to control by human intervention. Sun, wind, waves, and tides obey the rules of physics and their availability to produce energy comes from the interaction with systems where the human influence is very limited and whose dynamics are also difficult to forecast. In a smart meter world, where energy can be metered at high frequency, it is not far fetched to envision real-time pricing of energy on the basis of the actual energy supply. The goal is to transition from a demand-driven (or demand-following) energy system to a system where users adapt their consumption to the amount of energy available, therefore becoming supply-driven (or supply-following). In this context, real-time energy pricing and precise real-time measurement through a smart meter are the fundamental ingredients.

4 The End User View

The digitalization of the electric infrastructure is also shifting the user perspective. If in the past, the user had very limited means of knowing how energy was used, today, users can finally *understand* their energy footprint, resort to automation, and make conscious decisions based on real-time information. If in the past, one would see a monthly or bi-monthly energy bill, now it is easy to display real-time data about energy consumption of individual devices. Products such as Plugwise devices allow the reading of high frequency energy data. These plugs can be placed between any appliance and an electric socket and relay information via a mesh zig-bee network. One can then easily see the consumption of individual devices and also spot possible emerging spikes in energy consumption, or anomalies in the energy needs of devices. Similarly, a product like the Nest thermostat records precisely the temperatures that are set by the user, the actual room temperature, and it provides feedbacks correlating these temperatures with the weather conditions and users' decisions. In other terms, the digitalization of the infrastructure now allows the energy relevant information to abundantly flow towards the energy user.

4.1 Information Flow

There are three ways in which such information flow can hit the user. **First**, the information is returned to the user via a graph in an mobile app, a personal web-page, an email notification, a screen in his living room, or similar means. In this way, the user becomes aware of how energy is used. Such information can help change behavior by gathering insight and knowledge, Chapter 4. The information can be presented as raw (e.g., kW samples), aggregated (a graph of kWh over hourly intervals in a day), or metaphoric (number of trees necessary to compensate for the CO_2 emissions of the consumed energy). It is important to realize that having real-time information has much higher impact than simply knowing the characteristics of a device. If the energy labels help to make informed decisions when purchasing an appliance, they don't tell the full story. It is the way in which these machines are used that really determines the energy footprint.

Second, the information is collected for the user and decisions are made on his/her behalf autonomously by his automation equipment. The Nest thermostat is a nice example of this category. The thermostat gathers information by monitoring how the user sets the temperature in a room. After enough samples are collected, it learns the likely patterns of use and then starts controlling the environment on the user's behalf. This form of automation is very important, because it works without necessarily requiring conscious user involvement. One of the driving principle for Nest was that about 95 % of owners of programmable thermostats never program them. Another way of looking at this is that energy information is rich and complex and must be reduced before direct "consumption" by the end user.

Third, the flow of information is reversed. The user gathers awareness and makes direct control decisions. Instead of delegating the decision to an automation system, having the possibility to directly control appliances, possibly remotely, it makes informed decisions. This is the case of programming a dishwasher to run when owned solar panels are at peak production, or scheduling for an off-peak tariff hour. More and more appliances are on-line and can be remotely monitored and operated, think of the Philips Hue lights, the Samsung WW9000 washing machine series, and so on. Devices have a programmable interface that allows users to interact with them remotely via mobile app, to define behaviors based on contextual information, and be always on-line.

4.2 Information with Value

Home energy management systems will also be able to optimize the energy consumption of the user. Like the Nest example above, the home energy management system might be able to learn the energy patterns of the users and buy energy for the user at a discounted price. Another solution could be for the user to specify a goal (e.g., run appliances at the lowest possible cost, maximize the use of on-premise renewables) and some constraints on the comfort (e.g., the dishwasher has to be ready before 19.00 every day) and let the home energy management system identify the solution and manage the turning on and off of the equipment. We have conducted a similar experiment by creating a simple energy management system of the future connected to a realistic simulator of the smart grid to manage the electrical equipment of an office space (Georgievski et al. 2012; Pagani and Aiello 2015). In our solution, we managed to achieve a reduction in the cost of running a common set of appliances available in a modern office by 20 % without modifying the well-being perception of the users.

Incidentally, all the information that is useful for the user, is also useful for the network. The user energy data can help make accurate predictive models of energy usage within a household and, in aggregated form, help the network operator to manage the grid and its assets. In addition, new data an insights on the energy use can open the door to cheap and personalized energy consultancy therefore enabling new business opportunities and enabling further energy savings. The aspects of privacy and ownership of metering data are an important concern here, for this we refer to the Chapters 12 and 14.

5 The DSO View

The Distribution system operator (DSO) is responsible for operating the grid, ensuring the safety and availability of energy to its customers. The operator is responsible for infrastructure and equipment maintenance, if necessary, for developing the distribution system (medium and low voltage) in a given geographical area, where applicable, for managing its interconnections with other systems, and for ensuring the long term ability of the system to meet reasonable demands for the distribution of electricity (E.U.: European directive 2007). To meet its responsibilities, the DSO has to have a good model of what are the energy needs of the users over time, what are the maximum peaks that one can expect, and how should the infrastructure evolve to meet future needs, both geographically and quantitatively.

Before the wide adoption of smart meters, a Dutch DSO would estimate an average of 1 kW per household and, taking a very conservative approach, by over-estimating the growth in electricity use in the following years. Such information was then used for the dimensioning of the infrastructure. The reason for this opulent approach is that the biggest part of the costs for realizing an underground distribution infrastructure such as the one present in the Netherlands is the labor cost of excavation and laying of cables. Such an estimate was based on experience and has worked in practice for many years, though clearly one can do better. By precisely measuring, instead of estimating, one can dimension the system to the actual needs. Under-utilized and saturated lines will emerge and new more precise planning of the evolution of the grid can be made. The old way here was to put an analog sensor in the transformation station and have it inspected regularly (e.g., monthly) by a human operator visiting the facility. Currently, we are transitioning to ICT monitored and operated facilities.

The creation of precise models of utilization is especially needed now. In fact, the evolution of the grid is not just about the growth of population and urban areas; the evolution has to do with new ways of utilizing energy. The introduction of distributed micro-generation, the appearance of home-level storage facilities, and the increasing popularity of electric vehicles are changing the game. The distribution grid, which traditionally has been, unidirectional in the energy flows is turning into a multidirectional system where micro-generating sources are intermittent and there is a high mobility of load and the increasing appearance of storage.

5.1 Topology Adaptation

The distribution grid, given its *passive* role, has been engineered in the form of a radial, tree-like network. Such a topological design is correct and the most efficient when there are few large producers of energy at remote locations. In the new paradigm, energy is produced also locally and the energy production and consumption take place at neighborhood level. In this situation, if one wants to create a grid that is suited to the local energy production and distribution, designs other than the radial/tree-like should be investigated. A future with plenty of prosumers that produce small quantities of energy and sell or share it at the level of neighborhoods will affect the shape and working of the distribution grid. The change from a passive-only grid to a smart grid will require to rethink the role of the medium and low voltage grids (Brown 2008). In particular, the distribution grid has to be robust and the distribution cost has to be kept low not to put an additional burden to the stimulus for new small-scale renewable energy installations. In our study (Pagani and Aiello 2013; Pagani and Aiello 2014), we resort to Complex Network Analysis (Newman et al. 2006) not only to analyze the existing infrastructure, but also to drive the design of the next generation grid. *Complex Network Analysis* (*CNA*) is a branch of Graph Theory taking its root in the early studies of Erdős and Rényi (Erdös and Rényi 1959) on random graphs and considering statistical structural properties of evolving very large graphs having the goal of looking at the properties of large networks with a complex systems behavior. After analyzing real samples of the distribution grid of the Northern of the Netherlands (Pagani and Aiello 2011) and looking at the topological properties that influence the price, we noticed that there are network samples more prone, from a topological perspective, to accommodate local energy interactions. An increase in the average connectivity of the distribution network and topological designs that are less close to the tree-like structures (cf. Fig. 3a) such a small-world network (cf. Fig. 3b) can provide a reduction in the parameters affecting the costs of distributing electricity while improving robustness and resilience to failure. However, it is not realistic to think of rebuilding completely the distribution grid already on the ground to change its topology to make the local energy interaction more efficient. It is necessary to study how to make the current network more efficient without impacting significantly on the cost of the infrastructure. In Pagani (2014), we have considered several strategies to evolve the networks taking into account the cost burden of realizing more connections too. The strategy that provides a good balance between the performance and the cost in upgrading the infrastructure is connecting the nodes of the network (not yet connected) that have a small distance to each other. An example following this strategy for a real network sample is shown in Fig. 4.

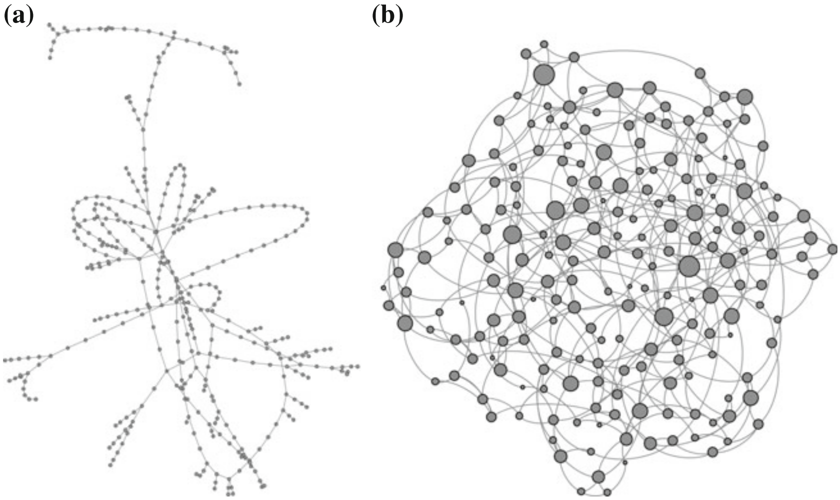
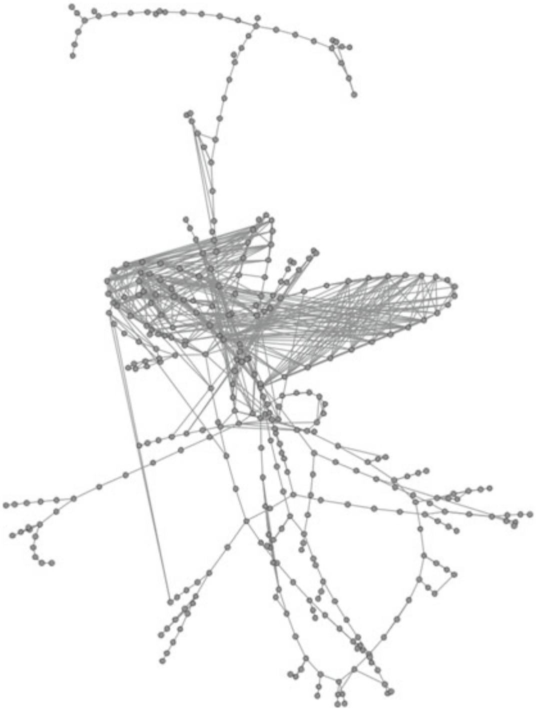


Fig. 3 Network topologies of a real (**a**) and a synthetic network (**b**). **a** A traditional radial distribution network. **b** A small world network (200 nodes, 399 edges). *Source* Pagani (2014)

Fig. 4 Evolution of a distribution network. *Source* Pagani (2014)



5.2 The Value of Analytics

DSOs are embracing the smart grid vision and widely deploying smart metering in order to improve their operations. The improvement comes from the embracing of analytics-based techniques to better analyze in real-time the actual condition of operation of the network. Traditionally, real-time telemetry services were confined to mission critical assets that needed to be continuously monitored or to the equipment used in the high voltage networks. With more and more cheap sensors and cheap data transmission, it is now possible to add sensors to almost any piece of equipment. The benefits to improve the operations of the utilities are enormous. The consulting firm Accenture estimates that smart grid analytics have a value ranging from 40$ to 70$ per electric meter per year where 40 % of this value is for the utilities and 60 % belongs to the customers (Azagury 2014). Concerning the utilities the most important areas of value are asset management, power quality, and revenue protection and billing. One can see the value of the benefits when the metering points are millions and millions. The above cited are just estimations since the roll-out of smart metering and sensing equipment are underway and utilities are developing analytics-based operations; the final answer on the benefits will be available in the near future.

5.3 A Parallel Between Telecoms and DSO

The major shift the DSOs are currently in, has some analogies to the revolution that happened in the telecommunication sector in the ’90s, which claimed many important players as victims. Let’s consider what happened back then.

The telecom sector, which was over 100 years old, was considered a natural monopoly, just like energy utilities. The telecom providers, mostly government owned, managed the service, network, and equipment layers. All R&D was done internally and any innovation sprouted by so-called non-market drivers. Fransman identifies as causes of the major paradigm shift that hit the telecom sector the following ones: cross-country competition, political pressure and consumer pressure (Fransman 2003). For instance, in 1985 the European Community emanates the Liberalization Directives under Article 90 of the Treaty of Rome determining the deregulation of telecommunications market for the next decade. Furthermore, Fransman notes “by the end of 1995, […] the now incumbent network operators [were] making the decision to leave more and more of the R&D related to the network and its elements to the specialist equipment suppliers. At the same time the incumbents decided to open their procurement, agreeing to buy from new suppliers in addition to their traditional suppliers.” In other words, the suppliers were becoming innovators and ready to play on the telecom market in more than just one role. New players were appearing from unexpected areas. For instance, an electronics company like Olivetti together with Mannesmann in 1995 enters the Italian market creating Infostrada, the first competitor of Telecom Italia. In the same period the Internet and the Web were emerging as infrastructures for all and people started requesting access to them. This was in contrast with the general worry of the telecoms of having enough bandwidth.

We claim that the electricity sector today is in a similar situation to the telecom one two decades ago (Aiello 2012). It is rooted in a tradition of natural monopoly, it is getting exposed to cross-country competition, political pressure is pushing for the unbundling (e.g., the EU directive 2009/72/EC), and there is consumer pressure for having free or deregulated access to the infrastructure. As we include renewables at all scales in our power grids and as consumers demand freedom to supply and to sell, low voltage capillary interconnectivity will be necessary so that neighbors can engage in energy trading and implicitly transform neighborhoods into energy neutral areas.

6 The ICT Provider View

ICT providers are going to play an important role in the future smart grid. Smart meters, home energy management systems, sensors, and ubiquitous computing technologies are the core expertise of ICT providers. The parties that have played a role in the expansion of an ICT-based society are going to be present in the digitalization of the grid together with domain specific providers that are forerunners in understanding the potentiality of the new energy grid and are responsible for its development.

ICT companies have the possibility to play novel roles to provide new added value services in the energy domain. In an information-driven grid, the data-driven companies offering services can increasingly have easy access to the data, perform appropriate computations and perform intervention on the smart grid equipment. For example, an ICT provider can plug its application into the energy management system of a home or an office and provide optimization for the use of equipment, give insight into the energy consumption of the appliances, understand the anomalies in energy usage, and foresee problems in the lifespan of the appliances. In addition, it is not difficult to imagine an ICT provider that takes the responsibility on behalf of the user for optimizing the energy use by utilizing local renewables and accessing the cheapest providers on an open retail energy market, thus acting as a virtual energy provider. Naturally, the automatic decisions must guarantee the comfort and economic provisions to the user. In such a dynamic and varied landscape, such as the smart grid characterized by several operators interacting in the different levels, a technology that enables interoperation and flexibility is required. The technological-software approach that is emerging and likely to stay for the implementation of the smart grid is the Service-Oriented Architecture one (SOA) (Pagani and Aiello 2012). Such a paradigm allows parties of the smart grid to interact on the service level (usually realized resorting to Web services standards) independently from the back-end system already in place. SOAs are also a powerful paradigm to easily allow the addition and removal of services on the fly, allowing a seamless interaction in an energy management system and the possibility for a true competition.

With the spread of electrical mobility, the increase in pervasive computing technologies, the ubiquity of devices connected with each other and the Internet, energy is going to become another product available and manageable through the Internet where specialized apps are going to emerge as widely popular. Examples of companies that are exploring this new ground are Opower in the energy awareness, billing services, demand response, and user engagement. A global player is AutoGrid which spans from the energy-related data from the grid operations, building energy optimization, and end-user equipment. Energy is transitioning towards being an exciting sector where the intertwining between Power Engineering and ICT is going to provide a vast amount of new services and solutions coming from various backgrounds to achieve a more efficient electricity infrastructure and sustainable energy footprint.

7 Concluding Remarks

The changes that are rapidly occurring in the electricity sector are empowered, if not driven, by ICT. Advanced metering infrastructures and smart devices which are energy aware are taking over a 100 year old infrastructure which used to be analog in its basic operation.

The intrusion of ICT in the power system field is neither straightforward nor risk free. As we have described in the chapter, there are important challenges of data management and it is still unclear how to extract value from data. Furthermore, ICT is generally less reliable than modern power systems. In the Netherlands, for instance, in 2014 the average downtime per year per customer is of just 20.0 min (Netbeheer Nederland 2015), that is, an availability of about 99.996198 %. This is two orders of magnitude better than the availability of a mobile network.

On the other hand, an infrastructure that has to accommodate for distributed and intermittent generation, for mobility of load and storage as electric vehicles do, of increasing user involvement, needs the power of ICT to manage the infrastructure and to accommodate for dynamic, adaptive and flexible solutions.

ICT and power system will have to go hand in hand and learn from each other. ICT research and development is challenged by dealing with a material infrastructure highly constrained by physical laws, while power systems research and development is challenged by having to decentralize decisions and rely on novel control mechanisms that give an increasing freedom to the end users.

Points for Discussion

- How much does the advent and success of Smart Grids depend on the full roll out of Smart Meters?
- Knowing how the Internet developed and changed our daily lives, can we draw a parallel with smart grids and predict their evolution in the future? Will energy sector manage to evolve from a commody to a vibrant ICT-based product for the consumer?
- The authors discuss energy distribution developments from an ICT perspective, consciously leaving social, economic, regulatory and political perspectives untouched. They conclude that the power system will have to deal with decentralized decision and new control mechanisms. How do you evaluate their conclusions in light of the non-ICT factors?

References

Aiello, M.: Spatial distributed information: From a silly chat to the smart grid. University of Groningen, Inaugural Speech (2012)

Aiello, M., Pagani, G.A.: The smart grid's data generating potentials. In: M. Ganzha, L.A. Maciaszek, M. Paprzycki (eds.) Proceedings of the 2014 Federated Conference on Computer Science and Information Systems, pp. 9–16 (2014)

Azagury, J.: Unlocking the value of analytics. accenture's digitally enabled grid program. Tech. Rep. 13-3457/11-6785, Accenture (2014)

Botte, B., Cannatelli, V., Rogai, S.: The telegestore project in enel's metering system. In: Electricity Distribution, 2005. CIRED 2005. 18th International Conference and Exhibition on, pp. 1–4 (2005)

Brown, R.: Impact of smart grid on distribution system design. In: Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, pp. 1–4 (2008). doi:10.1109/PES.2008.4596843

dos Santos, L., da Silva, A.G., Jacquin, B., Picard, M., Worms, D., Bernard, C.: Massive smart meter data storage and processing on top of hadoop. In: BigData Workshop, VLDB 2012 (2012)

Erdös, P., Rényi, A.: On random graphs. I. Publ. Math. Debrecen **6**, 290–297 (1959)

E.U.: European directive 2007/72/ec art. 2 n. 6 European Commission (2007)

Fransman, M.: The International Handbook on Telecommunications Economics, chap. Evolution of the Telecommunications Industry into the Internet Age. Edward Elgar Publishing, Cheltenham (2003)

Georgievski, I., Degeler, V., Pagani, G., Nguyen, T.A., Lazovik, A., Aiello, M.: Optimizing energy costs for offices connected to the smart grid. IEEE Transac on Smart Grid **3**(4), 2273–2285 (2012)

Holcomb, C.: Pecan street inc.: A test-bed for NILM. In: International Workshop on Non-Intrusive Load Monitoring, Pittsburgh, PA, USA (2012)

Kansal, P., Bose, A.: Bandwidth and latency requirements for smart transmission grid applications. IEEE Transactions on Smart Grid **3**(3), 1344–1352 (2012)

Laughman, C., Lee, K., Cox, R., Shaw, S., Leeb, S., Norford, L., Armstrong, P.: Power signature analysis. Power Energy Mag. IEEE **1**(2), 56–63 (2003). doi:10.1109/MPAE.2003.1192027

Navigant Research: Smart electric meters, advanced metering infrastructure, and meter communications: Global market analysis and forecasts, Navigant Research (2013). URL https://www.navigantresearch.com/research/smart-meters

Netbeheer Nederland: Betrouwbaarheid van elektriciteitsnetten in nederland—resultaten 2014. Tech. Rep. RMI-ME-150002575, Netbeheer Nederland, (2015)

Newman, M., Barabási, A.L., Watts, D.J.: The structure and dynamics of networks. Princeton University Press, USA (2006)

Pagani, G., Aiello, M.: Generating realistic dynamic prices and services for the smart grid. Systems Journal, IEEE **9**(1), 191–198 (2015)

Pagani, G.A.: From the grid to the smart grid, topologically. Ph.D. thesis, University of Groningen, Groningen (2014)

Pagani, G.A., Aiello, M.: Towards decentralization: a topological investigation of the medium and low voltage grids. IEEE Trans. Smart Grid **2**(3), 538–547 (2011)

Pagani, G.A., Aiello, M.: Service orientation and the smart grid state and trends. SOCA **6**(3), 267–282 (2012)

Pagani, G.A., Aiello, M.: From the grid to the smart grid, topologically. Tech. Rep, JBI, University of Groningen, Groningen. Available at arXiv:1305.0458 (2013)

Pagani, G.A., Aiello, M.: Power grid complex network evolutions for the smart grid. Physica A **396**, 248–266 (2014)

Parikh, P., Kanabar, M., Sidhu, T.: Opportunities and challenges of wireless communication technologies for smart grid applications. In: Power and Energy Society General Meeting, 2010 IEEE, pp. 1–7 (2010)

Shannon, C.: The mathematical theory of communication. University of Illinois Press, Urbana (1964)

Sims, R.E., Rogner, H.H., Gregory, K.: Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. Energy Policy **31** (13), 1315–1326 (2003)

Smart Business for Smart Users: A Social Agenda for Developing Smart Grids

G.P.J. Verbong, N. Verkade, B. Verhees, J.C.C.M. Huijben and J.I. Höffken

Abstract The promise of smart grids is very attractive. However, it is not yet clear what the future smart grid will look like. Although most researchers acknowledge that users will play a more prominent role in smart grids, there is a lot of uncertainty on this issue. To counter the strong technological bias in smart grid research and literature, we propose that research should focus more on the social and business dimension of smart grid developments. The main elements of such a research agenda are:

- Developing more socially embedded visions on smart grids and the services it will provide
- A shift in the focus on developing smart grids components and systems towards the services it will deliver
- Development and testing of innovative user-centered business models and ecosystems.

More general, on the role of users in smart grids, the main lesson is that user roles should be taken more seriously in relation to smart grids: experts should no longer regard users exclusively and/or simply as potential barriers to smart grid innovation but also as important stakeholders and potential participants in the innovation process.

G.P.J. Verbong (✉) · N. Verkade · B. Verhees · J.C.C.M. Huijben · J.I. Höffken
Department of Industrial Engineering and Innovation Sciences,
Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands
e-mail: g.p.j.verbong@tue.nl

N. Verkade
e-mail: n.verkade@tue.nl

B. Verhees
e-mail: b.verhees@tue.nl

J.C.C.M.Huijben
e-mail: j.c.c.m.huijben@tue.nl

J.I. Höffken
e-mail: j.i.hoffken@tue.nl

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_3

1 The Smart Grid as Panacea

The large scale introduction of intermittent low carbon energy sources like wind energy and solar PV at the supply side and the large scale introduction of electric vehicles (EVs) and heat pumps at the demand side are increasingly posing challenges for the existing electricity grids in many countries. Those grids have been designed for a centralised system where the electricity flows from large power plants through the transmission and distribution networks to passive end users or consumers. They have been constructed decades ago and in many cases are near the end of their technological lifetime. The simple solution for these ageing grids is reinforcing the current infrastructure by using cables and lines that can carry much heavier loads. The smart grid is another option for addressing the current electricity system challenges. There is no consensus on what a smart grid is. Wikipedia provides the following definition:

> A smart grid is a modernised electrical grid that uses analog or digital information and communications technology to gather and act on information - such as information about the behaviors of suppliers and consumers - in an automated fashion to improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity. Electronic power conditioning and control of the production and distribution of electricity are important aspects of the smart grid (Wikipedia 2015).

This definition captures beautifully the main promises of smart grids: introducing information and communication technology promises to improve the technological and economic operation of the electricity grid by making it more sustainable and reliable. It also enables a more efficient operation of the grid by reducing losses and at the same time it offers economic advantages for all stakeholders.

The promise of smart grids is so attractive that it has created a hype. Most industrialised nations, including the members of the EU, the USA, and many Asian countries, like China, Japan, South Korea and India, have joined the race to become a leader in the smart grid field. They have set up extensive R&D programs and are testing smart grids technologies in a large number of pilot projects. The roll-out of smart grids has become one of the spearheads in EU policy. Next to a safe integration of renewables, the ability to accommodate major loads and the creation of new economic activities, the implementation of smart grids is regarded critical for reaching energy and climate objectives. Another main objective is the empowerment of consumers. It is thus not surprising that in policy circles smart grids are seen to be stimulated at all costs. The investments needed only in the EU are estimated at about 140 billion euro until 2020 (Bowden 2014).

However, it is not clear at all what these smart grids will look like. Also, not all impacts will be positive. The Wikipedia website continues: “Roll-out of smart grid technology also implies a fundamental re-engineering of the electricity services industry” (Wikipedia 2015). The transition to a smart grid will have a major impact on the organisation of the electricity industry, and by implication on all stakeholders in the electricity system. The assumption that there will be only winners is rather naive: there will also be quite a few losers in this. Some actors will disappear completely, others will have to change their operations considerably and new ones will enter the field. Researchers point in particular to the crucial role of users in future smart energy systems. The expectation is that the role of users will change from a passive end user into a more active one (Goulden et al. 2014). In more radical visions, users will become the main players in the future. Although most researchers acknowledge the changing role of users in smart grids, there is a lot of uncertainty on this issue. What are the real advantages of the smart grid for the users and when, why and how would they embrace the new services a smart energy system offers? And who is going to offer those new services and what kind of innovative business models have to be developed? Moreover, smart grids will introduce new potential risks and contested issues as well, including privacy issues, cyber security and data ownership. A larger involvement of users also raises new issues like the potential exclusion of certain groups of users (access to the smart grid) and responsibility for (parts of the) smart energy system. This article will not provide answers to these questions, but we will elaborate on the kind of research we think is needed to approach these issues more successfully.

The quote on the Wikipedia website continues with the phrase "(…) although typical usage of the term is focused on the technical infrastructure". This refers to the strong technological bias in smart grid research and literature, despite the expected increased role of users and new actors that will be involved. To counter this, we believe research should focus more on the social and business dimension of smart grid developments. We take the following developments as starting points:

- Decentralised or distributed generation of sustainable energy will increase year by year and will become a substantial part of the overall energy supply system; and because of the intermittency and two-directional flows, the electricity system is becoming more complex. This is the main argument for adding "intelligence" to grids: more sensing, measuring and monitoring will be introduced. At the demand side, there are two main strategies to deal with these issues: storing electricity and increasing flexibility of demand by introducing demand response or Demand Side Management (DSM). Until recently the emphasis has been on DSM, as there was no business case for local storage, e.g. in batteries, or local system services (Van Vlimmeren 2010). However, this is changing rapidly due to progress in battery technology (see the recent announcement of Tesla's Powerwall), but also because of changes in policy. Reduction of feed-in tariffs and other support schemes for solar PV will encourage local consumption of locally generated electricity (self-consumption).
- Linked to the increasing application of IT devices and software, these developments will trigger major changes in local energy systems in houses and buildings. A new local energy system will emerge, consisting of a smart meter, ICT, display, a home energy management system and several smart appliances (or home automation). This new system "behind the meter" will have a huge but yet unknown impact on daily routines and practices of users.

- For a major part of the 20th century the role of the government in the energy domain increased but under the spell of neoliberalism in the 1980s and 1990s the government retreated and increasingly relied on the market and market based instruments. The current system is still struggling with these changes. The energy system is still in transition, although not necessarily in the direction of a more sustainable one (Verbong and Geels 2007).
- Changing relations between state, market and civil society are especially apparent in the field of electricity. In the Netherlands this dynamic has been called the "energieke samenleving",[1] implying that the relations between state, market and civil society are changing. Indicative for this development in the energy sector is the appearance and diffusion of energy cooperatives and other local and regional energy initiatives in many countries (Seyfang et al. 2013; Yildiz et al. 2015). These local energy cooperatives (or other organisational forms) are platforms in which citizens cooperate in working towards a more self-sustainable, renewable and localised energy system.
- The combination of these developments is creating a difficult situation for the incumbents. It is threatening their main assets: large fossil fuel-fired power plants. Because of the way the electricity market is organised, these power plants are increasingly becoming uneconomic. Some utilities like E.ON announced a dramatic change in strategy and a focus on renewables and service (E.ON 2014). This results in interesting new hybrid business models that incorporate both mainstream and niche market players (Huijben and Verbong 2013).

With users no longer perceived as passive consumers but as active participants, their role in smart grid innovation, either individually or collectively, is of key interest. Following this user centered perspective we identify the following research fields as being of particular importance when researching current dynamics of the changing electricity landscape. First we will address the use of new approaches to develop smart grids visions that include the social and user dimension. In the next section, we will focus on energy consuming social practices, followed by the emerging field of business models studies. Which—we will argue—needs to include a more explicit focus on user centered business models. In the final section we will summarise our finding in an agenda for socially and business oriented smart grids research: smart business for smart users.

2 Envisioning the Smart Grid

As indicated, our current energy system is changing rapidly. The liberalisation of energy markets, the process of European (dis)integration, increasing geopolitical instability and the issue of climate change are threatening the dominant mode of

---

[1] Literally this translates as 'the energetic society'.

generation and distribution. Distributed generation, increasingly by renewable energy sources like wind energy and solar, also are putting the traditional system of large scale power plants and HV grids under pressure. The fast diffusion of the application of IT in the energy domain contributes to the uncertainty and raises questions about the future development of the energy system.

The traditional approach to deal with this uncertainty has been technological forecasting and roadmapping. These approaches are characterised by a rather linear extrapolation of on-going developments or, as in roadmapping, the steps needed to reach the targets set by the stakeholders involved. The first energy crisis in the 70s demonstrated the limited usefulness of these approaches. Royal Dutch Shell used scenarios as a method for dealing with the uncertainty. The core idea of scenario planning is to explore a set of different scenarios based on a few main driving forces. This enabled Shell to develop robust strategies that would work in different scenarios, in different circumstances. These scenarios and the scenario methodology, developed by Shell and other organisations, have had a large impact on future studies, but they focus predominantly on the supply side of the energy system (e.g. availability of resources, prices of resources, technological innovations).

The increasing focus on sustainability introduced a new normative approach of exploring the future. A sustainable future becomes the starting point and via a process of backcasting the necessary (policy) measures can be identified. The problem with backcasting however is that it remains very difficult to determine what a sustainable future will look like. The normative approach leads to often unrealistic or one-sided assumptions on the future; moreover, most backcasting scenarios also have a strong technological bias. The focus has shifted now to include the social dimension, as in socio-technical scenarios and the process of framing and envisioning the future. This challenge has been taken up by Shell in the New Lens scenarios, published in 2014, but more on a global scale, e.g. by envisioning a strong role for the government in its Mountain scenario (Shell 2014).

Visions and scenarios can be very powerful, in particular if these can be visualised in one or few persuasive images. The role of visions (and expectations) has been studied by STS scholars, in particular by the 'Sociology of expectations' (Van Lente 1993; others); other bodies of knowledge include the Leitbild perspective and Transition Management. These literatures point to the performative nature of visions. Expectations (and visions) *act*, that is, visions not only describe a future situation, but by its articulation and acceptance they become a factor in the development (Van Lente 1993; Dignum 2013).

Wiek and Iwaniec (2014) developed quality criteria for visions and visioning for the sustainability domain. They distinguish between the normative quality (visionary and sustainable), transformational quality (relevant, nuanced, motivational, shared) and construct quality (systemic, coherent, plausible, tangible) (Wiek and Iwaniec 2014, p. 501). They also stress the importance of the design process and provide some guidelines for this process, including the use of creativity techniques, visualisation techniques and participatory settings. These criteria and guidelines are useful for developing more user centered smart grid visions.

The smart grid concept, as presented in the literature, covers very different visions and scenarios. These range from a slightly improved version of the current grid to a self-healing Energy Internet, from a large European Super Grid, to a collection of micro grids (or DisGenMiGrids, Wolsink 2012). What they have in common is that the smart grid is presented as the solution for all problems and as a great economic opportunity for leading nations and industries. From our perspective, these smart grid visions are technological or techno-economic visions. They focus too much on technological fixes and pay little attention to social dynamics and contexts, relating to beliefs, decisions, struggles and interactions between various actors and social groups (Verbong and Geels 2010). If there is attention for dynamics of change, the vision (or scenario) emphasises the impact of factors like energy prices, investments, and balancing supply and demand. Although these economic mechanisms are important, most visions and scenarios pay hardly any attention to cultural aspects, regulatory paradigms and user behavior. Experts from government agencies or network operators often acknowledge that users will play a different, more active role in the future energy system, but the roles they propose reflect the ideas of the current players in the energy system and these do not match with the new emerging reality. They claim e.g. that the perception of a potential outage is more important than the actual time this occurs or argue for that an overrule button is necessary to give people the feeling of control (Verbong et al. 2013, p. 122).

To counter this supply system and technology push bias, the emphasis has to shift to a more socially embedded vision. In such a vision the *function* of the energy system is taken as a focal starting point, and the question *what do we need energy for?* becomes central. This argument has been made by Walker and Cass (2007) in their paper on the different modes of renewable energy in the UK. The authors concluded that "the social organisation of a local energy system is a combination of different interacting arrangements and relations between actors and institutions". For the analysis, they use four sets of questions. These refer to:

- *Function and service of the system,* in particular what is the generated energy being used for in terms of the services it provides, like comfort, warmth, visibility, mobility etc.? Also, who uses these services?
- *Ownership and return*: this is about who owns the system and how this ownership is organised: privately, publicly, collectively? The ownership is relevant for the allocation of costs and benefits.
- *Management and operation*: who manages, controls and maintains the system and how is this organised?
- *Infrastructure and networking*: this is about the relation to larger networks (Walker and Cass 2007).

The third question obviously is relevant for smart grid business models. 'Who manages and controls' is important for cooperation and/or compliance of users. The fourth question provides the context for the ecosystem setup (see below). We will first focus on the first two questions. By focusing on the services (i.e. the function) of the energy system, Walker and Cass make a very important point. Although the energy system is vital for modern society, for most users the only relevant aspect is that they can do what they want to do. If these activities need energy, the energy system has to deliver. Only in case of malfunctioning do users become aware of the system. In most European countries, the reliability of the system is very high. In some emerging economies, in particular in India, grid unreliability is a real problem and other options are being employed, ranging from installing backup generators to local off grids systems. The fact that the energy system primarily *enables* other functions has an important consequence for envisioning a smart grid. Instead of the energy system itself, its function(s) should be the starting point for vision (and) analysis, and with this the services it delivers for cooking, comfort, cleaning, communication, mobility, entertainment etc. Thus, a focus on social practices that need energy (Shove 2014), rather than on the energy system, offers a more fruitful view onto the challenges and opportunities of a changing electricity landscape.

The second question related to ownership and return is becoming more prominent as well. In the traditional mode of operation the energy system provided the energy and the users paid a bill. As consumers are turning into prosumers by installing a PV system on their roof, or as citizens are becoming active in local energy cooperatives, the issue of how to organise the energy system is becoming increasingly relevant. In fact, the participation in energy generation or collective energy initiatives can be regarded as a new social practice, an indication of seizing new opportunities that technology offers and of new societal dynamics. As a result new pattern of and actors in value creation and appropriation emerge (Adner and Kapoor 2010; Huijben and Verbong 2013; Zott et al. 2011).

3 Social Practices

The solution that smart grid technology provides rests heavily on DSM, technology which allows conveniently shaping the demand patterns of households without impacting quality of life. Smart grid promises come with an implied change of the consumer into prosumers or energy managers. This promise is contested because, as we have concluded above, electricity is consumed for a reason: it is essential for our daily practices, which are bound up in routines and social relations.

Practice theories offer a promising basis for a programme of research on patterns of consumption, because its focus is on the mundane activities of everyday life (Warde 2014). By emphasising routines and practical consciousness over actions and deliberation, it offers an alternative to dominant models for consumption behavior. Research on energy consumption and the policies built and aimed on this have generally been dominated by one of two interpretations of human behavior and decision making. Reckwitz (2002) clearly positioned these accounts (in extremis) as the voluntarist *homo economicus* who makes conscious, rational and weighed decisions to reach maximum individual benefit, and the functionalist *homo sociologicus* who is guided by norms, rules and regulations solidified in political and social institutions. Neither account is wrong, and both make sense to a degree, but neither one alone can give a satisfying explanation of human action. Giddens' (1984) concept of structuration is often cited as a way out of this dichotomy. By focusing on practices itself, the opposing branches of structure-centric functionalism and actor-centric voluntarism are brought together.

For the research on smart grids the question is how a social practice approach can be used to study the development and implementation of smart grids. The concept of elements of practice provides a conceptual lens to identify building blocks of practice (Schatzki 1996; Shove and Pantzar 2005; Warde 2005; Gram-Hanssen 2010). Three elements of social practice can be distinguished: stuff, skills and meanings. Stuff or material refers to all material elements applied in the practice, including objects, infrastructure and the body. Skills or competences are learned through doing and refer to the routines of bodily and mental know-how to perform the practice, the ability to appreciate objects and situations and applying knowledge about what is normal or appropriate. Meaning or images entail the reasons to engage in a practice, the reasons about what it is for and what is a good outcome, which are socially shared ideas.

Through time the individual performances can change as elements change through new technology, new understandings or new goals. As links between elements are made, renewed, shifted and broken, practices emerge, change and fade out (Shove et al. 2012). When individual performances change in some way, this feeds back into the collective understanding of the practice. This somewhat abstract structuring mechanism is what makes practices social, even though they might be performed in private. When performing a practice, individuals integrate elements that they take from their interaction with society: the norms, values and expectations that guide their action, technologies and data, and competences they've learned in society.

Within these elements lies a key to understanding consumption from a practice perspective; if any practice is to change to be more sustainable, the elements that it is made up of will have to change. Social and technological innovations act as potential new elements, which could become part of existing consuming practices. Smart grid innovations could also lead to the emergence of new practices of energy monitoring, storage and management, which we call emerging e-practices (Naus et al. 2014). Smart technology will only realise its promised benefits if it becomes part of practices, be it emerging e-practice through which energy is generated or managed, or in 'smarter' energy consuming practices. There is uncertainty however on how these consuming practices will evolve with the social and technological innovations emerging within a smart energy system. Supposedly smart technologies might not provide the user with meaningful benefits, for example because the financial gain is small or because energy itself doesn't capture the user interest. Existing patterns of consuming practices might persist despite them not corresponding with the profile of self-supplied electricity and the idea of the responsible energy managing householder. The promise of smart grid technology might not be realised if it does not become part of daily practices. By focusing on domestic practices we claim that it is possible to assess more realistically the entry and use of energy-related social and technological innovations in the household, which could enable a radical transformation of the local energy system. This means that both the existing patterns of consuming practices as well as the potentially emerging e-practices connected with the new technology have to be studied.

4 User-Centered Business Models

The focus on social practices will help to get away from a technology push approach to smart grids. The provision and consumption of energy is usually not a goal unto itself: the energy system rather enables all kind of social practices that need energy. In modern society this includes almost all social practices, ranging from the energy needed to provide comfort (heating and cooling in houses) to almost all communication and entertainment practices. The ubiquitous presence and use of smartphones, tablets and other IT based devices is only possible because of the existence of a highly reliable grid. One of the promises of the smart grid, next to improving the system (reliability, renewable energy) and reducing electricity bills, is that it offers great opportunities for economic development: companies can use the smart grid infrastructure to develop new services for users (Giordano and Fulli 2012). However, despite some experiments and pilots, there is still much uncertainty about what kind of services will be useful and accepted by users as well as how to relate to existing user needs and social practices.

Research on new services focuses on the development of new business models that can provide these services to the end user. Business models are considered to be vehicles for bringing new technologies like renewables to the market (Boons and Lüdeke-Freund 2013; Zott et al. 2011). Smart design of business models and including new services can help to overcome investment barriers to end users. For example, providing finance to house owners with low income spurred solar PV markets in the US (Drury et al. 2012). Additionally, in the Netherlands collective buying of solar panels enabled easy investment to the end user who did not have to take care of selection of a supplier or installation and maintenance since this was arranged by a central party (Huijben and Verbong 2013). Business models are also considered to be a source of innovation and competitive advantage for a company (Zott et al. 2011). This in particular applies to (potentially) radical innovations; in this case, there usually is no proper exemplar and new business models have to be developed and tested in practice (Huijben and Verbong 2013). By performing business model experiments, action is taken to find new information about ‘latent possibilitiess’ that were previously unknown rather than simply analysing the environment (Chesbrough 2010, p. 361). On the other hand business models can enact their context as well (Osterwalder and Pigneur 2010). Business model mapping can support the design of such experiments by analysing current and designing future business models (Chesbrough 2010). Another important aspect of innovations in complex systems like the smart grid is that business models need to cross individual focal firm boundaries (Zott et al. 2011). In this case, value is created in a network of actors rather than by an individual firm alone (Huijben and

Verbong 2013; Zott et al. 2011). This is implied in the notion of a business *ecosystem* (Adner and Kapoor 2010).

In an ecosystem a network of suppliers, lead producers, but also customers and other stakeholders (co-)produce goods and services that are valued by the customers. The lead producer usually is ecosystem leader. Lead producers often are innovative companies. However, if we translate this to the smart grid research, it becomes obvious that at the current state of smart grid development it is not clear who the ecosystem leader is or will be. The obvious option would be the utilities. But in the Netherlands the large utilities are hardly active in the smart grid field, in fact a substantial part of their assets are being threatened by the rapid growth of renewables and cheap coal. For Germany this includes the forced closure of nuclear power plants. Several of the largest utilities in Europe are under heavy pressure. Their challenge is to survive the energy transition (Van Berlo 2014). German utility E.ON has drawn the conclusion that the answer is to focus on renewables and offering energy services to their clients. New entrants also have adopted this strategy: new Dutch energy supplier Greenchoice offers its customers specific payment schemes to enable them to participate in renewable energy projects (Huijben and Verbong 2013). Another candidate as lead actor are the distribution network operators (DNOs). DNOs in the Netherlands, like Alliander, Enexis, Stedin, have been heavily involved in smart grid pilots. It is fairly obvious why smart grids are relevant for these companies, but DNOs have different interests in developing smart grids, as their task focuses on maintaining the balance in the grid and the reliability of the system. If DNOs would be the lead actor in the development of smart grids, the smart grid business model would look completely different from a utility led smart grid. For example, preventing the occurrence of peak loads will increase the life span of key components of the grid like transformer stations and delay the need to invest.

Other interesting options are entrants from sectors outside of the energy domain. The most obvious candidate is the IT sector, as this sector has to supply both hardware and software for making the grid smart. In fact, there is a clear trend that IT companies are getting involved, for example in the case of online crowd funding (Vasileiadou et al. 2015). But again, the challenge is not so much the technological part of the system, but much more the kind of services that can be provided. Discussion has mainly focused on saving energy by giving feedback on energy consumption or reducing electricity bills by using favorable tariff schemes. Both approaches have their shortcomings. As we have been arguing, the starting point should be the provision of services (Verbong et al. 2013). Companies should develop business models that focus on the social practices that need electricity and the management of electricity itself. Framed differently: we need business models that meet the demands of the user. The limited success of energy services that are available in the market, e.g. to increase energy efficiency, follow from a mismatch between existing social practices and the service offered (Hargreaves et al. 2013). To conclude, there is a need for user-centered business model and ecosystem design with a strong focus on learning and experimentation. Such models should be co-produced by users and suppliers. This brings us to the role of users in sustainable innovations, including smart grids.

5 The User as Innovator

Users can—and probably will—play a much more active role in smart grid innovations than has been the case so far. Users are not only purchasers and consumers of a technology but they can be involved in various degrees in the production process (e.g. through providing input to designers) or even act as a co-producer and add value themselves (Habich et al. 2015). In innovation studies literature, users have traditionally been conceptualised as buyers/consumers, but over the last decades, we observe a shift towards the study of the so-called ‘democratisation’ of innovation (Von Hippel 2005), meaning that the field acknowledges that (and researches how) users can play roles such as (co-)producers of innovations, as well. This trend is supported by improvements in computer and communications technology that enable users to develop their own new products and services. This enabling role of IT for users to engage in innovative activities obviously extends to the smart grid field as well.

So in what ways can citizens, as users or non-users of an innovation, influence its development? A scan of innovation studies literature reveals many different roles, and although the heterogeneity of frameworks and theories in the field renders it impossible to come to overarching, integrative statements about the precise *mechanisms* of user involvement, we can at least attempt to create a *typology* of roles by juxtaposing them according to two dichotomies (see Fig. 1). The first dichotomy is that of constraining or barrier-like user roles versus enabling or empowering ones: users can either help a transition to smart grids or block it. The second dichotomy is that of passive versus active roles (i.e. is the positive or negative influence the result of strategic behavior or not?).

Below, we will elaborate on these quadrants. As an aside, it is interesting to note that within all four quadrants, individual users roles are present (e.g. investigating

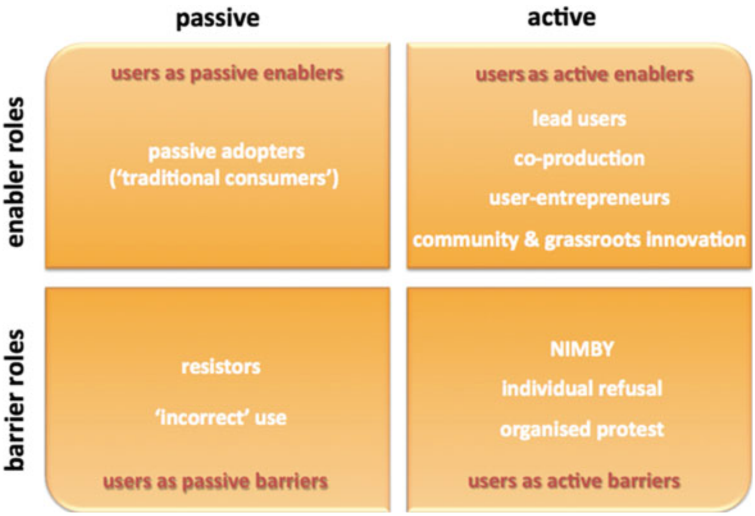


Fig. 1 A typology of user roles in sustainable innovation

the psychological, cultural, physiological characteristics that render them more or less inclined to opt in or out), as well as collective ones[2] (e.g. adopt a more sociological perspective in which various group dynamics play a role).

5.1 Passive Barrier Roles

In the lower left quadrant, we find various passive barrier roles: e.g. not participating in using the available options of the smart energy system due to individual preferences and/or collective practices, or 'incorrect' use due to lack of knowledge. Individuals are subsumed into adopter categories (early adopters, early majority, late majority and laggards) that aim to explain non-adoption. Often, non-users roles are simply seen as resistors to an innovation: rejecters, excluded and expelled users are largely ignored (Wyatt 2003). When smart grid literature talks about users, it predominantly talks about this quadrant, and 'solutions' often take the form of educating (or 'domesticating') users to move them to the upper left quadrant.

5.2 Passive Enabler Roles

In that upper left quadrant, we find the 'traditional consumer': a passive adopter of an innovation (in this case: a participant in smart energy systems).

5.3 Active Barrier Roles

But more active user-barriers to implementation exist, as well. We find these active barrier-roles in the lower right quadrant: active resistance by individual households to a smart grid innovation (e.g. refusing to install smart meters or to give access to data) and the so-called NIMBY ('Not In My Back Yard')-phenomenon, as well as more collective roles that can range from large-scale social movements actively resisting innovations through organised protests and political pressure (e.g. against nuclear power (Geels and Verhees 2011)) to more local, yet highly organised resistance (Höffken 2012).

5.4 Active Enabler Roles

Active enabler roles reside in the upper right quadrant. For example, users can become so-called 'lead users' (Von Hippel 1976) that act as a key sources of

---

[2] One might view 'individual' versus 'collective' roles as a third dichotomy but we thought it wise not to formally introduce it as a third dimension to our tentative typology for reasons of clarity.

information and ideas that lead to innovations which are then marketed by firms (e.g. households actively engaging in smart grid projects and providing feedback to suppliers, DNOs and utilities). Other active enabling roles are e.g. individual households as small decentralised renewable energy producers (e.g. through smart grid-connected solar PV and/or energy storage in EV batteries); or even 'user entrepreneurs' who convert sustainable solutions to a problem they experience into a business. In addition, *collective* user roles that actively enable sustainable innovation are captured by concepts such as 'collaborative consumption' (e.g. co-housing, car sharing), 'cloud-based' and 'peer-to-peer' business models in the IT domain, and the 'collective buying power'-based business model: autonomous associations of users who cooperate for mutual benefit (e.g. collective purchasing of PV panels to bring down prices; Huijben and Verbong 2013). Others models for collective enabling of sustainable innovation include 'crowdfunding' (wherein collective users are a source of capital for technological innovations: these collective user investors thus influence the innovation process in a much more active way than simply buying innovations; Vasileiadou et al. 2015), and 'cooperatives' (groups of users that do not own their own land or roofs but collectively rent plots or roof space and install relatively large capacities of collectively purchased wind turbines or solar panels and in doing so, effectively become small, collective energy producers (Asmus 2008; Dewald and Truffer 2011; Huijben and Verbong 2013). Finally, 'community innovation' is worth mentioning is this respect: groups of users collective users that act as initiators, designers and maintainers of technological projects in their own locality (e.g. street, neighborhood, village), as well as 'grassroots innovation' (Seyfang and Smith 2007), in which social movement organisations (a form of collective users) actively produce sustainable innovations for such niche markets but, in doing so, expand beyond their locality and form the seeds of mainstream solutions. The numerous Local Energy Cooperatives are a prime example of such collective engagement.

And these are just the roles that 'actual' users can play. We have not yet even addressed the so-called 'socially constructed' or 'projected user' (a fictitious individual user whose supposed needs producers target); the 'configured user' (a user who is 'trained' in his/her interaction with an innovation by the 'script' embedded in the smart grid technology (Akrich 1992; Woolgar 1990)); or 'mediated' or 'represented' users (users that are spoken for by organisations that claim to represent user groups: collectives that mediate between real users and producers).

As stated earlier, all these possible user roles have their own complex social dynamics and generative mechanisms. Research exists on all of these roles: individual or collective, constraining or enabling, passive or active. It is quite impossible to review these mechanisms here comprehensively: instead, we have tried to paint a picture of the plethora of possible roles and the very different consequences they may have for a transition to smart grids. The main lesson here is that user roles should be taken more seriously in relation to smart grids: experts should no longer regard users exclusively and/or simply as potential barriers to smart grid innovation but also as important stakeholders and potential participants in the innovation process. Our suggestion is to take stock of users roles across the whole matrix of

Fig. 1 and not just the left-hand quadrant: don't forget that your users can be, for better or worse, at least as smart as your grids!

6 Smart Business for Smart Users: A Research Agenda

This article has addressed some of the main problems for smart grid research. Due to the increasing number of options technology offers, the future smart energy system will differ radically from the current one, resulting in large uncertainty on almost all dimensions of a future smart grid. In particular this applies to the role of users in future smart energy systems. We simply do not know how users will adopt, adapt and co-create the part of the future energy systems that is relevant not only for the users but certainly also for all other stakeholders involved. What we do know is that a technology-dominated approach will very likely fail or at least will not produce the intended results. That is why we propose a different agenda for research on smart grids.

To summarise: the main elements of a social science research agenda are:

- Developing more socially embedded visions on smart grids and the services it will provide; this should not be left to the 'experts', but include all relevant actors
- A shift in the focus on developing smart grids components and systems towards the services it will deliver, taking energy consuming practices as a focal starting point
- Development and testing of innovative user-centered business models and ecosystems; there are pilot projects that experiment with new business models, but often still too much technology driven
- More general more attention to the innovative role users can have in smart grid development, and broader in sustainable innovations

Although we did not address this in this article, smart grids are a phenomenon that is not confined to Western societies in the global North. Studying users in smart grid dynamics beyond the Western confines will therefore enable a wealth of information that will enrich the theoretical and practical vocabulary of current research and contribute to a more nuanced understanding regarding the what, why and how of users and smart grids.

Points for Discussion

- This chapter focuses on the potential roles of energy users. It mentions, but does not elaborate the changing relations between state, market and civil society not only in the West, but worldwide. How will the four user roles identified in this chapter affect the relations between governments, firms and civil society organizations? What are the likely consequences for mobilizing political support for any of these four roles?

References

Adner, R., Kapoor, R.: Value creation in innovation ecosystems: how the structure of technological interdependence affects firm performance in new technology generations. Strateg. Manag. J. **31**(3), 306–333 (2010)

Akrich, M.: The de-scription of technical objects. Shaping Technol./Building Soc. 205–224 (1992)

Asmus, P.: Exploring New Models of Solar Energy Development. The Electricity Journal **21**(3), 61–70 (2008)

Boons, F., Lüdeke-Freund, F.: Business models for sustainable innovation: state-of-the-art and steps towards a research agenda. J. Clean. Prod. **45**, 9–19 (2013)

Bowden, J.: European smart grid roll-out on target. Eur. Energy Rev. [Online] 14 Aug 2014. Available at http://europeanenergyreview.com/site/pagina.php?id=4296. Accessed 25 June 2015

Chesbrough, H.: Business model innovation: opportunities and barriers. Long Range Plan. **43** (2–3), 354–363 (2010)

Dewald, U., Truffer, B.: Market formation in technological innovation systems—diffusion of photovoltaic applications in Germany. Industry Innov. **18**(3), 285–300 (2011)

Dignum, M.: The power of Large Technological Visions: The promise of hydrogen energy. PhD-Thesis: TU/e (2013)

Drury, E., Miller, M., Macal, C.M., Graziano, D.J., Heimiller, D., Ozik, J., Perry IV, T.D.: The transformation of southern California's residential photovoltaics market through third-party ownership. Energy Policy **42**, 681–690 (2012)

E.ON: New corporate strategy. 30 Nov 2014 [Online]. Available from: http://www.eon.com/. Accessed 25 June 2015

Giddens, A.: The Constitution of Society: The Outline of the Theory of Structuration. University of California Press, Berkeley (1984)

Giordano, V., Fulli, G.: A business case for Smart Grid technologies: a systemic perspective. Energy Policy **40**, 252–259 (2012)

Geels, F.W., Verhees, B.: Cultural legitimacy and framing struggles in innovation journeys: a cultural-performative perspective and a case study of Dutch nuclear energy (1945–1986). Technol. Forecast. Soc. Chang. **78**(6), 910–930 (2011)

Goulden, M., Bedwell, B., Rennick-Egglestone, S., Rodden, T., Spence, A.: Smart grids, smart users? The role of the user in demand side management. Energy Res. Soc. Sci. **2**, 21–29 (2014)

Gram-Hanssen, K.: Standby consumption in households analyzed with a practice theory approach. J. Ind. Ecol. **14**(1), 150–165 (2010)

Habich, A, Raven, R., Schot, J., Thøgersen, J., Verbong, G., Verhees, B.: The Multi-Level Perspective and its relevance for EU-Innovate, A WP1 interim report EU-InnovatE (2015)

Hargreaves, T., Longhurst, N., Seyfang, G.: Up, down, round and round: connecting regimes and practices in innovation for sustainability. Environ. Plan. A **45**(2), 402–420 (2013)

Huijben, J.C.C.M., Verbong, G.P.J.: Breakthrough without subsidies? PV business model experiments in the Netherlands. Energy Policy **56**, 362–370 (2013)

Höffken, J.: Power to the people? Civic engagement with small scale hydroelectric plants in India. Den Bosch: BoxPress. Ph.D. Dissertation (2012)

Naus, J., Spaargaren, G., Van Vliet, B., Van der Horst, H.: Smart grids, information flows and emerging domestic energy practices. Energy Policy **68**, 436–446 (2014)

Osterwalder, A., Pigneur, Y.: Business Model Generation: a Handbook for Visionaries, Game Changers, and Challengers. Wiley, New Jersey (2010)

Reckwitz, A.: Toward a theory of social practices: a development in culturalist theorizing. Eur. J. Social Theory **5**(2), 243–263 (2002)

Schatzki, T.R.: Social Practices: A Wittgensteinian Approach to Human Activity and the Social. Cambridge University Press, Cambridge (1996)

Seyfang, G., Smith, A.: Grassroots innovations for sustainable development: towards a new research and policy agenda. Environ. Politics **16**(4), 583–603 (2007)

Seyfang, G., Park, J.J., Smith, A.: A thousand flowers blooming? An examination of community energy in the UK. Energy Policy **61**, 977–989 (2013)

Shell: New lens scenarios. A shift in perspective for a world in transition (2014). [Online] http://www.shell.com/global/future-energy/scenarios/new-lens-scenarios.html. Accessed 25 June 2015

Shove, E.: What is energy for? Social practice and energy demand. Theory, Culture Soc. **31**(5), 41–58 (2014)

Shove, E., Pantzar, M.: Consumers, producers and practices: understanding the invention and reinvention of Nordic walking. J. Consum. Culture **5**(1), 43–64 (2005)

Shove, E., Pantzar, M., Watson, M.: The dynamics of social practice. Everyday life and how it changes. Sage, London (2012)

Van Berlo, P.: Business model innovation for Dutch power utilities: why, what and how? How the multi-level perspective and business model theory contribute to thinking about the sustainability transition from an incumbents perspectiv. M.Sc. thesis: TU/e (2014)

Van Lente, H.: Promising technology. The Dynamics of Expectations in Technological Developments. Enschede (1993)

Van Vlimmeren, Y.: The introduction of local system services: the case of storage in the low voltage network. M.Sc. thesis: TU/e, Alliander, N.V (2010)

Vasileiadou, E., Huijben, J.C.C.M., Raven, R.P.J.M.: Three is a crowd? Exploring the potential of crowdfunding for renewable energy in The Netherlands. J. Cleaner Prod. (2015, in press)

Verbong, G.P.J., Geels, F.W.: The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004). Energy Policy **35**, 1025–1037 (2007)

Verbong, G.P.J., Geels, F.W.: Exploring sustainability transitions in the electricity sector with socio-technical pathways. Technol. Forecast. Soc. Chang. **77**, 1214–1221 (2010)

Verbong, G.P.J., Beemsterboer, S., Sengers, F.: Smart grids and smart users?: involving users in developing a low carbon electricity economy. Energy Policy **52**, 117–125 (2013)

Von Hippel, E.: The dominant role of users in the scientific instrument innovation process. Res. Policy **5**, 212–239 (1976)

Von Hippel, E.A.: Democratizing innovation. MIT press, Cambridge, MA (2005)

Walker, G., Cass, N.: Carbon reduction, ‘the public’ and renewable energy: engaging with socio-technical configurations. Area **39**(4), 458–469 (2007)

Warde, A.: Consumption and theories of practice. J. Consum. Culture **5**(2), 131–153 (2005)

Warde, A.: After taste: culture, consumption and theories of practice. J. Consum. Culture **14**(3), 279–303 (2014)

Wiek, A., Iwaniec, D.: Quality criteria for visions and visioning in sustainability science. Sustain. Sci. **9**(4), 497–512 (2014)

Wikipedia (2015) *Smart grid.* [Online] Available from: https://en.wikipedia.org/wiki/Smart_grid. Accessed 25 June 2015

Wolsink, M.: The research agenda on social acceptance of distributed generation in smart grids: renewable as common pool resources. Renew. Sustain. Energy Rev. **16**(1), 822–835 (2012)

Woolgar, S.: Configuring the user: the case of usability trials. Sociol. Rev. **38**(S1), 58–99 (1990)

Wyatt, S.: Non-users also matter. In: Oudshoorn, N., Pinch, T. (eds.) How Users Matter: The Co-construction of Users and Technologies. MIT press, Cambridge, MA (2003)

Yildiz, Ö., Rommel, J., Debor, S., Holstenkamp, L., Mey, F., Müller, J.R., Radtke, J., Rognli, J.: Renewable energy cooperatives as gatekeepers or facilitators? Recent developments in Germany and a multidisciplinary research agenda. Energy Res. Soc. Sci. **6**, 59–73 (2015)

Zott, C., Amit, R., Massa, L.: The business model: recent developments and future research. J. Manag. **37**(4), 1019–1042 (2011)

Transition to Smart Grids: A Psychological Perspective

Ellen van der Werff, Goda Perlaviciute and Linda Steg

Abstract A transition to smart grids requires a wide range of changes in household energy behaviour. In this chapter we discuss four key issues important for understanding and promoting behaviour in smart grids. First, we need to identify which behaviour needs to be changed. A transition to smart grids involves changes in a wide range of energy behaviours, including the adoption of sustainable energy resources, energy-efficient technologies, and automated control technology; investments in energy efficiency measures in buildings such as insulation; and user behaviour. Second, we need to know which factors influence behaviour in smart grids. We discuss the role of motivations and contextual factors. Third, it is important to test effects of interventions aimed to promote smart energy behaviours. Interventions can be aimed at changing the actual costs and benefits of behaviour, or at changing people's perceptions and evaluations of different costs and benefits of behavioural options. Fourth, we need to understand which factors influence the acceptability of energy policies and energy systems changes aimed to promote smart grids. In this chapter we address important findings from psychological studies on these topics.

1 Introduction

Smart grids involve substantial changes in energy infrastructures, technologies and user behaviour. To develop reliable, sustainable and affordable smart grids, it is not sufficient to develop new infrastructure and technologies (Goulden et al. 2014; Oldfield 2011; Wolsink 2012; Verbong et al. 2013). In fact, smart grid technologies and infrastructure will only realise their full potential if people find them acceptable and if they change their behaviour accordingly. To enhance efficiency and sustainability of smart grids, the supply and demand of (renewable) energy needs to be

---

E. van der Werff (✉) · G. Perlaviciute · L. Steg
University of Groningen, Groningen, The Netherlands
e-mail: ellen.van.der.werff@rug.nl

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_4

matched and overall energy consumption needs to be reduced. To achieve this, changes in a wide range of behaviours are needed, including the adoption of sustainable energy sources and technologies, the adoption of smart grid technologies and energy-efficient appliances, and changes in user behaviour. We will refer to these behaviours as smart energy behaviours. A key question is: which factors influence whether people engage in these different behaviours, and how can these factors be addressed to motivate and empower people to actively participate in smart grids? Social sciences can play an important role in answering these questions (Geelen et al. 2013; Gangale et al. 2013; see also Sovacool 2014). Social scientists can study which factors influence behaviour in smart grids, and examine how these factors can be addressed in energy policy and energy system changes. Besides, social scientists can study which factors determine the effectiveness and acceptability of technologies and policies aimed to promote the efficiency and sustainability of smart grids.

In this chapter, we review psychological studies aimed at understanding and promoting behaviour in smart grids by individuals and households. We propose a general framework, comprising four key issues:

1. identification and measurement of behaviours that need to be changed to promote smart grids,
2. examination of factors underlying smart energy behaviours, including the adoption of sustainable energy resources, energy-efficient technologies, and automated control technology; investments in energy efficiency measures in buildings such as insulation; and user behaviour.
3. designing and testing interventions to change behaviour needed to optimise smart grids, including information, financial incentives, regulations and technological changes,
4. studying factors underlying public acceptability of energy policies and changes in energy systems aimed to promote smart grids.

We discuss important findings from psychological studies on these four topics.

2 Which Behaviour Changes Are Needed to Promote Smart Grids?

Smart grids typically rely on renewable energy, which can be produced on a local level by so-called prosumers. It is therefore important to understand what motivates people to produce and use renewable energy sources. Besides, since the production of renewable energy sources fluctuates across time, energy supply and demand needs to be matched to secure a stable and efficient grid. To achieve this, consumers can either accept or adopt technologies to store renewable energy (e.g., electric vehicles, batteries) or shift energy use to times when renewable energy sources are abundant (e.g., when the sun is shining). Shifting energy use to times when renewable energy is available can either be done autonomously or by installing technologies that automatically switch specific appliances on or off on the basis of the available energy supply (e.g., Gellings and Samotyj 2013; Kobus et al. 2013). An important question here is under which conditions consumers are willing to accept and adopt different ways of demand and supply matching. Finally, the efficiency of smart grids will be enhanced if consumers would reduce their overall energy use. Hence, we need to understand under which conditions consumers are willing and able to reduce their energy use.

Various studies have examined behaviours relevant to smart grids, including the adoption of renewable energy sources such as solar or wind energy (see Perlaviciute and Steg 2014, for a review), investment in innovative technologies such as electric vehicles (Bockarjova and Steg 2014; Noppers et al. 2014), using appliances when energy is abundant (Kobus et al. 2013), and the adoption and use of specific components of smart grids (see Sintov and Schultz 2015, for a review). However, such behaviours are typically studied in isolation. Yet, smart grids require changes in a wide range of energy behaviours, as we explained above. Hence, an important question is how these different types of behaviours are related, and how changes in a broader range of smart energy behaviours can be realised. A key issue here is whether and under which conditions engagement in one type of smart energy behaviour is likely to spillover to other behaviours (Truelove et al. 2014). Some studies have found evidence of negative spillover effects, in which case engagement in smart energy behaviour reduces the likelihood of subsequent smart energy behaviours. For example, people were more likely to increase their energy consumption after reducing their water use (Tiefenbeck et al. 2013). Such effects are likely when individuals think that engagement in one sustainable behaviour legitimates not acting sustainably in another occasion (Kaklamanou et al. 2015). Yet, literature suggests that such negative spillover (or rebound) effects may be small and generally not fully offset the efficiency gains of the initial measure (Frondel et al. 2012). Still, little is known about which processes underlie negative spillover effects, and how to prevent negative spillover or 'rebound' effects.

Interestingly, other studies have found positive spillover effects, suggesting that initial smart energy behaviour makes it more likely that people engage in other smart energy behaviours. For example, individuals who recycled were more likely to buy organic food and use environmentally-friendly modes of transport one and two years later (Thøgersen and Ölander 2003). Also, green buying promoted subsequent recycling, the use of public transport, car-pooling, printing on both sides, saving water, and switching off lights (Lanzini and Thøgersen 2014). Such positive spillover effects are likely when people relate the initial sustainable energy behaviours to themselves, thereby strengthening their environmental or energy-saving self-identity (Van der Werff et al. 2013, 2014a, b). More particularly, when people realise they engaged in smart energy behaviours (or more generally pro-environmental behaviours), they are more likely to see themselves as a pro-environmental person, which motivates them to engage in pro-environmental or energy saving behaviours in subsequent situations. An important question is under which conditions such positive spillover effects are most likely. Also, as yet it is not clear how stable positive spillover effects are, as long-term effects have typically not been considered.

3 Factors Underlying Behaviour in Smart Grids

Interventions aimed to encourage behaviours to promote active participation in smart grids will be more successful if they target important antecedents of such behaviours, and remove significant barriers to change. Hence, it is important to examine which factors affect the likelihood that people engage in behaviours that increase the efficiency and sustainability of smart grids and the acceptability of smart grids. In this section, we discuss two general factors that underlie smart energy behaviour: people need to be motivated to engage in the relevant behaviours, and they need to be able to do so.

3.1 Motivations

Whether or not people engage in behaviours needed to promote smart grids will depend on their motivation to do so. People will be more motivated to engage in these behaviours when they evaluate the consequences of such behaviours more favourably, that is, when they believe that the behaviour has relatively more benefits and less costs. In this respect, they are likely to consider individual as well collective consequences of behaviour, as we illustrate below. Next, we discuss general motivational factors, notably values, which affect how people evaluate and weigh the costs and benefits of behaviours, and which choices they make.

Individual costs and benefits reflect consequences that affect people's self-interest, for example financial costs, time, pleasure, and comfort. People are more likely to engage in smart energy behaviour when they believe such behaviour has relative low individual costs and high individual benefits, resulting in overall positive evaluations of the relevant actions. Some behaviours that increase efficiency of smart grids are perceived to be somewhat costly. For example, people think that renewable energy sources are rather expensive, which could hinder their adoption (cf. Perlaviciute and Steg 2014). A study revealed that financial costs are a strong predictor of preferences for energy systems; financial costs appeared to be more important than the level of control over smart grid technologies, and whether renewable energy was produced on a central versus local level (Leijten et al. 2014).

Interestingly, while privacy concerns with regard to energy use monitoring technology such as smart metering may hinder acceptability of such technology (Krishnamurti et al. 2012; Hess 2014), a study found that privacy concerns may be underpinned by the costs and benefits that people expect from such technology for them personally (Bolderdijk et al. 2013c). More specifically, privacy concerns were most prominent when people anticipated negative individual consequences (e.g., paying more for energy use) from implementing the monitoring technology, suggesting that privacy concerns may depend on expected consequences of such technologies for people. Communicating the individual benefits of such technologies (e.g., possibility to save money) may thus alleviate privacy concerns.

Besides instrumental costs and benefits such as prices, time, and comfort, people also consider affective and social costs and benefits. For example, people are more likely to engage in pro-environmental behaviours when they expect to derive pleasure from such behaviour (Gatersleben and Steg 2012). People may also engage in smart energy behaviour when they expect that others would approve of it (Harland et al. 1999), or when they think others engage in these behaviours too (Nolan et al. 2008). Moreover, people may engage in behaviours that support smart grids when they expect that the particular behaviour enhances their status, particularly when the behaviour is somewhat costly, to signal to others that they have sufficient resources to make altruistic sacrifices (cf. Griskevicius et al. 2010). People are more likely to adopt smart grid components such as electric cars and renewable energy systems when they evaluate their symbolic aspects, that is, the extent to which these innovations signal something positive about the owner or user to others and themselves, more favourably (Noppers et al. 2014). Positive symbolic outcomes may thus encourage people to adopt various smart grid components, even when some instrumental drawbacks are present, which is often the case in the early introduction phases of smart grids. Interestingly, behaviour can have a larger signalling value for prestige and identity effects when it is somewhat costly. When smart energy behaviour is very easy, convenient or profitable, it is hard to claim that you engaged in the behaviour because you care for others and the environment. In contrast, when engaging in smart energy behaviour is somewhat costly or effortful, it is more likely to signal that you care about others and the environment (Van der Werff et al. 2014a).

Some smart energy behaviours have clear individual benefits, which may promote such behaviour. Examples are saving energy at home or switching energy use to times when tariffs are low, which both save money. Furthermore, renewable energy systems may enhance people's status, as described above.

People not only consider individual consequences of behaviour, but also consequences for others and the environment. Smart energy behaviours typically benefit the environment as they result in a reduction of CO_2 emissions (Steg et al. 2014a, b). Many people care about the environment, and take environmental considerations into account when they make decisions (Steg and De Groot 2012). People are motivated to see themselves as morally right, and to do the right thing, which may encourage smart energy behaviours (Bolderdijk et al. 2013b). Indeed, several studies revealed that moral considerations, affect energy behaviour, such as the purchase of energy-saving light bulbs (Harland et al. 2007), electricity saving at work (Zhang et al. 2013), and energy saving behaviours at home (Van der Werff and Steg 2015). Interestingly, engaging in smart energy behaviour may make people feel good because they derive pleasure and satisfaction from doing the right thing (Venhoeven et al. 2013). People may even physically feel warmer by engaging in smart energy behaviour, because such behaviour boosts the self, a phenomenon known as a warm-glow effect (Taufik et al. 2014).

Engaging in smart energy behaviour such as reducing one's overall energy use to match demand and supply of (renewable) energy, is likely to strengthen environmental self-identity, that is, the extent to which a person sees himself or herself as a pro-environmental person (Cornelissen et al. 2008; Van der Werff et al. 2013, 2014a). Interestingly, environmental self-identity is particularly strengthened when people engaged in pro-environmental behaviours that are somewhat costly or uncommon, probably because such behaviours are more likely to signal how pro-environmental a person is (Van der Werff et al. 2014a). As indicated above, a strong environmental self-identity is likely to encourage positive spillover effects, increasing the likelihood that people engage in a wide range of behaviours that increase the efficiency and sustainability of smart grids. People may engage in smart energy behaviours when such behaviours are somewhat (but not too) costly or effortful, as this boosts their self-concept (Taufik et al. 2014; Van der Werff et al. 2014a).

An important question is to what extent people consider and weigh individual and collective considerations of smart energy behaviour, and which factors enhance the likelihood that they will consider different individual and collective consequences in the choices they make. Values appear to be an important factor in this respect. Values reflect life goals or ideals that define what is important to people and what consequences they strive for in their lives in general (Schwartz 1992). Values can affect a wide range of evaluations, beliefs, and actions (Steg et al. 2014a, b). Four types of values have been found to be relevant for people's evaluations and behaviour in smart grids: hedonic values that make people focus on pleasure and comfort, egoistic values that make people focus on safeguarding and promoting one's personal resources (i.e., money, status), altruistic values that make people focus on the well-being of other people, and biospheric values that make people focus on consequences for nature and the environment (De Groot and Steg 2008; Steg and De Groot 2012; Steg et al. 2014b).

Values affect how important people find different consequences of smart grids, and how they evaluate these consequences. More specially, people focus on consequences of smart grids that have positive or negative implications for their important values (Parkhill et al. 2013; Steg et al. 2014b). For example, the stronger their biospheric values, the more positively people evaluated renewable energy sources, which are generally seen as having positive implications for one's biospheric values, such as reducing CO_2 emissions (Perlaviciute and Steg 2015; Bidwell 2013). In contrast, stronger egoistic values were related to less positive evaluations of renewable energy sources, which are likely to have negative consequences for one's egoistic values, such as being expensive and intermittent (Perlaviciute and Steg 2015). Interestingly, people evaluate various costs and benefits of renewable energy sources in line with their overall value-based judgements, even if these costs and benefits are not particularly important to them based on their key values. For example, the stronger their biospheric values, the more positively people evaluated personal consequences of renewable energy sources such as financial costs (Perlaviciute and Steg 2015), while stronger altruistic values led to more positive evaluations of effects of wind energy developments on local landscape (i.e. wildlife, noise, and scenic views) and local economy. People seem to base their evaluations of smart grids on aspects that are most relevant for their important values, which guide their acceptability ratings, and possibly behaviour.

These value-based acceptability judgements may further affect the evaluation of other characteristics of smart grids, which may be less important to people based on their values. In other words, people are likely to evaluate smart grids in an overly positive or negative way that is in line with their value-based judgements. A thorough understanding of which values actually underlie people's evaluations and acceptability ratings is therefore crucial for developing effective intervention and communication strategies.

People are more aware of environmental problems caused by their behaviour when they more strongly endorse bioshperic values, or less strongly endorse egoistic values (Nordlund and Garvill 2002; Steg et al. 2005; Stern et al. 1995). This in turn influences their choices. As explained before, many smart energy behaviours have positive collective consequences, and negative individual consequences. In line with this, research revealed that in general, people have more favourable evaluations of and are more likely to engage in smart energy behaviours if they strongly endorse biospheric and, to a lesser extent, altruistic values, while they are less likely do so if they strongly endorse egoistic and/or hedonic values (see Steg and De Groot 2012 for a review). Strong biospheric values also strengthen environmental self-identity (Van der Werff et al. 2013; Gatersleben et al. 2012), which in turn increases the likelihood of positive spillover effects, as explained earlier.

3.2 Contextual Factors

In general, people care about the environment, and strongly endorse biospheric values. Despite this, many people do not consistently engage in smart energy behaviour. How can we explain such a value-behaviour gap? Besides a lack of motivation to do so, smart energy behaviour can be inhibited by various other factors. First, people may not know which behaviours are needed to optimise smart grids (Steg et al. 2015). Second, contextual factors may inhibit people to engage in value-congruent actions. Contextual factors define the costs and benefits of different energy behaviours thereby influencing individual motivations (Steg and Vlek 2009; Stern 1999). In some cases, contextual factors inhibit people to act upon their biospheric values and moral considerations (Abrahamse and Steg 2011; Diekmann and Preisendörfer 2003). For example, shifting energy use in time can be effortful when people have to control their appliances autonomously, which may result in less smart energy behaviours (see Sintov and Schultz 2015, for a review). Technologies can be implemented that automatically switch apparatuses off and on at different times, thereby balancing energy supply and demand. However, a study in the Netherlands showed that people prefer making changes in energy use themselves rather than relying on technology to make these choices for them (Leijten et al. 2014). Also, costs may inhibit smart energy behaviours. For example, people may not have sufficient financial resources to purchase solar panels or other smart grid technologies. In such cases, subsidy schemes can be implemented that make investments in smart grid technologies more affordable. By doing so, contextual factors facilitate smart energy behaviour, and support individuals' biospheric values and moral considerations. Contextual factors even may make some behaviours simply impossible (e.g., Corraliza and Berenguer 2000). For example, laws may be in place that prohibit people to sell their excess of self-produced solar energy to their neighbours, or the lack of charging stations may inhibit the use of electric vehicles.

Besides defining the costs and benefits of smart energy behaviours, contextual factors can serve as cues that activate specific values in a particular situation, making it more likely that these values steer decision making in that situation (Steg 2015; Steg et al. 2014a). Values are more likely to affect behaviour when they are activated in a particular context, making it more likely that people base their decisions on these values. For example, bikini models or chocolate can activate hedonic values; status symbols or signs of money can activate egoistic values; while religious symbols, statues of Justitia and environmental symbols can activate altruistic and biospheric values (Lindenberg 2012; Perlaviciute 2014). Also, high behavioural costs are likely to activate values related to these costs, notably hedonic and egoistic values, which makes it less likely that people act upon their biospheric values (Steg et al. 2014a; Steg 2015). Furthermore, signs of immoral or norm violating behaviour by others can activate hedonic and egoistic values, making altruistic and biospheric values less influential in the particular situation. The opposite is true for cues that clearly signal that others respect norms and acted morally right (Steg et al. 2014a; Steg 2015).

4 Interventions to Promote a Transition to Smart Grids

Various studies have examined which interventions are effective to change energy behaviours. Below, we review the literature on interventions to encourage smart energy behaviour. We first discuss structural strategies that aim to enhance people's ability and motivation to engage in smart energy actions by making such actions more attractive via incentives. Second, we discuss psychological strategies that aim to increase people's ability and motivation to engage in smart energy actions without actually changing their costs and benefits.

4.1 Structural Strategies

As indicated earlier, smart energy behaviours may involve some degree of effort, discomfort or can be financially costly. For example, investing in solar panels involves initial financial investments, and shifting your energy consumption in time by autonomously switching off appliances can be a hassle. This implies that smart energy behaviours are oftentimes not rewarding or pleasurable, at least in the short term. Yet, perceptions of costs and benefits of behaviour are not always accurate. In such cases, it may be sufficient to change the perceptions of costs and benefits of options via information strategies that aim to correct such misperceptions (Abrahamse and Matthies 2012).

It is often assumed that people are not willing to engage in sustainable behaviours unless some personal benefits are involved. This suggests external incentives are needed to motivate people to engage in smart energy behaviour, such as subsidies on solar panels or smart devices, or special arrangements such as free parking spaces for electric cars (cf. Bolderdijk and Steg 2015). In addition, compensation can be provided to motivate local communities to host renewable energy infrastructure (e.g. wind farms), who face possible risks and costs of these infrastructures (e.g. visual hinder and noise), we will elaborate on this in the section on distributive fairness. Alternatively, external incentives could make excessive energy use, particularly at certain times of the day, more costly or less pleasurable, for example, by introducing taxes or laws and regulations. Also, a transition to smart grids may involve the introduction of dynamic pricing (Clastres 2011). With time-of-use-pricing energy tariffs are differentiated, resulting in lower tariffs at times where a lot of renewable energy is available (e.g., when the sun is shining), and higher tariffs when energy supply is low which may change energy use accordingly (Kobus et al. 2013).

Incentives that are aimed at changing contextual factors that define the costs and benefits of sustainable energy choices are often necessary when smart energy behaviours are very costly (Steg and Vlek 2009), as even people with strong biospheric values will be unlikely to engage in such behaviour. For example, few people would be willing to purchase a smart energy appliance if it is twice as expensive as other options. Yet, strategies that mainly incentivise behaviour may be less effective than sometimes assumed, and can sometimes even be counter-effective (see for a review Bolderdijk and Steg 2015). In fact, incentives provide a fickle basis for consistent smart energy choices when employed in isolation. They make people focus on immediate personal costs and benefits of behaviour, thereby activating hedonic and egoistic values rather than biospheric values (Steg 2015; Steg et al. 2014a). Consequently, people may particularly engage in the relevant behaviours when such behaviour is extrinsically rewarding (De Groot and Steg 2009). For example, it was found that financial incentives promoted eco-driving, but that these positive effects disappeared as soon as the incentives were removed (Bolderdijk et al. 2011). In addition, external incentives can inhibit positive spillover effects when subsequent actions have no clear external rewards, which is not uncommon in the energy domain (Thøgersen 2013). For example, people who considered economic rather than environmental reasons for car-sharing were less likely to engage in another sustainable behaviour on a following occasion (Evans et al. 2013). Similarly, if people engage in smart energy behaviour because they follow rules or regulations, rather than because they freely chose to do so, the behaviour may not be attributed to the self, and hence weaken rather than strengthen environmental self-identity, which can inhibit positive spillover. For example, when appliances are operated via automated control systems people are less likely to switch them off (Murtagh et al. 2015). Therefore, people may not attribute the smart energy use to the self, which may make it less likely that they will next take a shorter shower or reduce the thermostat setting. This implies that many different incentives need to be implemented to encourage wide-scale behaviour changes needed to realise smart grids, each increasing the relative attractiveness of the specific behaviour targeted. Such a strategy is overall not efficient and cost-effective. In addition, external incentives are not likely to result in behaviour changes when such changes are perceived not to be worth the effort (Bolderdijk and Steg 2013b, 2015). Many single smart energy behaviours yield small benefits and are therefore perceived as hardly worth the effort (Dogan et al. 2014). For example, unplugging a single coffee machine or microwave would save less than 6 € a year. In sum, although targeting extrinsic motivations by introducing incentives may be needed to promote some smart energy behaviours, such incentives are not likely to encourage people to engage in the many behaviours needed to increase the efficiency and sustainability of smart grids.

4.2 Psychological Strategies

Therefore, it is also important to employ strategies that target or enhance motivations to engage in smart energy behaviour. Strategies that target and strengthen individuals' intrinsic motivation to engage in smart energy behaviour may be particularly promising in this respect, as these strategies are more likely to result in durable behaviour changes.

First, information can be provided aimed to change consumers' beliefs about the pros and cons of smart energy behaviours, and to increase their awareness of environmental problems caused by their behaviour. Such information may enable and motivate consumers to change their behaviour. Research suggests that providing general information about energy problems and energy conservation generally results in an increase in knowledge and awareness (Bradley et al. 1999; Staats et al. 1996), but this increase in knowledge does not necessarily motivate them to change their behaviour accordingly (Abrahamse et al. 2005; Staats et al. 1996). Information is more likely to encourage smart energy behaviour when it resonates with people's central values. For example, an environmental campaign increased knowledge among all exposed to the campaign, but only resulted in stronger pro-environmental intentions and increased environmental policy support for those who strongly endorsed biospheric values (Bolderdijk et al. 2013a). Similarly, interventions aimed at strengthening public support for smart grids will be more effective if they target values that underlie people's evaluations and acceptability ratings. For example, educating people about the environmental consequences of smart grids may not motivate them to change their energy behaviours, if, based on their egoistic values, they mostly focus on energy price and/or quality of energy supply. In this case, introducing subsidies for adopting renewable energy or improving the functionality of smart grids could be more motivating for people; such strategies could at the same time enhance intrinsic motivation to support durable changes in behaviour, as explained above. More generally, information strategies have been more successful when they are tailored to specific characteristics of the target population (Abrahamse et al. 2005, 2007). Besides, information is more likely to change beliefs and behaviour if people evaluate the source favourably and trust the source (Clayton et al. 2015).

Second, people can be informed about which personal actions are effective to increase the efficiency and sustainability of smart grids by providing them with feedback about their energy use or energy savings. Feedback appears to be an effective strategy for reducing household energy use (Abrahamse et al. 2005), although some exceptions exist (see Fischer 2008). Feedback on household energy use is considered to be an important part of smart grids. It is therefore essential to understand under which conditions feedback is most likely to motivate people to engage in behaviours that optimise smart grids. Feedback is more effective when it is given immediately after the behaviour occurs, and when it is provided frequently, as this enhances people's understanding of the relationship between the feedback and their behaviour (Geller 2002). Smart meters offer possibilities for providing immediate and frequent feedback on household energy use via different means such as websites, mobile phones, and home displays (Sintov and Schultz 2015). Smart meters, however, typically provide feedback on overall energy use, which might still tell little to people about how they can reduce their energy use. In this respect, feedback on a more detailed level, for example, on an appliance level, may be more effective (Fischer 2008; Ehrhardt-Martinez et al. 2010). Furthermore, with dynamic pricing, smart meters may provide people with feedback on current energy tariffs, and ways to save costs by shifting energy use in time. People may not always be motivated or able to consciously process feedback on their energy use. When they lack the motivation or resources to consciously process information and feedback on their energy behaviours, ambient persuasive technologies can be offered that promote behaviour change without the need for user's conscious attention and hence with little cognitive effort (Midden and Ham 2012). For example processing interactive lighting feedback, such as a light that turns green, is less cognitively demanding than processing factual feedback, such as statistics on your energy use, and may facilitate and motivate people to engage in smart energy behaviour even in cognitively demanding situations.

A range of social influence strategies can be employed to encourage smart energy behaviours (see Abrahamse and Steg 2013, for a review). Social influence occurs when one's emotions, beliefs or behaviour are influenced by others. Social influence approaches that make use of face-to-face interaction appeared particularly effective, such as block leader approaches, and behaviour modelling. Block leader approaches, in which case local volunteers help inform other people in their neighbourhood about a certain issue, seem to be one of the most effective social influence strategies. Block leader approaches are more effective when the relevant social network has more ties (Weenig and Midden 1991). Behaviour modelling, in which case confederates or "models" demonstrate a recommended behaviour, appeared to be an effective strategy to encourage sustainable behaviour too (Winett et al. 1985).

Commitment making is another effective social influence strategy, in which case people make a promise to engage in smart energy behaviour. Also, implementation intentions appeared to be successful in promoting behaviour changes, in which case people not only promise to engage in smart energy behaviour, but also indicate how and when they will do so. Importantly, both strategies appear to have long-term effects on behaviour (see Abrahamse et al. 2005; Abrahamse and Steg 2013; Lokhorst et al. 2013, for reviews). Commitments are more effective when made in public rather than private (Abrahamse et al. 2005). Although little is known about the processes through which both strategies promote behaviour changes, one plausible explanation is that they strengthen personal norms. Once people committed themselves to engage in smart energy behaviour, they are motivated to act in line with their promise, as they want to (appear to) be consistent (Abrahamse and Steg 2013). Evoking cognitive dissonance between individuals' reported attitudes and behaviour is another strategy using people's desire to be consistent. For example, people who first reported a favourable attitude towards energy conservation, and later were made aware of their relatively high energy usage, significantly reduced their energy use (Focella and Stone 2013).

Social influence strategies that generally operate in a fairly anonymous way, such as descriptive norm information, social comparison feedback, and group feedback, can also encourage sustainable behaviour, but are less effective than strategies that rely on face-to-face interactions (Abrahamse and Steg 2013). Descriptive norm information entails that individuals receive information on the behaviour of others, while social comparison feedback involves receiving feedback about one's own performance relative to the performance of others. In case of group feedback, people receive information on the performance of a group. Descriptive norm information and social comparison feedback is not very effective when people figure out that most (significant) others do not act sustainably. In fact, if individuals learn that most others do not engage in smart energy behaviours, providing feedback on the behaviour of others may even be counter effective, as people are likely to follow this norm (Brandon and Lewis 1999; Schultz et al. 2007). Another factor that influences the effects of descriptive norm information and social comparison feedback is credibility of information on the behaviour or performance of others. For example, it would be unwise to communicate that most others engage in smart energy behaviours while it is obvious that this is not actually the case (cf. Terwel et al. 2009).

Besides informing people about the smart energy behaviour of others, they can also be reminded of smart energy behaviours they themselves already engaged in. As explained earlier, such strategies are likely to strengthen one's environmental self-identity, particularly when one's previous behaviours clearly signal that one acted pro-environmentally, thereby promoting subsequent smart energy behaviours (Van der Werff et al. 2014a). As discussed above, the latter is more likely to be the case when people are reminded of a range of actions they engaged in, or when they are reminded of behaviours that were somewhat costly or unique. This implies an interesting paradox. On the one hand, it may be important to stress that many others engage in smart energy behaviour, as people are likely to act in line with such descriptive norms. Yet, on the other hand, stressing that only few people engage in smart energy behaviour can also encourage smart energy behaviour, via a different process, by strengthening one's environmental identity after engaging in such behaviours.

5 Acceptability of Smart Grids

Smart grids can be promoted via different energy policies and changes in energy systems, which should be acceptable to the public. We already discussed how values can influence perceived costs and benefits of smart grids. Besides, public acceptability depends on how and by whom a transition to smart grids is developed and implemented. We describe three factors that play a crucial role in this respect, namely distributive fairness, trust in involved parties, and public engagement and participation.

5.1 Distributive Fairness

Acceptability of the transition to smart grids does not only depend on the benefits, costs and risks, but also on how these benefits, costs and risks are distributed among groups involved, which reflects perceived fairness. Smart grid solutions will be seen as unfair if certain groups in society face most of the costs, while other groups mainly enjoy the benefits; this may reduce their acceptability (Schuitema and Jakobsson Bergstad 2012). For example, communities hosting renewable energy technology such as wind farms may experience noise and visual hinder, while the possible benefits such as reduced CO_2 emissions, affordable energy, and energy independence are shared on a national or even global scale. As a consequence, people may oppose these technologies.

Fair distribution of costs and benefits can be pursued in multiple ways, which are not mutually exclusive. First, risks and costs of smart grids can be reduced as much as possible in order to enhance fairness and secure public acceptability. For example, technical solutions can be sought to reduce the noise caused by wind turbines, and costs of renewable energy sources can be reduced via subsidies. A second (parallel) strategy to pursue a fair distribution of costs, risks and benefits is providing additional benefits to those exposed to most costs and risks. For example, individuals can be financially compensated, or developers of renewable energy projects could establish local funds that can be used to reduce energy bills for local people, to stimulate local economy, or to create or expand local facilities (Walker et al. 2014). Offering reductions on energy prices for example increased people's willingness to host wind farms (e.g. Groothuis et al. 2008). It has been proposed that collective benefits (e.g. investing in local facilities) are less likely to be seen as 'bribes' by citizens than individual financial compensations (e.g. one-time payments to residents; Ter Mors et al. 2012). However, this proposition has not been empirically tested. Interestingly, the amount of compensations may be less important for perceived fairness and acceptability judgements than who will benefit from the compensation. For example, people prefer royalties from a wind energy project to be allocated to local funds rather than to state funds (Krueger et al. 2011). This is probably because it is seen as more fair when local communities benefit from hosting energy infrastructure (cf. Schuitema and Steg 2008). Yet, financial compensation to local funds will not enhance acceptability and may even backfire when these compensations are perceived as attempts to ‘buy local support’ (Walker et al. 2014; cf. Ter Mors et al. 2012).

5.2 Trust in Involved Parties and Acceptability

A transition to smart grids entails multiple aspects, including complex energy technology, that go beyond the knowledge and expertise of consumers. People therefore need to rely on other parties, such as energy companies, governments, and scientists, to form their opinion on smart grids. Trust in involved parties will especially affect evaluations and perceptions when people have little knowledge about new systems or solutions, which is the case for smart grids (cf. Siegrist and Cvetkovich 2000). The extent to which people trust involved parties can influence acceptability of smart grids (cf. Ngar-yin et al. 2012; Huijts et al. 2012; Perlaviciute and Steg 2014; Steg et al. 2015). Lack of trust in energy companies can also strengthen privacy concerns related to smart metering technology, which can weaken public support for these technologies (Butler et al. 2013). Similarly, public distrust in national governments can hinder the implementation of energy policies, such as dynamic pricing schemes aimed at balancing the energy supply and demand (Mah et al. 2012). Yet, lack of trust may not always result in lack of support for proposed changes. For example, people expressed much support for a sustainable energy transition, but at the same time they expressed their concern whether energy companies are capable of realising sustainable energy transitions in a way that aligns with societal and environmental values (Butler et al. 2013).

5.3 Public Involvement

Smart grids are likely to rely more strongly on decentralised and local energy production. This changes the role of consumers from passive recipients to active producers of energy, so-called prosumers. Smart grids may also require more active public user involvement in planning, developing, and implementing smart grids. Public involvement comprises different dimensions, varying from one-way communication from developers to consumers to active public involvement in decision-making processes, which can have important implications for public acceptability of smart grids (cf. Devine-Wright 2011; Steg et al. 2015). Technocratic top-down decision making processes may inhibit public acceptability of smart grids, while collaborative approaches taking people’s interests and concerns into account in which people actually have a say enhance acceptability of energy policies and changes in energy systems (Devine-Wright 2011; Wolsink 2007). Acceptability of smart grids is likely to be higher if people have been actively involved in the decisions-making process, as this enhances legitimacy of the decisions made (U.S. National Research Council 2008; Schuitema and Jakobsson Bergstad 2012).

6 Conclusion

In this chapter, we discussed factors influencing behaviour in smart grids. We proposed a general framework to study ways to understand and encourage smart energy behaviours needed to promote the efficiency and sustainability of smart grids, comprising four key issues. First, we argued that smart grids involve changes in a wide range of energy behaviours, including the adoption of sustainable energy resources and energy-efficient and smart technology, and changes in energy use behaviour. We indicated that it is important to consider the conditions under which engagement in one smart energy behaviour is likely to promote engagement in other smart energy behaviour, resulting in positive spillover. Second, we proposed that it is important to examine main factors underlying these different types behaviours and acceptability of smart grid solutions needed to optimise smart grids. We discussed two main factors influencing such behaviour that are closely intertwined: motivations and contextual factors. Third, it is important to understand factors influencing the effects of different interventions aimed at promoting smart grids by changing important antecedents of smart energy behaviours. It is not only important to study structural strategies that are aimed at changing the actual costs and benefits of behaviour, but also psychological strategies that affect how individuals perceive and evaluate different pros and cons of behavioural options. Fourth, smart grids will probably not be implemented when they are not supported by the public. Therefore, it is important to understand which factors affect the acceptability of a transition to smart grids. We discussed that acceptability judgements not only depend on the perceived benefits, costs and risks of smart grids, but also on trust in the parties involved. Besides, perceived fairness plays a role, which depends on the distribution of benefits, costs and risks across groups in society, and the level of public involvement in the decision making process.

Points for Discussion

- How will the difficulties of stimulating smart energy behaviour at the individual and household level affect the introduction of smart grids at the community level? Can a smart grid for, say, a city of more than one million inhabitants be built and implemented if only a proportion of the population actively supports it? What would be needed?

References

Abrahamse, W., Matthies, E.: Informational strategies to promote pro-environmental behaviour: changing knowledge, awareness and attitudes. In: Steg, L., van den Berg, A.E., de Groot, J.I.M. (eds.) Environmental Psychology: An introduction, pp. 223–243. Wiley, Oxford, UK (2012)

Abrahamse, W., Steg, L.: Factors related to household energy use and intention to reduce it: the role of psychological and socio-demographic variables. Human Ecol. Rev. **18**(1), 30–40 (2011)

Abrahamse, W., Steg, L.: Social influence approaches to encourage resource conservation: a meta-analysis. Glob. Environ. Change **23**, 1773–1785 (2013)

Abrahamse, W., Steg, L., Vlek, Ch., Rothengatter, T.: A review of intervention studies aimed at household energy conservation. J. Environ. Psychol. **25**, 273–291 (2005)

Abrahamse, W., Steg, L., Vlek, Ch., Rothengatter, T.: The effect of tailored information, goal setting and tailored feedback on household energy use, energy-related behaviors and behavioral antecedents. J. Environ. Psychol. **27**, 265–276 (2007)

Bidwell, D.: The role of values in public beliefs and attitudes towards commercial wind energy. Energy Policy **58**, 189–199 (2013)

Bockarjova, M., Steg, L.: Can protection motivation theory predict pro-environmental behavior? Explaining the adoption of electric vehicles in The Netherlands. Glob. Environ. Change **28**, 276–288 (2014). doi:10.1016/j.gloenvcha.2014.06.010

Bolderdijk, J.W., Gorsira, M., Keizer, K., Steg, L.: Values determine the (in)effectiveness of informational interventions in promoting pro-environmental behavior. PLoS ONE **8**(12), e83911 (2013a). doi:10.1371/journal.pone.0083911

Bolderdijk, J.W., Knockaert, J., Steg, E.M., Verhoef, E.T.: Effects of pay-as-you-drive vehicle insurance on young drivers' speed choice: results of a Dutch field experiment. Accid. Anal. Prev. **43**, 1181–1186 (2011)

Bolderdijk, J.W., Steg, L.: Promoting sustainable consumption: the risks of using financial incentives. In: Thøgersen, J., Reisch, L. (eds.) Handbook of Research in Sustainable Consumption. Edward Elgar, Cheltenham, UK (2015)

Bolderdijk, J.W., Steg, L., Geller, E.S., Lehman, P.K., Postmes, T.: Comparing the effectiveness of monetary versus moral motives in environmental campaigning. Nat. Clim. Change **3**, 413–416 (2013b). doi:10.1038/NCLIMATE1767

Bolderdijk, J.W., Steg, L., Postmes, T.: Fostering support for work floor energy conservation policies: accounting for privacy concerns. J. Organ. Behav. **34**, 195–210 (2013c)

Bradley, J.C., Waliczek, T.M., Zajicek, J.M.: Relationship between environmental knowledge and environmental attitude of high school students. J. Environ. Educ. **30**, 17–21 (1999)

Brandon, G., Lewis, A.: Reducing household energy consumption: a qualitative and quantitative field study. J. Environ. Psychol. **19**, 75–85 (1999)

Butler, C., Parkhill, K.A., Pidgeon, N.: Deliberating energy transitions in the UK—transforming the UK energy system: public values, attitudes and acceptability. UKERC, London (2013)

Clastres, C.: Smart grids: another step towards competition, energy security and climate change objectives. Energy Policy **39**(9), 5399–5408 (2011)

Clayton, S., Devine-Wright, P., Stern, P.C., Whitmarsh, L., Carrico, A., Steg, L., Swim, J., Bonnes, M.: Psychological research and global climate change. Nat. Clim. Change **5**(7), 640–646 (2015)

Cornelissen, G., Pandelaere, M., Warlop, L., Dewitte, S.: Positive cueing: promoting sustainable consumer behavior by cueing common environmental behaviors as environmental. Int. J. Res. Mark. **25**(1), 46–55 (2008)

Corraliza, J.A., Berenguer, J.: Environmental values, beliefs, and actions. A situational approach. Environ. Behav. **32**(6), 832–848 (2000)

De Groot, J.I.M., Steg, L.: Value orientations to explain beliefs related to environmental significant behavior: how to measure egoistic, altruistic, and biospheric value orientations. Environ. Behav. **40**(3), 330–354 (2008)

De Groot, J.I.M., Steg, L.: Mean or green: which values can promote stable pro-environmental behavior? Conserv. Lett. 2, 61–66 (2009)

Devine-Wright, P.: Public engagement with large-scale renewable energy technologies: breaking the cycle of NIMBYism. Wiley Interdisc. Rev. Clim. Change **2**(1), 19–26 (2011)

Diekmann, A., Preisendörfer, P.: Green and greenback. The behaveioural effects of environmental attitudes in low-cost and high-cost situations. Rationality Soc. **15**(4), 441–472 (2003)

Dogan, E., Bolderdijk, J.W., Steg, L.: Making small numbers count: environmental and financial feedback in promoting eco-driving behaviours. J. Consum. Policy **37**, 413–422 (2014). doi:10.1007/s10603-014-9259-z

Ehrhardt-Martinez, K., Donnelly, K.A., Laitner, J.A.: Advanced Metering Initiatives and Residential Feedback Programs: A Meta-Review for Household Electricity-Saving Opportunities. American Council for an Energy Efficient Economy, Washington, D.C. (2010)

Evans, L., Maio, G. R., Corner, A., Hodgetts, C. J., Ahmed, S., Hahn, U.: Self-interest and pro-environmental behaviour. Nat. Clim. Change **3**, 122–125 (2013)

Fischer, C.: Feedback on household electricity consumption: a tool for saving energy? Energ. Effi. **1**, 79–104 (2008)

Focella, E.S., Stone, J.: The use of hypocrisy for promoting environmentally sustainable behaviors. In: van Trijp, H.C.M. (ed.) Encouraging sustainable behaviour, pp. 203–215. Psychology Press, New York (2013)

Frondel, M., Ritter, N., Vance, C.: Heterogeneity in the rebound effect: further evidence for Germany. Energy Econ. **34**(2), 461–467 (2012). doi:10.1016/j.eneco.2011.10.016

Gangale, F., Mengolini, A., Onyeji, I.: Consumer engagement: an insight from smart grid projects in Europe. Energy Policy **60**, 621–628 (2013)

Gatersleben, B., Steg, L.: Affective and symbolic aspects of environmental behaviour. In: Steg, L., van den Berg, A.E., de Groot, J.I.M. (eds.) Environmental Psychology: An introduction, pp. 165–174. Wiley, Oxford, UK (2012)

Gatersleben, B., Murtagh, N., Abrahamse, W.: Values, identity and pro-environmental behaviour. Contemp. Soc. Sci. J. Acad. Soc. Sci. **9**(4), 374–392 (2012)

Geelen, D., Reinders, A., Keyson, D.: Empowering the end-user in smart grids: recommendations for the design of products and services. Energy Policy **61**, 151–161 (2013)

Geller, E.S.: The challenge of increasing proenvironmental behavior. In: Bechtel, R.B., Churchman, A. (eds.) Handbook of Environmental Psychology, pp. 525–540. Wiley, New York (2002)

Gellings, C.W., Samotyj, M.: Smart Grid as advanced technology enabler of demand response. Energy Effi. **6**, 685–694 (2013). doi:10.1007/s12053-013-9203-0

Goulden, M., Bedwell, B., Rennick-Egglestone, S., Rodden, T., Spence, A.: Smart grids, smart users? The role of the user in demand side management. Energy Res. Soc. Sci. **2**, 21–29 (2014)

Griskevicius, V., Tybur, J.M., Van den Bergh, B.: Going green to be seen: status, reputation, and conspicuous conservation. J. Pers. Soc. Psychol. **98**, 392–404 (2010)

Groothuis, P.A., Groothuis, J.D., Whitehead, J.C.: Green vs. green: measuring the compensation required to site electrical generation windmills in a viewshed. Energy Policy **36**(4), 1545–1550 (2008)

Harland, P., Staats, H., Wilke, H.: Explaining proenvironmental behavior by personal norms and the theory of planned behavior. J. Appl. Soc. Psychol. **29**, 2505–2528 (1999)

Harland, P., Staats, H., Wilke, H.A.: Situational and personality factors as direct or personal norm mediated predictors of pro-environmental behavior: questions derived from norm-activation theory. Basic Appl. Soc. Psychol. **29**(4), 323–334 (2007)

Hess, D.: Smart meters and public acceptance: comparative analysis and governance implications. Health Risk Soc. **16**(3), 243–258 (2014)

Huijts, N.M.A., Molin, E.J.E., Steg, L.: Psychological factors influencing sustainable energy technology acceptance: a review-based comprehensive framework. Renew. Sustain. Energy Rev. **16**(1), 525–531 (2012)

Kaklamanou, D., Jones, C.R., Webb, T.L., Walker, S.R.: Using public transport can make up for flying abroad on holiday: compensatory green beliefs and environmentally significant behavior. Environ. Behav. **47**(2), 184–204 (2015)

Kobus, C.B.A., Mugge, R., Schoormans, J.P.L.: Washing when the sun is shining! How users interact with a household energy management system. Ergonomics **56**(3), 451–462 (2013)

Krishnamurti, T., Schwartz, D., Davis, A., Fischhoff, B., Bruine de Bruin, W., Lave, L., Wang, J.: Preparing for smart grid technologies: a behavioral decision research approach to understanding consumer expectations about smart meters. Energy Policy **41**, 790–797 (2012)

Krueger, A.D., Parsons, G.R., Firestone, J.: Valuing the visual disamenity of offshore wind power projects at varying distances from the shore: an application on the Delaware shoreline. Land Econ. **87**(2), 268–283 (2011)

Lanzini, P., Thøgersen, J.: Behavioural spillover in the environmental domain: an intervention study. J. Environ. Psychol. **40**, 381–390 (2014)

Leijten, F.R.M., Bolderdijk, J.W., Keizer, K., Gorsira, M., Van der Werff, E., Steg, L.: Factors that influence consumers' acceptance of future energy systems: the effects of adjustment type, production level, and price. Energ. Effi. **7**, 973–985 (2014). doi:10.1007/s12053-014-9271-9

Lindenberg, S.M.: How cues in the environment affect normative behavior. In: Steg, L., Van den Berg, A.E., De Groot, J.I.M. (eds.) Environmental Psychology: An Introduction, pp. 119–128. Wiley, Oxford, UK (2012)

Lokhorst, A.M., Werner, C., Staats, H., Van Dijk, E., Gale, J.L.: Commitment and behaviour change: a meta-analysis and critical review of commitment-making strategies in environmental research. Environ. Behav. **45**, 3–34 (2013)

Mah, D.N.Y., van der Vleuten, J.M., Ip, J.C.M., Hills, P.R.: Governing the transition of socio-technical systems: a case study of the development of smart grids in Korea. Energy Policy **45**, 133–141 (2012)

Midden, C., Ham, J.: Persuasive technology to promote pro-environmental behaviour. In Steg, L., van den Berg, A.E., de Groot, J.I.M. (eds.) Environmental Psychology: An Introduction, pp. 243–25. John Wiley & Sons, Oxford, UK (2012)

Murtagh, N., Gatersleben, B., Cowen, L., Uzzell, D.: Does perception of automation undermine pro-environmental behaviour? Findings from three everyday settings. J. Environ. Psychol. **42**, 139–148 (2015). doi:http://dx.doi.org/10.1016/j.jenvp.2015.04.002

Ngar-yin Mah, D., Van der Vleuten, J.M., Chi-man Ip, J., Hills, P.R.: Governing the transition of socio-technical systems: a case study of the development of smart grids in Korea. Energy Policy **45**, 133–141 (2012)

Nolan, J.M., Schultz, P.W., Cialdini, R.B., Goldstein, N.J., Griskevicius, V.: Normative social influence is underdetected. Pers. Soc. Psychol. Bull. **34**, 913–923 (2008)

Noppers, E., Keizer, K., Bolderdijk, J.W., Steg, L.: The adoption of sustainable innovations: driven by symbolic and environmental motives. Global Environ. Change **25**, 52–62 (2014). http://dx.doi.org/10.1016/j.gloenvcha.2014.01.012

Nordlund, A.M., Garvill, J.: Value structures behind pro-environmental behavior. Environ. Behav. **34**, 740–756 (2002)

Oldfield, E.: Addressing energy poverty through smarter technology. Bull. Sci. Technol. Soc. **31** (2), 113–122 (2011)

Parkhill, K.A., Demski, C., Butler, C., Spence, A., Pidgeon,N.: Transforming the UK Energy System: Public Values, Attitudes and Acceptability –Synthesis Report, UKERC, London (2013)

Perlaviciute, G.: Goal driven evaluations of sustainable products. PhD thesis, University of Groningen, Faculty of Behavioural and Social Sciences (2014)

Perlaviciute, G., Steg, L.: Contextual and psychological factors shaping evaluations and acceptability of energy alternatives: integrated review and research agenda. Renew. Sustain. Energy Rev. **35**, 361–381 (2014)

Perlaviciute, G., Steg, L.: The influence of values on evaluations of energy alternatives. Renew. Energy **77**, 259–267 (2015)

Schuitema, G., Jakobsson Bergstad, C.J.: Acceptability of environmental policies (pp. 255–266). In: Steg, L., van den Berg,A.E., de Groot, J.I.M. (eds.) Environmental Psychology: An Introduction, pp. 255–266. Wiley, Oxford, UK (2012)

Schuitema, G., Steg, L.: The role of revenue use in the acceptability of transport pricing policies. Trans. Res. F Psychol. Behav. **11**, 221–231 (2008)

Schultz, P.W., Nolan, J., Cialdini, R., Goldstein, N., Griskevicius, V.: The constructive, destructive, and reconstructive power of social norms. Psychol. Sci. **18**, 429–434 (2007)

Schwartz, S.H.: Universals in the content and structures of values: theoretical advances and empirical tests in 20 countries. In: Zanna, M. (ed.) Advances in Experimental Psychology, vol. 25, pp. 1–65. Academic Press, Orlando, FL (1992)

Siegrist, M., Cvetkovich, G.: Perception of hazards: The role of social trust and knowledge. Risk Anal. **20**(5), 713–720 (2000)

Sintov, N.D., Schultz, P.W.: Unlocking the potential of smart grid technologies with behavioral science. Front. Psychol. **6**, 410 (2015)

Sovacool, B.K.: Diversity: energy studies need social science. Nature **511**, 529–530 (2014)

Staats, H.J., Wit, A.P., Midden, C.Y.H.: Communicating the greenhouse effect to the public: evaluation of a mass media campaign from a social dilemma perspective. J. Environ. Manage. **45**, 189–203 (1996)

Steg, L.: Environmental psychology and sustainable consumption. In: Thogersen, J., Reisch, L. (eds.) Handbook of Research in Sustainable Consumption. Edward Elgar, Cheltenham, UK (2015)

Steg, L., De Groot, J.I.M.: Environmental values. In: Clayton, S. (ed.) The Oxford Handbook of Environmental and Conservation Psychology, pp. 81–92. Oxford University Press, New York (2012)

Steg, L., Vlek, C.: Encouraging pro-environmental behaviour: an integrative review and research agenda. J. Environ. Psychol. **29**, 309–317 (2009)

Steg, L., Dreijerink, L., Abrahamse, W.: Factors influencing the acceptability of energy policies: a test of VBN theory. J. Environ. Psychol. **25**(4), 415–425 (2005)

Steg, L., Bolderdijk, J.W., Keizer, K., Perlaviciute, G.: An integrated framework for encouraging pro-environmental behaviour: the role of values, situational factors and goals. J. Environ. Psychol. **38**, 104–115 (2014a). http://dx.doi.org/10.1016/j.jenvp.2014.01.002

Steg, L., Perlaviciute, G., Van der Werff, E., Lurvink, J.: The significance of hedonic values for environmentally-relevant attitudes, preferences and actions. Environ. Behav. **46**(2), 163–192 (2014b). doi:10.1177/0013916512454730

Stern, P.C.: Information, incentives, and proenvironmental consumer behavior. J. Consum. Policy **22**, 461–478 (1999)

Stern, P.C., Dietz, T., Kalof, L., Guagnano, G.A.: Values, beliefs, and pro-environmental action: attitude formation toward emergent attitude objects. J. Appl. Soc. Psychol. **25**, 1611–1636 (1995)

Taufik, D., Bolderdijk, J.W., Steg, L.: Acting green elicits a literal 'warm glow'. Nat. Clim. Change **5**, 37–40 (2014). doi:10.1038/nclimate2449

Ter Mors, E., Terwel, B.W., Daamen, D.D.L.: The potential of host community compensation in facility siting. Int. J. Greenhouse Gas Control **11**, S130–S138 (2012)

Terwel, B.W., Harinck, F., Ellemers, N., Daamen, D.D.L.: How organizational motives and communications affect public trust in organizations: The case of carbon dioxide capture and storage. J. Environ. Psychol. **29**, 290–299 (2009)

Thøgersen, J.: Psychology: inducing green behavior. Nat. Clim. Change **3**, 100–101 (2013)

Thøgersen, J., Ölander, F.: Spillover of environment-friendly consumer behaviour. J. Environ. Psychol. **23**(3), 225–236 (2003)

Tiefenbeck, V., Staake, T., Roth, K., Sachs, O.: For better or for worse? Empirical evidence of moral licensing in a behavioral energy conservation campaign. Energy Policy **57**, 160–171 (2013)

Truelove, H.B., Carrico, A.R., Weber, E.U., Raimi, K.T., Vandenbergh, M.P.: Positive and negative spillover of pro-environmental behavior: an integrative review and theoretical framework. Glob. Environ. Change **29**, 127–138 (2014)

U.S. National Research Council. In: Dietz, T., Stern, P. (eds.) Public participation in environmental assessment and decision making. Washington, D.C.: National Academy Press (2008)

Van der Werff, E., Steg, L.: One model to predict them all: Predicting energy behaviours with the norm activation model. Energy Res. Social Sci. **6**, 8–14 (2015). doi:10.1016/j.erss.2014.11.002

Van der Werff, E., Steg, L., Keizer, K.: It is a moral issue: the relationship between environmental self-identity, obligation-based intrinsic motivation and pro-environmental behaviour. Glob. Environ. Change **23**, 1258–1265 (2013). doi:10.1016/j.gloenvcha.2013.07.018

Van der Werff, E., Steg, L., Keizer, K.E.: Follow the signal: when past pro-environmental actions signal who you are. J. Environ. Psychol. **40**, 273–282 (2014a). doi:10.1016/jenvp.2014.07.004

Van der Werff, E., Steg, L., Keizer, K.E.: I am what I am, by looking past the present: The influence of biospheric values and past behaviour on environmental self-identity. Environ. Behav. **46**(5), 626–657 (2014b). doi:10.1177/0013916512475209

Venhoeven, L.A., Bolderdijk, J.W., Steg, L.: Explaining the paradox: how pro-environmental behaviour can both thwart and foster well-being. Sustainability **5**, 1372–1386 (2013). doi:10.3390/su5041372

Verbong, G.P.J., Beemsterboer, S., Sengers, F.: Smart grids or smart users? Involving users in developing a low carbon electricity economy. Energy Policy **52**, 117–125 (2013)

Walker, B.J., Wiersma, B., Bailey, E.: Community benefits, framing and the social acceptance of offshore wind farms: an experimental study in England. Energy Res. Social Sci. **3**, 46–54 (2014)

Weenig, M.W.H., Midden, C.J.H.: Communication network influences on information diffusion and persuasion. J. Pers. Soc. Psychol. **61**, 734–742 (1991)

Winett, R.A., Leckliter, I.N., Chinn, D.E., Stahl, B., Love, S.Q.: Effects of television modeling on residential energy conservation. J. Appl. Behav. Anal. **18**, 33–44 (1985)

Wolsink, M.: Wind power implementation: the nature of public attitudes: equity and fairness instead of 'backyard motives'. Renew. Sustain. Energy Rev. **11**(6), 1188–1207 (2007)

Wolsink, M.: The research agenda on social acceptance of distributed generation in smart grids: Renewable as common pool resources. Renew. Sustain. Energy Rev. **16**, 822–835 (2012)

Zhang, Y., Wang, Z., Zhou, G.: Antecedents of employee electricity saving behavior in organizations: an empirical study based on norm activation model. Energy Policy **62**, 1120–1127 (2013). doi:10.1016/j.enpol.2013.07.036

What Are Smart Grids? Epistemology, Interdisciplinarity and Getting Things Done

J. Anne Beaulieu

Abstract Smart grids are defined in a variety of ways that are more or less continuous with current energy systems and technologies. Since their emergence in the first decade of the 21st century, a number of trends have become visible in the way smart grids are defined, from revolutionary break, to additive ('adding an ict layer'), to enabling the energy transition. Smart Grids as a term is increasingly accused of being a rather vague label for a variety of innovations. This scepticism around the term indicates that it may be moving from being the latest buzzword to being decried as 'hype'. But this multiplicity is in itself interesting. Closer consideration of what we talk about when we talk about smart grids provides insights into the current paths to innovation that are emerging and into the changing requirements to energy systems. In this chapter, I put forth three ways of looking at definitions of smart grids and the functions they fulfill: as promissory work, as creation of new objects and as boundary work. By considering the functional value of definitions beyond description, a richer, more critical discussion can arise. Shedding this light on the definitions of smart grids provides a tool for interdisciplinary interaction and a useful analytic basis for collaborative work on smart grids.

1 Introduction: Kinds of Work Done by Definitions

Readers of this volume will not need convincing that smart grids matter. But some may ask: why do *definitions* of smart grids warrant attention? A brief contrast between two definitions may be the best way to start drawing attention to the potential of definitions as a way of engaging with smart grids from an interdisciplinary perspective. Let's consider the definition put forth by the U.S. Department of Energy (2009):

J.A. Beaulieu (✉)
University of Groningen, Groningen, The Netherlands
e-mail: j.a.beaulieu@rug.nl

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_5

> A smart grid uses digital technology to improve reliability, security, and efficiency (both economic and energy) of the electrical system from large generation, through the delivery systems to electricity consumers and a growing number of distributed-generation and storage resources.

A second definition by the European Technology Platform contains interesting similarities, when it come to a focus on electricity and on delivery, and in the mention of consumers:

> A smart grid is an electricity network that can intelligently integrate the actions of all users connected to it—generators, consumers, and those that do both—in order to efficiently deliver sustainable, economic and secure electricity supplies. (http://www.smartgrids.eu/ETPSmartGrids)

These definitions also contrast in interesting ways, for example on the emphasis on centralization (stronger in the US version), and on the role of ICT. Also significant are the differences in the kind of impact that is expected: in the US, the expectation is one of improvement, while in the European definition, integration is the aim. A focus on definitions can therefore orient us to particular ambitions and goals.

A third definition, this time from a textbook on smart grids, highlights other aspects of smart grids:

> The Smart Grid can be described as the transparent, seamless and instantaneous two-way delivery of energy information, enabling the electricity industry to better manage energy delivery and transmission and empowering consumers to have more control over energy decisions (Hossain et al. 2012, 23).

Here, information is much more central to the function of smart grids and there are roles for consumers as active agents, like in the European definition (but not the American one). Note also that this definition begins with descriptors that are actually quite prescriptive. The smart grid will have to have the qualities of transparency and seamlessness and will have to be instantaneous.

This brief consideration of definitions shows that they put forth a reality, promising improvements and progress, that they articulate particular features of objects and that they situate smart grids as belonging to different spheres—markets, infrastructures, or information technologies. Definitions put forth a reality, foreground and background, include and exclude, assign active and passive roles. They are therefore better seen, not as a camera, but as an engine, to echo Mackenzie (2008).

This chapter is therefore an invitation to consider definitions as the basis for a productive encounter. The apparently simple question 'What are smart grids?' can be the starting point of very important and useful explorations that will lead to better smart grids. This is a question that can be posed earnestly: seeking a description or definition. Asking the question in this way points to a belief in the existence of smart grids and assumes that they are worthwhile objects to get to know. In this sense, the question orients us to smart grids as a particular thing, a solution to a problem, a functional answer to a set of requirements.

This question can also be asked derisively, with the asker actually emphasising doubt in the existence if this object or casting doubt on its coherence. It can also be a way to point to the mistaken belief that something like smart grids would even exist. In this sense, the question orients us to smart grids as potential hype, as a hollow term that mostly has rhetorical value and serves to make promises about potential energy systems.

A third way to ask this question is to expect a range of different answers, answers that may contrast. Asking the question in this way orients us to the status of object-in-becoming of smart grids, to their unfinished, dynamic, multiple status. As such, asking what are smart grids becomes a way to explore a technology-in-the-making, before the answer to what is a smart grid is fully settled.

In this chapter, I will explore this third way of exploring 'what are smart grids'. I will consider smart grids as a 'partially existing object' (Schick and Winthereik 2013). This means that its ontological status is uncertain, and that there is disagreement about what it is, in the view of different actors. This approach is not 'merely' an interesting intellectual puzzle or linguistic exploration. Considering smart grids as partial objects is also a way to draw attention to what needs to happen for smart grids to become 'fully existing objects'. In other words, before definitions are stabilised and before there is agreement on what is a smart grid, a lot needs to happen. This work of settling down the meaning of particular technologies and systems is a crucial part of a shift towards new energy systems.

Definitions and how they orient the development of innovations and our relation to technologies have been the object of much work in science and technology studies. In the sections that follow, I focus on three approaches to the function of definitions that are especially relevant when considering smart grids: promissory work, creation of objects and boundary-work.

2 Definitions and Promissory Work

New technologies are often involved in what is called 'promissory work'. This kind of work takes place in a number of settings where technologies get defined: proposals, media reports, research agendas. Promissory work is about shaping expectations about innovations and new technologies (Brown and Michael 2003). It is crucial in attracting investments (material, intellectual and institutional) and in coordinating actors around particular agendas. In a context of uncertainty about outcomes, expectations provide structure and legitimation (Van Lente 1993). All of this helps to create 'organising visions' that "help to mobilize the material and intellectual resources needed for innovation (Pollock and Williams 2010, 527)."

For a technology such as smart grids, put forth in a context where the future is uncertain in specific ways (global warming, oil peak, global stability), shaping expectations may be especially important. Also, in a context where actors are expected to reach across boundaries (Borup et al. 2006) the expectations of grand solutions or new paradigms such as smart grids may be especially significant (more on this below). It is also important to note that expectations may not follow a linear path, from introduction to gradual greater enthusiasm and general diffusion, but that there may different periods of enthusiasm and backlash and indifference among different groups, all of which are difficult to predict.

As an example of promissory work around a definition of smart grids, consider the discussion of smart grids in a McKinsey report of 2009. Typically, the introduction of a consultancy report will be a likely place to find promissory work. It's important to note, however, that promissory work is also found in other kinds of documents and that it also has a function in scientific work—think of research proposal or calls for scientific events. In this short text, a number of stakeholders who have something to gain from smart grids are explicitly named: utilities, technology vendors and policy-makers are all actors who will not only contribute, but also benefit from smart grids. Speaking of the smart grid:

> Its advent promises improved reliability by enabling quicker and more effective response to outages, greater customer awareness of energy usage and costs, and facilitation of the adoption of technologies such as renewable generation sources and electric vehicles (Mark et al. 2010, 2).

Smart grids are put forth as a development that is inevitable, though the early stages of its realisation may be painful or difficult. As such, the promissory work is that of a better future that will come at the cost of disruptive dynamics that may at first hinder the very actors who are responsible for the realisation of smart grids. Such promissory work tells a tale of innovation in which smart grids will come at a cost, but will be worth it in the end.

There is also a strong message of opportunity entwined with the definition of smart grids that is put forth. Smart grids are a development that arises at a site where a number of prospects can come together and reinforce each other. The promise of smart grids is that they will enable taking a range of challenges, but also the reaping of benefits because of developing trends: adding intelligence to the grid, a global platform to tackle greenhouse gas emissions, and also

> the presence of ample global stimulus funds for energy infrastructure and smart grids in particular, the heightened interest in renewable energy, and the promise of electric vehicles (Mark et al. 2010, 2).

Smart grids are defined as the set of technologies that carry a particular promise for a set of actors who must invest in them, overcoming challenges but harvesting "enormous opportunities" that are created by situating smart grids the confluence of a number of trends. Such promissory work shapes how smart grids are conceived and what we expect they can bring about for new energy systems, and especially in this version, for economic benefit.

This is but one example. Contrasting different versions of the promise would further highlight the way certain promises tend to cluster around the notion of smart grids. The point here is that by examining promissory work, we are able to understand how smart grids become situated as a future that must be realised. Analysing such promissory work makes clear what we project as a script for change, a possibility for a different future. Such promises around technologies are key to realising them, and deserving of attention.

3 Definitions and the Creation of Objects

A second way in which we can approach definitions is to consider how they are creating particular objects. Whereas in the previous section, we considered a definition of a smart grid in terms of the kind of future it might bring about ("what is a smart grid for"), in this section the focus is on how definitions are powerful accounts of what objects are (or should be). Definitions that provide accounts of objects tend to be found in scientific articles and other scientific outputs, in policy documents and in legal documents. There are also sets of definitions, such as standards, that are meant not only to describe but also to regulate explicitly what objects can be. By considering definitions in this way, we can gain deeper insight into how particular aspects of objects become essential (Jensen 2006; Jensen and Winthereik 2013). For example, when defining toothbrushes, little attention is paid to their colour. When defining wine, colour is a key feature. This contrast is trivial, but if we perform the same exercise on smart grids, we come to understand how they are being shaped and how they transform from partially-existing-objects to concrete ones, whose existence might become so obvious, we might wonder why we actually even bothered to debate them. Can we imagine that we would all obviously know what a smart grid is, in the same way that we all know a toothbrush when we see one or that most of us can unfailingly distinguish red from white wine?

One very effective way in which definitions come to be stabilised is via the creation of standards. In the case of smart grids, we can consider the work of USEF (discussed in the chapters by Ngyen et al. 2016 and by De Boer and Verhaegh 2016), as a network of actors who are working towards a set of standards that would modulate how the various technologies that make up smart grids interact.

> A unified smart energy framework will enable consumers to transform into individual energy "up- and downloaders" while keeping the overall, differentiated energy system safe, reliable, and affordable and ensuring the system develops toward increasing sustainability (USEF 2014, 4).

Such standards define the parameters of elements of the smart grids. Typically, standards both enable and constrain what can be done with the technology:

> To achieve the desired interoperability and enable system components to evolve independently, all participants in a USEF market system must share a common logical architecture and standardized interfaces. USEF defines the logical interface standard, but does not define how to implement it. This stimulates innovation and competition among both technology providers and other stakeholders active in the energy value chain. In order to kick-start this process, the USEF Foundation provides a reference implementation that can serve as the basis for full-fledged commercial USEF implementations (USEF 2014, 46).

Interestingly, definitions that constrain what an object can be are not only limiting but also empowering: by following a common standard, all these technologies will share in the same definition of the problem, possibilities and solutions for a smart grid, thereby helping to develop and extend a particular version of a new energy system. However, precisely because of the alignment that is enabled by the settling down of definitions, it is important to consider what it includes and excludes. The range of what a smart grid can be is narrowed through the implementation of definitions-as-standards, even as they become more and more robust and materially embedded.

When definitions become more and more prescriptive, the assumptions and roles that are built into them also become more difficult to change. For example, many of the promises about smart grids have to do with new roles for new actors, and put forth the potential of smart grids to help bring about autonomy or empowerment of consumers. Expectations about users of technologies are also inscribed in the way technologies are defined by designers, engineers and regulators. Kinds of users can also be differentiated because they matter more to a technology (Van Kammen 2000) or to an infrastructure (Summerton 2004). In the case of smart grids, we could think about how particular versions of smart grids shape the kinds of users it can have and the way they might act with smart grids—a user who cares about increasing their energy efficiency and reducing total use; a user who is rationally-driven to make price-based decisions, etc. We might also consider how smart grids may be shifting an early principle of access for all users, where universal access was the goal (Summerton 2004). While smart grids promise more autonomy for users, it may also be that some versions of smart grids lead to greater differentiation between users, positing some as more lucrative—and therefore more likely to be granted privileged access to the grids. Marvin and colleagues (Marvin et al. 1999) described such a dynamic in the UK energy sector, and point to the potential for polarisation and marginalisation of some users. While we can currently observe diversity in how smart grids are defined and in the roles of their users, this diversity may be limited (see also chapter by Kester 2016, for an analysis of the dominant framings of smart grids) and may become more narrow as particular sets of definitions of smart grids become dominant (for example, through the adoption of standards such as USEF) and take on a paradigmatic role.

4 Definitions and Boundary Work

A third kind of work that definitions do, besides putting forth promises and embedding particular aspects, is to link particular objects to particular lifeworlds. This is significant because smart grids become associated with specific sets of problems that they can help solve:

> The way in which a problem is conceived decides what specific suggestions are entertained and which are dismissed; which data are selected and which rejected; it is the criterion for relevancy and irrelevancy of hypotheses and conceptual structures (Dewey 2008).

For example, smart grids are often presented as the solution to greater integration of renewable energy sources. Yet, when considering an energy transition, we are dealing with more than shifts in kinds of fuels, or in a change in the so-called ‘energy-mix’. If smart grids are defined as the solution to ‘intermittent’ energy sources, this puts a specific emphasis on how smart grids can help maintain levels of consumption and the status quo of much of the system. Consider this broader framing:

> Today's electric grid was designed to operate as a vertical structure consisting of generation, transmission and distribution and supported with controls and devicee to maintain reliability, stability, and efficiency. However, the system operators are now facing new challenges including penetration of RER in the legacy system, rapid technological change, and different types of market players and end users (Momoh 2012, 1).

If we embrace the idea that it is important to keep framing energy transition as being broader and more radical than a shift in kinds of fuels, than a broader definition of smart grids is crucial.

But more specifically, different definitions of smart grids align them with particular social worlds. By drawing boundaries around what is relevant to smart grids, kinds of experts and expertise are included and excluded (Beaulieu et al. 2013). This has been termed boundary work, the simultaneous practice of demarcation and coordination between different social worlds (Gieryn 1995). I will return below to the implications for interdisciplinary work below.

For now, consider the following thought experiment: What if sociologists were inventing smart grids? In a setting where engineering and ICT are the dominant disciplines involved in shaping smart grids, this may seem like an irrelevant or even a silly question. Yet it is precisely the obvious, non-controversial alignment of smart grids with specific kinds of technologies and kinds of materials that is the result of boundary-work. Why are smart grids so naturally the domain of engineers and computer scientists? And why does it matter that they are?

While my aim here is to stimulate asking particular kinds of questions about how we define smart grids rather than to provide all the answers, an illustration of how things might be different if a different kind of boundary-work was performed can be useful in understanding how boundary work of definitions is a crucial analytic handle. Drawing different boundaries around a problem definition lead to different kinds of solutions.

Demand-side management is an activity that is often associated with smart grids and one that will be fairly familiar to readers of this book. In an analysis of demand-side management, Evans and colleagues (Evans et al. 1999) showed that depending on how utilities defined demand-side management, radically different styles of demand-side management were developed. In cases where demand-side management was defined as the development and implementation of new technologies, the style of demand management that arose was one in which the user is passive (appliances are switched on/off by utility) or reactive (variable prices are meant to discourage consumption when demand is high relative to supply). There was also a focus on finding the one (technological) solution that would solve demand-side management—a technological magic bullet. On the other hand, where utilities considered that demand-side management could be defined as a social problem, social innovations also arose, such as engagement with customers. In this style of demand-side management, the model was more participatory and the responsibilities were more widespread. There was also more room for local understandings and bottom-up solutions. Evans and colleagues also noted that a greater diversity of solutions (rather than a single dominant technological fix) were developed.

Definitions of smart grids draw boundaries around problems. This is of course necessary, because otherwise it becomes very difficult to get things done. Definitions keep things doable. On the other hand, drawing boundaries includes particular life worlds and their resources. When boundaries are too strictly drawn, the result is that interaction across boundaries becomes difficult to achieve and the creation of solutions drawing on resources across fields becomes very difficult.

5 Conclusion

The last section links definitions to the issue of interdisciplinary collaboration—a very practical issue, to which this volume hopes to contribute. Starting from 'definitions of smart grids', a form that is explicitly present in presentations on and discussions of smart grids, I've highlighted some of the kinds of work done by definitions besides providing a description.

Drawing on different lines of work in science and technology studies, I have shown that definitions can help muster support for new projects, promising particular outcomes that are of interest to particular actors. Promissory work creates expectations about new knowledge and new technologies, and may be increasingly important in a world of growing complexity and uncertainty.

Definitions of smart grids also play a role in creating objects, shaping and standardising them so that they become reliable, taken for granted forms. This kind of work is very important for projects like 'integration' or 'interoperability'. Fixed, standardized and widely accepted definitions are reliable and can enable processes of scaling up and carry promises of universalization. However, the more fixed a definition, the more difficult it becomes to adapt and diversify it, so that particular roles and uses that are excluded remain so.

Finally, definitions are also ways of drawing boundaries around relevant social worlds. Whether smart grids are the terrain of engineers or of economists or of multi-disciplinary teams depends on the way we associate particular definitions to specific fields of knowledge.

The argument for considering the work done by definitions that is made in this chapter is not meant to debunk definitions of smart grids. On the contrary, the suggestion is to contrast different ways of approaching definitions of smart grids. To understand the kinds of work done by definition, we must spend time with the question 'what are smart grids', rather than rush to answer it. In the course of the summer schools from which this chapter arises, the tendency was strong for some participants to ask: 'what are smart grids, really'.

If we always insist on getting an answer to 'what are smart grids, really', we invest in a descriptive approach. This tends to yield essentialistic and even dogmatic answers. The tendency will be to insist on either a narrow, core set of features to define smart grids, or else end up with an inclusive, grocery list approach, where the diversity of elements that make up a smart grids seems unfocussed at best, or endless at worst. Is this really desirable in a context where smart grids are still a partially existing object that needs to be embraced, if it is ever to be realised?

Instead, I suggest that we approach the question of ‘what are smart grids’ analytically, staying with the question rather than rushing to answer it. In considering definitions of smart grids, we need to ask

- who is defining smart grids?
- in what context?
- for which purpose?
- with which consequences?

With such an approach, we might better understand what gets systematically included and excluded. This is not an academic exercize and can have very practical results. For example, we’ve seen that users and publics are shaped by how a technology develops (Jensen and Winthereik 2013). The following questions can make clear assumptions that future energy systems:

- What roles do our definitions of smart grids provide for users?
- What does it mean that we may be leaving public engagement to a stage of the development when the technology is stabilised and black boxed?

Similarly, we might ask about the kinds of expertise that are invoked in our definitions of smart grids:

- Are we building in failure, by leaving some elements outside the problem (and therefore outside the solution)?

Definitions are certainly needed to get stuff done. The point is that by paying more attention to the very work that definitions do, we can use them better, with fuller knowledge that the way we talk, think, and act about definitions shape smart grids and new energy systems, how they will work and who has a say in this.

Points for Discussion

- Can you trace in your own work how your definitions of smart grids and other central concepts relate to the typology, developed in this chapter, of promissory work, creation of new objects and boundary work?
- To what extent and through which means is it possible to prevent misunderstanding when talking to people from various backgrounds about smart grids? What can be gained or lost from such interdisciplinary interactions?

Acknowledgments This chapter is based on a presentation at the Groningen Energy Summer School 2014. The arguments and examples presented here were shaped by discussions with the participants and speakers of GESS14 and this stimulating input is gratefully acknowledged.

References

Beaulieu, A., van Heur, B., de Rijcke, S.: Authority and expertise in new sites of knowledge production. In: Wouters, P., Beaulieu, A., Scharnhorst, A., Wyatt, S. (Eds.) Virtual Knowledge. MIT Press, Cambridge (2013)

Borup, M., Brown, N., Konrad, K., Van Lente, H.: The sociology of expectations in science and technology. Technol. Anal. Strateg. Manag. **18**(3–4), 285–298 (2006). doi:10.1080/09537320600777002

Brown, N., Michael, M.: A sociology of expectations: retrospecting prospects and prospecting retrospects. Technol. Anal. Strateg. Manag. **15**(1), 3–18 (2003). doi:10.1080/0953732032000046024

De Boer, P., Verhaegh, N.: Smart grid pilot projects and implementation in the field. In: Beaulieu, S., De Wilde (Eds.) Smart Grids from a Global Perspective: Bridging Old and New Energy Systems. Springer, Berlin (2016)

Dewey, J.: Logic—The Theory of Inquiry. Read Books (2008)

Evans, R., Guy, S., Marvin, S.: Making a difference: sociology of scientific knowledge and urban energy policies. Sci. Technol. Human Values **24**(1), 105–131 (1999). doi:10.1177/016224399902400106

Gieryn, T.: Boundaries of science. In: Sheila, J., Gerald, M., James P., Trevor, P. (Eds.) Handbook of Science and Technology Studies, pp. 393–444. Sage, Thousand Oaks, CA (1995)

Hossain, E., Zhu, H., Vincent Poor, H.: Smart Grid Communications and Networking. Cambridge University Press, Cambridge (2012)

Jensen, C.B.: Virtual Ethnography and the Study of Partially Existing Objects: The Case of ICT4DEV (2006)

Jensen, C.B., Winthereik, B.R.: Monitoring Movements in Development Aid: Recursive Partnerships and Infrastructures. The MIT Press, Cambridge (2013)

Kester, J.: Conducting a Smarter Grid: reflecting in the power and security behind smart grids with Foucault. In: Beaulieu, S., De Wilde (Eds.) Smart Grids from a Global Perspective: Bridging Old and New Energy Systems. Springer, Berlin (2016)

Mackenzie, D.: An Engine, Not a Camera: How Financial Models Shape Markets. The MIT Press, Cambridge (2008)

Mark, D., Ostrowski, K., Tai, H.: McKinsey on smart grid (2010). http://sedc-coalition.eu/wp-content/uploads/2011/06/McKinsey-10-08-05-Smart-Grid-Benefits.pdf

Marvin, S., Graham, S., Guy, S.: Cities, regions and privatised utilities. Progress Plann. **51**(2), 91–165 (1999). doi:10.1016/S0305-9006(98)00028-2

Momoh, J.: Smart Grid: Fundamentals of Design and Analysis, 1st edn. Wiley-IEEE Press, Hoboken (2012)

Ngyen, B., Alkano, D., Scherpen, J.: The optimal control problem in smart energy grids. In: Beaulieu, S., De Wilde (Eds.) Smart Grids from a Global Perspective: Bridging Old and New Energy Systems. Springer, Berlin (2016)

Pollock, N., Williams, R.: The business of expectations: how promissory organizations shape technology and innovation. Soc. Stud. Sci. **40**(4), 525–548 (2010). doi:10.1177/0306312710362275

Schick, L., Winthereik, B.R.: Innovating relations—or why smart grid is not too complex for the public. Sci. Technol. Stud. **26**(3), 82 (2013) http://www.sciencetechnologystudies.org/v26n3Schick

Summerton, J.: Do electrons have politics? constructing user identities in swedish electricity. Sci. Technol. Human Values **29**(4), 486–511 (2004). doi:10.1177/0162243904264487

U.S. Department of Energy: Smart grid system report (2009) http://energy.gov/oe/downloads/2009-smart-grid-system-report-July-2009

USEF: An Introduction to the Universal Smart Energy Framework (USEF) (2014)

Van Kammen, J.: Do users matter? Users' involvement in the development of anti-fertility vaccines. University of Amsterdam (2000)

Van Lente, H.: Promising technology: the dynamics of expectations in technological developments. Eburon (1993)

Part II

Control and Regulation of Smart Grids: Technical, Legal, Economic, and Social Approaches

Cyber-Security Vulnerabilities: An Impediment Against Further Development of Smart Grid

Hassan Farhangi

Abstract This chapter discusses anomalies which may not be attributed to expected operational deviations and/or mishaps associated with component failure and/or environmental conditions. The question here is: what are known cyber-security vulnerabilities which could be used to aid in the detection of patterns and signatures associated with various types of attacks and intrusions in the system which need to be detected and analyzed using Smart Grid's sensory data, such as Smart meter's and/or PMU's data, to help differentiate between "cyber-attacks in progress" as opposed to "expected system anomalies" due to operational failures of its components?

1 Introduction to Smart Grid

The electrical network is a critical infrastructure with a significant level of risk where isolated incidents if not detected and mitigated rapidly can lead to cascading outages. A secure power delivery grid is required to sustain essential services, such as water, public security, transportation, etc. The extent of the power grid, different levels of access ranging from less accessible (e.g., the control center computers) to more accessible (e.g., smart meters) and the increasingly cyber-enabled technologies that are used multiply the probability and the nature of cyber-related risks.

The resulting cybersecurity threats will be with us for the foreseeable future so long as new functions, components and technologies penetrate our critical infrastructure. Research work of this nature will accelerate the modernization of Canada's

---

H. Farhangi (✉)
Smart Microgrid Applied Research Team, British Columbia Institute of Technology,
Burnaby, BC, Canada
e-mail: Hassan_Farhangi@bcit.ca

H. Farhangi
Simon Fraser University, Burnaby, BC, Canada

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_6

electricity grid and its evolution towards a secure, reliable, efficient and resilient critical infrastructure by creating technologies required to minimize the cybersecurity vulnerability barriers to its national roll-out. The knowledge gained through this project will help Canadian Utilities develop, validate and demonstrate mitigation solutions against potential terrorist attacks.

Smart Grid technologies allow utilities to improve the service offered to users and increase the power network efficiency. The utility industry has already embarked on infusing its network with technologies and components which generate substantial amount of sensory data and measurements about the status and health of various power system networks. For instance, in addition to automated metering, Smart Meters could be used to enhance power quality monitoring and management of various programs, such as demand response, load profiling and load shifting. Technologies such as Synchro Phasors, or PMU's (Phasor Measurement Units) could be used for automated tuning and configuration of transmission network's compensation and reliability assets.

All such technologies create an enormous amount of data which could be mined in real-time to gauge and measure the health and status of the system at any given point in time or in any required proximity and/or geography. At the same time, these are the very same networked and IP-enabled components which are the potential targets for cyber-attacks.

2 Smart Grid Vulnerabilities

While the Legacy Grid uses a wide variety of network and communication technologies, each with their own intrinsic vulnerabilities. The larger system as a whole enjoys layers of Air Gaps which protect the utility's service from external attacks and malicious intrusions. However, the move to introduce new layers of command and control, required by various Smart Grid technologies, tends to remove the Air Gaps. In other words, Smart Grid capabilities require the setup of new networks of sensors and data measurement technologies (e.g., AMI, PMU). Such technologies rely largely on wide-area integration of utility assets, with new sensing/control components using IP networks, which expose an already vulnerable system to more serious and dangerous attacks.

Of the two major overhauls of the existing grid, namely Advanced Metering Infrastructure and Smart Distribution Substations, the former exposes the utility to a wider set of attacks and intrusions compared to the latter. While the implication of successful attacks on the integrity and continuity of service is much larger in the case of the latter, the probability of attacks on the former is much larger simply due to the fact that Smart meters are designed to exist on the edge of the utility network, thus interfacing with a largely unprotected/uncontrollable customer-owned domain (called Home Area Network or HAN). In contrast, Distribution Substations, regardless of their level of automation and/or intelligence and independent of their close proximity to built-up areas of the city, are designed to reside within the safe haven of the utility network, interfacing on both sides with utility controlled assets and systems.

Although, HAN-based devices are currently limited in terms of variety and functionality, the prospect exists of such devices multiplying exponentially in the future and thus creating substantial new vulnerabilities for the system if unprotected. The issue is further compounded when one realizes that due to strict regulatory regimes in Europe and North America, utilities have very little control, if any, on what may reside beyond the periphery of their networks. Such components may include, but are not limited to Residential Energy Management Systems, Smart Thermostats, Smart Appliances, Electric Vehicle Charging Stations, customer-owned co-generation components, etc.

These new devices will be engaging the grid in a wide variety of energy transactions as well as data/command exchange. They may need to have access to utility generated real-time information such as consumption information, utility imposed tariffs, maximum demand ceilings, and pricing signals. In return they may send to the utility such information as ‘bids to sell electricity back to the grid’, their expected maximum demand, request for billing, request for service, etc.

Nevertheless, intrusions and attacks on the network, originated from compromised Smart Meters, will be limited to the feeder and/or the substation which connects to that particular meter. In other words, it would be highly unlikely that such attacks would have large cascading impact on utility grid’s upper layer networks simply due to the fact that the AMI system is not yet fully integrated into the command and control architecture of utility’s field components or substation equipment. Current AMI systems interface with the utility back office through a single point of integration, called Head-End System (HES), which is normally well-protected with adequate firewalls, key management and deep packet inspections (which is critical for stopping the movement of malicious codes from lower layers of the system to the enterprise bus). However, further lateral integration between AMI system and utility assets (e.g., at substation and field network level) could pose major security risk to the utility’s distribution network in the event of large scale coordinated attacks through the AMI network.

In contrast, Smart Substations are less prone to attacks from edge devices and components. Nevertheless, vulnerabilities associated with various layers of communication, command and control, which in totality constitutes a Smart Substation, could create major risk factors and vulnerabilities for Smart Grid. Attacks on Smart Substations through such security holes, although less probably compared to AMI, can have devastating consequences for the grid. In the remainder of this chapter I will focus on the AMI system and Smart Substations as the focus of utility’s current overhaul investments. I will examine the operational nature of such attacks, their perceived vulnerabilities, Use Cases and test platform setup.

3 Categorization of Smart Grid Vulnerabilities

There could be many cases in which components or subsystems of a Smart Grid could be subject to intrusion or unauthorized access. However, not all intrusions are created similarly. Given the fact that perfect security is hard to achieve, utilities have to be extremely strategic in terms of their investments in cyber security solutions for their assets.

Vulnerabilities could be compromised by a lot of different players with diverse intentions. As such, it is not justifiable for any utility to incur just about any cost to protect their system against any and all possible intrusions. A threat evaluation framework needs to be established by every entity, using which the utility can determine the impacts of various types of attack on their assets, services and infrastructure and thereby establish which attacks they could possibly live with and which ones need to be stopped at all costs. Work done in this area, available in the public domain, suggests the Threat-Evaluation Framework to be based on the following three attributes in reverse order of importance (from least critical to most serious):

1. *Confidentiality*: Exposure of system's confidential information, or those of its users, are exposed to unauthorized access.
2. *Availability*: Unplanned and unscheduled unavailability of whole or part of the system for use as a result of an intrusion or attack. In other words, whole or part of the system stops responding to Request for Service signals from other system components for certain periods which may vary according to their functionality.
3. *Integrity*: System functionality to be compromised, resulting in its deliverables (data or commands) to other parts of the system to be regarded as untrustworthy.

It should be noted that "Denial of Service" attacks on various components could seriously jeopardize the system integrity if:

- Synchro Phasor Data are unavailable for a period more than micro seconds
- Protection Relays are unavailable for a period more than milliseconds
- Wide Area Monitoring is unavailable for a period more than sub-seconds
- SCADA System is unavailable for a period more than seconds
- Pricing Signals are unavailable for a period more than minutes
- Consumption Data are unavailable for a period more than hours
- Service Quality Data are unavailable for a period more than days

4 Vulnerabilities Associated with Smart Substations

An important technology used in existing utility substations is SCADA: Supervisory Control And Data Acquisition. SCADA is a term used to describe a collection of components, subsystems, communication channels, etc. tasked with measurements, monitoring and control of field devices within the utility network. The data measure and its monitoring from field devices are transferred to a data aggregation point, commonly called a RTU (Remote Terminal Unit), which could be accessed from the utility's control center through a wide variety of communication channels, including Plain Old Telephone System (POTS), Microwaves and Satellites.

Decisions made at the control center are based on the data captured and communicated by the SCADA system. The Control Centre's decisions are made by operators on the basis of system status demonstrated by SCADA data. As such, the integrity of SCADA data is paramount in enabling System Operators take the right decisions and make the right choices. Nevertheless, vulnerabilities associated with SCADA are not rare. As an example, the following are known SCADA vulnerabilities, which utilities are concerned about:

- *Operating System/Applications Trap Doors*: These are undocumented entry points into OS or software applications often created by vendors during development and/or validation phases which should be removed prior to product shipments, failing which such trap doors provide hackers with unimpeded access to the inner core of the affected applications.
- *Inadequate Access Control*: Absence of Security hardened checks and balances in the access privileges assigned to different staff, who may be using default values for such access authorizations, makes it easy for hackers to guess such passwords and illegally enter the system through repeated trials of known default passwords.
- *Denial of Service*: Attempt to exhaust system resources though massive access requests.
- *Inadequate Firewalls*: Wrong set of rules or configurations of firewalls, allowing intruders to get past these devices at will.
- *Network Configurations*: Unsecured ports and entry points, allowing intruders to neutralize firewalls and gain access to inner parts of the system.
- *Vulnerable Communication Protocols*: Legacy communication protocols with known cybersecurity vulnerabilities, such as DNP3.

5 Vulnerabilities Associated with the AMI System

Advanced Metering Infrastructure (AMI) is one of the first Smart Grid technologies implemented by various utilities across the globe. AMI incorporates two-way communication systems into the mainstream consumption metering technologies. Using AMI the utilities can have a real-time view of the load they would have to serve and can also change their service attributes without physical access to the meters in the field. As such, remote access and real-time control constitutes an essential part of the AMI system. Those are the exact features which, if poorly protected, would lend themselves to malicious tamper, intrusion and cyber-attacks.

This section provides an overview of AMI system topology, system functions and vulnerabilities associated with AMI systems in general.

5.1 Advanced Metering Infrastructure

As Fig. 1 demonstrates, the AMI system comprises of precision measurement devices, also known as Smart Meters, and their associated communication systems. Given the AMI system's role as the interface between the service provider (i.e., the electric utility) and their customer (electric loads), it is obvious that Smart Meters can no longer be a simple measurement device. They are rather a gateway between the utility's back-office tools and consumer's appliances.

Having said that, this end-to-end approach (i.e., power plant to power plug) is nowhere implemented in the developed world. Here regulatory regimes do not allow the utility to have any control over customer loads which reside in the customer's domain. This means that out of the two communication systems indicated in Fig. 1, one facing upstream towards the utility domain and the other facing downstream towards customers' Home Area Network (HAN), only the upstream channel is activated and protected. Later on, we will see how the downstream communication channel could potentially be used as a backdoor to attack the AMI system.

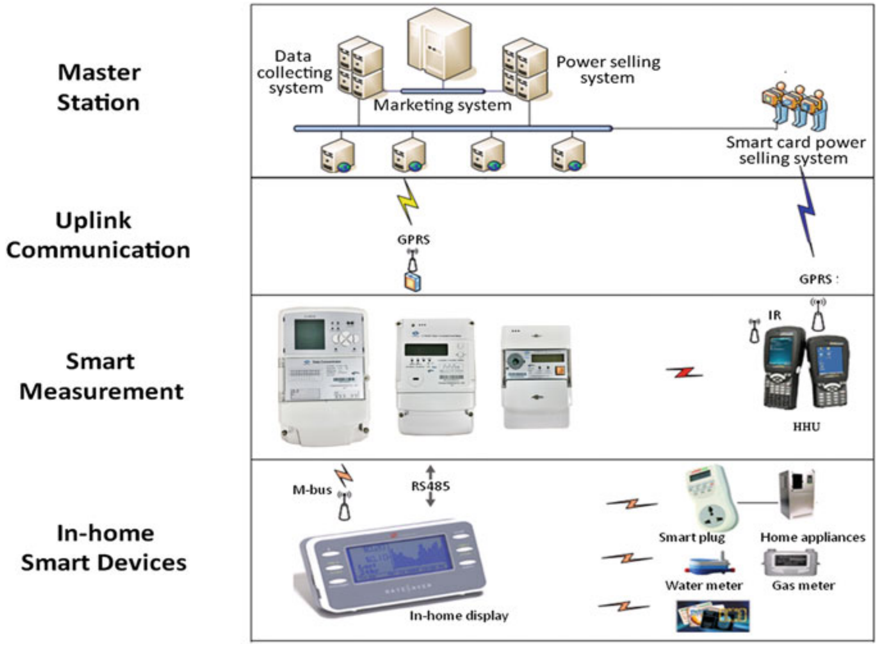


Fig. 1 Simplified AMI system topology (*courtesy* Linyang)

In addition to communication systems, Fig. 1 identifies such other functions as Metering Data Management System (MDMS) as constituent components of the AMI system. MDMS resides on the utility back-office enterprise bus and is well-protected. In fact MDMS is the AMI system interface with the rest of utility assets and infrastructure.

5.2 AMI System Topology

Figure 2 shows a much more realistic view of current implementation of AMI systems across the world. One can immediately see that given the diversity of consumers (residential, commercial and industrial) and the multitude of urban, suburban and remote service areas which the utility system has to serve, many types of metering devices, communication technologies and networks need to co-exist and be tightly integrated into a single AMI system.

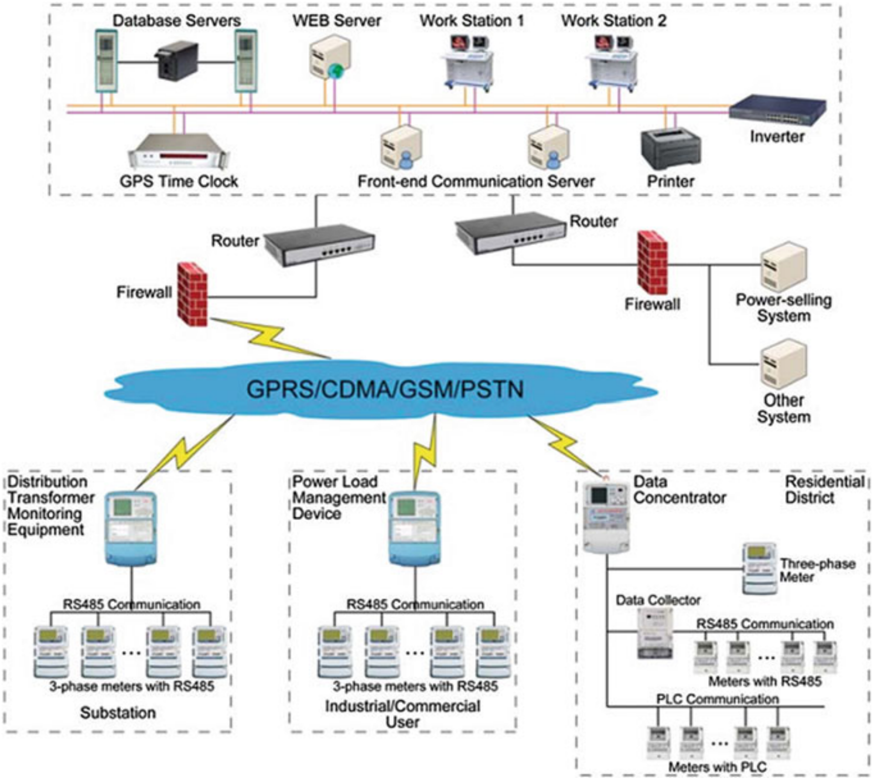


Fig. 2 Mainstream AMI system topology (*courtesy* Linyang)

Moreover, the fact that no single standard or protocol exists to facilitate and realize such complex integration among so many diverse components and technologies, one can see that the AMI system could potentially be one of the most vulnerable components of the Smart Grid system. The fact that AMI systems reside on the edge of the utility network, and therefore are in close proximity to non-utility controlled domains, makes cyber protection of AMI assets more difficult and challenging.

Given the critical issues utilities are facing in terms of cyber protection of seemingly disjoint systems, each with their own standards, communication protocols and security regimes, the mainstream industry is focusing on dividing the AMI cybersecurity issues into its constituent domains. In other words, each domain is protected differently, and based on the sensitivity and criticality of the role they play in advancing AMI functionality.

5.3 AMI Network Domains

Due to the complexity of AMI command and control requirements it became obvious in the early days of the AMI system developments that no single network domain could be defined to incorporate all functions which an AMI system is expected to deliver. As such, the AMI functions were categorized as those related to configuration/programming, consumption measurements and load control.

In face of the regulatory constraints for direct load control, provisions related to such control were assumed to be housed within customer's HAN which is outside the utility's reach by definition. Instead, indirect load control was realized through pricing signals, time-of-use tariffs and maximum demand controls. Figure 3

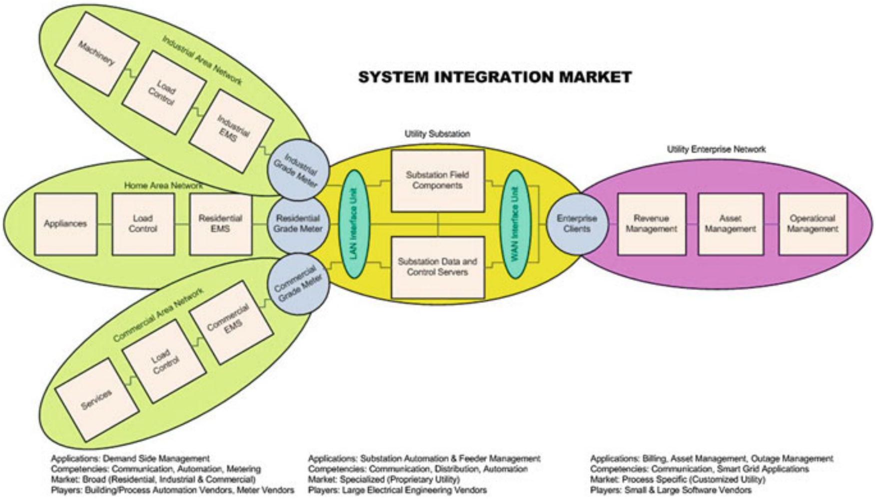


Fig. 3 AMI integrated network domains

embodies this domain segmentation approach in which different customers with different requirements are each bundled in their own domain (designated as HAN), while the meters exist on a separate network (designated as LAN), and the utility back-office having its own fully secured and firewalled domain on the enterprise bus.

5.4 *Cyber Threats Impacting AMI Systems*

Given the state of AMI system development and the degree of its integration with upstream Smart Grid functions, the consumption/sensory data produced by AMI components have not found their rightful application in utility's Field Area Networks (FAN). In other words, the utility's field assets do not yet have a critical need for having real-time access to AMI data. Figure 4 demonstrates that the mainstream implementation of AMI systems across the globe routes AMI data directly through an aggregation device to the utility's back-office where the AMI MDMS system resides. Traditionally, the utility's enterprise bus is well protected using state-of-the-art firewalls and security provisions. Nevertheless, certain AMI functions and tasks may lend themselves to intrusions and attacks, thus putting the integrity of the entire system in jeopardy.

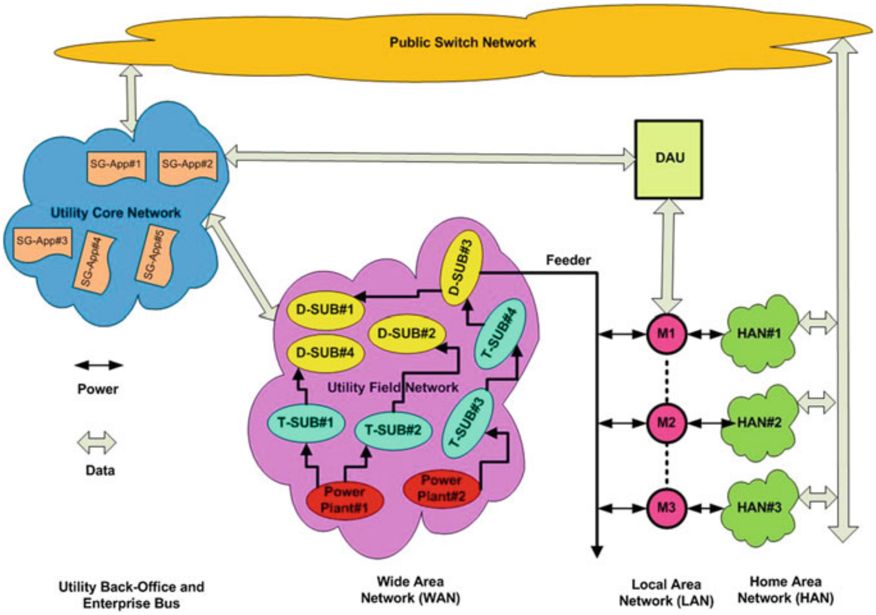


Fig. 4 Mainstream AMI implementations

Numerous vulnerabilities could be identified which could be exploited to attack an AMI system. Here I will discuss the nature of such threats and the mechanics of their occurrence, while the next section shall deal with their potential impact on the integrity of the AMI system and its constituent functions.

Vulnerabilities inherent in the AMI system could loosely be categorized as those which are intrinsic in AMI communication systems, those which are inherent to the AMI system's physical security, and last but not least those related to data/command exchange protocols which AMI system is built upon. Some of the threats which have their roots in multitudes of aforementioned vulnerabilities are:

- *Eavesdrop*: Unauthorized real-time interception of AMI communications between different nodes within the AMI system with the intention of stealing data.
- *Intercept/Alter*: Unauthorized real-time interception of AMI communications between different nodes within the AMI system with the intention of changing data.
- *Masquerade*: Unauthorized access to AMI data by pretending to be a legitimate user.
- *Man-in-the-middle*: Inserting oneself in the middle of a legitimate exchange of data/command between two authorized users of the AMI system without either party noticing that they are directly talking to each other.
- *Record/Replay*: Subsequent to a man-in-the-middle attack, recorded transactions could be replayed at a later point in time for a legitimate user with the intention of forcing the receiving party to execute certain commands which the system is not prepared for.
- *Malicious Code Insertion*: Subsequent to a man-in-the-middle attack, recorded transactions could be replayed at a later point in time, laced with malicious codes, for a legitimate user with the intention of forcing the receiving party to facilitate the transport of those codes to upstream layers of the system without being detected.
- *Denial of Service*: Directing massive queries at various entry points of the AMI system with the intention of exhausting system resources and thus disabling the system entirely.
- Other physical vulnerabilities associated with the AMI system's absence of security provisions for certain components include, but are not limited to Optical Port, Zigbee Radios, Bluetooth radios and WiFi radios.

In addition to the above, no standard security provisions are prescribed for Home Area Networks. As such, devices and appliances operating within HAN could be the source of potential attacks on the AMI system. Nevertheless, given the fact that currently there is no planned integration between HAN and Smart Meters such vulnerabilities may not be a critical issue.

Nevertheless, Residential Energy Management Systems are appearing on the horizon. Such systems require real-time access to certain data which Smart Meters produce (e.g., consumption data) or attributes which Smart Meters have access to (e.g., tariffs). In that case, Smart Meters have to include a DMZ (a demilitarized zone) where such data could safely be shared with HAN-stationed devices and functions.

5.5 *AMI Cybersecurity Provisions*

Because of the nature of threats against AMI systems Smart Meters attempt to protect their functions at two different levels: the access layer and the transport layer. Figure 5 demonstrates that the security provisions in Smart Meters focus on ensuring that only authorized users gain access to the system, as well as on protecting the transactions they engage in through an encryption system. In other words, access to the system is only made available to those users, nodes and devices that are authenticated through a series of system queries, with escalating complexity, as legitimate users. Moreover, given the different roles and requirements which different users may have, the system is designed to provide different modes of privileged access to different users based on a pre-determined access level.

To protect the data/command transactions at the transport layer a complicated system of key-management is used to ensure proper encryption and decryption at both ends. Figure 6 depicts the key management system implemented in the mainstream smart metering industry. Here a set of public and private keys are exchanged between different nodes, whose legitimacy has been verified through a system of pre-registration and authentication of such nodes. Some keys are basically used to facilitate the real-time production and exchange of other keys. Key management system is evolving and as such is becoming one of the major provisions in the AMI system to ensure protection of access as well as AMI system transactions.

It should be mentioned that, given the resource constraints of most Smart Meters, more stringent security provisions which require access to higher levels of computing and storage resources may not be feasible to be implemented by Smart Meters. Instead, such provisions are normally realized in the links between the Data Aggregator Units (DAU) and the upper layer system on the utility enterprise bus.

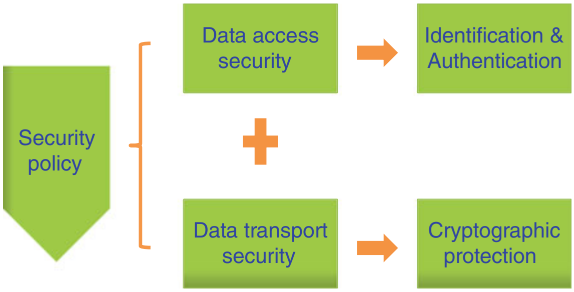


Fig. 5 AMI Cybersecurity provision (*courtesy* Linyang)

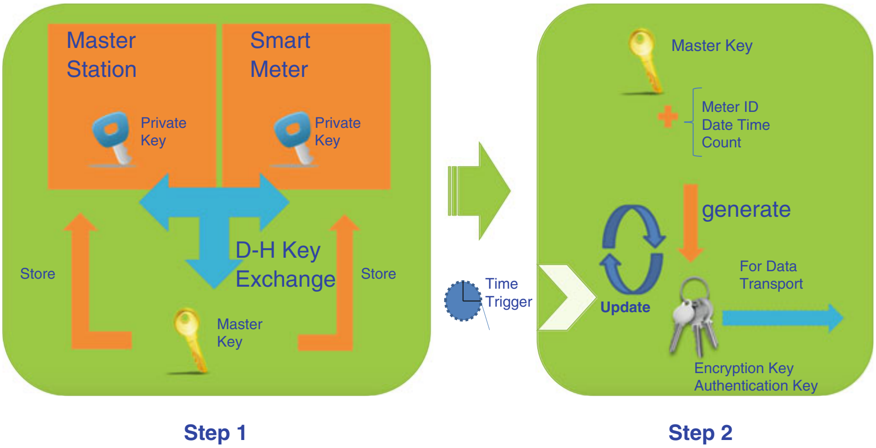


Fig. 6 AMI key management (*courtesy* Linyang)

6 Suitability of Microgrid as a Testbed for Cybersecurity

Governments across the globe acknowledge that future wars could be fought in the cyberspace, rather than in the conventional theatres. As such, efforts are under way across North America to understand the dynamics of such wars, the way they may be waged, and mitigation strategies and solutions each nation and/or entity should adopt to counter it.

It is not far-fetched to see the need for sovereign states on all sides of the globe to dedicate specialized resources and assets to simulate such attacks, while devising counter-attack strategies and solutions to minimize the impact of such attacks on their critical infrastructure. In this tug of war, it would be logical to see opposing parties developing all types of ammunitions, attack scenarios, defensive postures and counter-attacks. Moreover, given the critical role that the electric grid plays in supporting and sustaining economic activities and life in developed nations, it is a given that the electricity grid in every country will be the highest value target for cyber-attacks.

To develop, validate and qualify national defences against such attacks one can see that a sufficiently scaled up replica of the electricity grid (or a Microgrid) is required where such controlled experimentations, attacks and validation could take place.

6.1 Overview of BCIT Microgrid

The British Columbia Institute of Technology (BCIT) Smart Microgrid is located at BCIT Burnaby Campus in B.C, Canada which is one of the largest well-equipped post-secondary campuses in Vancouver, Canada. In partnership with BC Hydro (BC's largest utility company), BCIT has designed and developed a Smart Microgrid to provide electrical utility companies, technology providers, researchers and academics a living-lab environment for the development, validation and qualification of technologies, architectures, protocols, configurations and operations of the evolving Smart Grids.

BCIT's Burnaby Campus consists of over fifty buildings such as campus houses, classrooms, administration buildings, workshops, food outlets, students' services and dormitories. Moreover, the campus includes different types of power plants including thermal, PV arrays and wind turbine. There is also a smart house which functions as a Nano-grid. The scale and the diversity of activities at BCIT Burnaby campus has created electrical consumption profiles ranging from heavy industrial for instructional purposes, to office type consumption in classrooms along with a residential-type profile in dormitories.

BCIT's Smart Microgrid, as depicted in Fig. 7, was designed as a convergence platform where communication technologies, smart control, co-generation and information technology were integrated to develop solutions, validate technologies, and accelerate the commercialization of technologies and architectures for the Smart Grid. End customers, government agencies, leading technology providers, research institutes and universities worked closely together to develop a state-of-the-art Smart Microgrid, and enable researchers and stakeholders to collaborate in production and commercialization of needed technologies for future Smart Grids.

BCIT Microgrid has delivered a real-time Smart Grid platform that models commercial, industrial and residential loads. Smart Meters are able to measure consumption parameters (e.g., active power, reactive power, voltage, current, demand, etc.) with high precision and accuracy through implemented AMI. Smart Meters are secure and capable of storing the required data for a number of billing cycles.

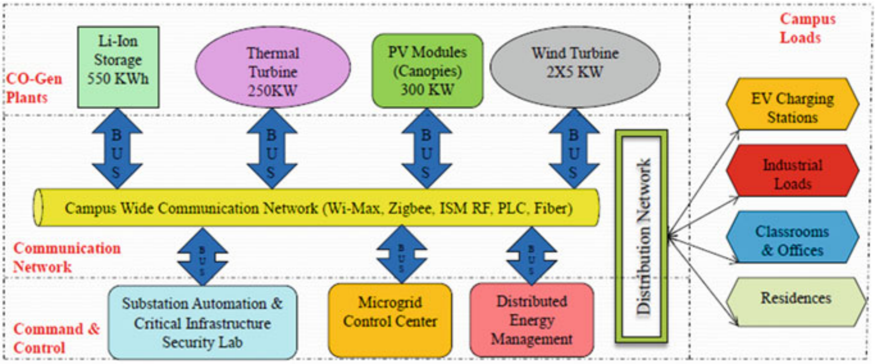


Fig. 7 BCIT Smart Microgrid architecture

Other features of BCIT smart metering system include: Assigning a budget to drive change through cost accountability; implementing behavioural change campaigns; improve reporting granularity; identifying high energy users (opportunities); benchmarking and prioritizing energy saving regions; creating simple awareness and external exposure; and providing building operator alarms and supporting full building continuous re-commissioning. In BCIT Microgrid, Smart Meters are installed in various buildings and on some target loads to be monitored:

- Technologies adopted based on environments challenges (e.g., PLC)
- Different MDMS are integrated under utility EMS
- Reliability of technologies are checked
- Sub-metering systems installed: NE1 Main Bus-work, NE1 Chiller, NE1 Elevator, NE3—AFRESH Home, NW6—CNC Machine 1, NW6—CNC Machine 2 and NE8
- Special category of meters in NE2 Joinery and NE4 Carpentry for PLC Meters to test communication in 'noisy' environment

Student Residences Metering allowed real-time meter reading for residential part of campus. Currently, there is one meter per house installed by BCIT TC staff. Moreover, there are three empty meter sockets available per house for future needs. Utilities eagerly are interested in interference issues regarding Zigbee meters in dense urban settings. BCIT smart metering infrastructure were developed and installed by the Smart Applied Research Team (SMART). SMART has worked with Tantalus Systems Corp. (Tantalus) to provide RF wireless network for Smart Microgrid smart meters.

BCIT Energy Management System (EMS) is able to collect data from smart meters, measure power generation, perform data modelling and analysis, monitor operating sensors, reduce electrical consumption, react to pricing signals and demand response, implement communication standards from NIST, IEC, ANSI, EPRI, ASHRAE, etc. and be presented by web-based portals. BCIT has also an EMS Residence Portal designed to increase awareness of electrical consumption.

The main target for the EMS residence portal is to reduce consumption by modifying consumer behaviour. Portal design was based on social science research. In the energy management program consumers became sensitive to how they were conserving energy compared with their neighbours. Hence, the main focus of utilizing residential energy management portal was to empower consumers to make the right energy saving decisions.

The BCIT Advanced Metering Infrastructure (AMI) system is able to measure, collect and analyze energy consumption, and to communicate with other metering components such as smart electricity meters, gas meters, heat meters and water meters. The AMI consists of hardware, software, aggregators, communications, energy displays and controllers, customer associated systems and MDMS. The BCIT Intelligent Micro Grid Network integrates the following components in a meshed network:

- Smart Meters, that measure several consumption parameters (e.g., active power, reactive power, voltage, current, demand)
- In-Home-Units, to measure consumption and display simply for end-users
- Communication Modules, provide meters communicating with other meters, or with data aggregators
- Access-Networking Middleware, to secure meshed network setup and management
- Data Aggregator Unit (DAU) to exert command and control over a meshed network of slave components (the Aggregator has access to all nodes)
- Load Control, to control smart appliances to monitor and adjust their performance and service level according to user and/or utility needs.

The BCIT AMI system provides data to the EMS and other Microgrid functions such as Demand Response. It is possible to collect data of Microgrid loads through BCIT AMI every 15 min or even every 5 min for different purposes.

6.2 The BCIT Microgrid as a Cyberwar Theatre

Given the critical role that cybersecurity plays in advancing or hampering the rollout of Smart Grid in North America, the Canadian Safety and Security Program (CSSP), has been established to strengthen Canada's ability to anticipate, prevent, mitigate, prepare for, respond to, and recover from natural disasters, serious accidents, crime, and terrorism through the convergence of science and technology (S&T) with policy, operations, and intelligence.

The CSSP is led by Defence Research and Development Canada's Centre for Security Science (DRDC CSS), in partnership with Public Safety Canada, which provides security and public safety policy guidance to the program. The CSSP supports federal, provincial, or municipal government-led projects in collaboration with response and emergency management organizations, non-governmental agencies, industry, and academia. Under guidance and funding from DRDC's CSSP program, BCIT has been working closely with its stakeholders in government and the private sector, in conducting focussed research in the area of smart grid cybersecurity with the following strategic objectives:

- Reducing inherent vulnerability of Smart Grid components and protocols
- Minimizing the impact of cyber intrusions and attacks on Critical Infrastructure
- Creating multiple lines of defense against Cyber Attacks across the system
- Developing systemwide deterrence strategies and continuously validating and upgrading the potency of solutions against new attacks

Given the multitude of approaches, projects and developments one can pursue in the area of smart grid cyber security, we have so far utilized the test setup depicted in Fig. 8 to focus on the following broad cybersecurity projects:

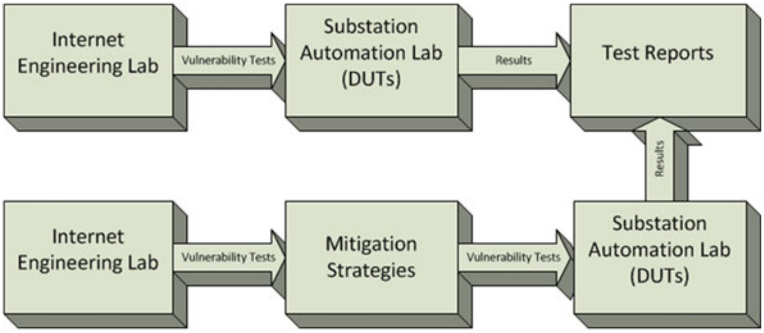


Fig. 8 The BCIT Cybersecurity test setup

- Tampering with pricing signals, causing rapid demand changes, causing feeder failures or generation system imbalance
- Tampering with AMI communication links
- Emulating changing Substation assets parameters (VVO, CB, VR, etc.) causing substation shutdown and domino failures
- Attacking Control Centre HMI—often Windows or Linux machines with inherent security vulnerabilities
- Intruding into LTE—hacking, spoofing, injecting viruses, attacking DoS
- Intruding into WiMAX—jamming, interference, rogue base stations, protocol fuzzing, spoofed management frames

We have also focussed on identifying potential IEC 61850 and ANSI C12.22 vulnerabilities and conducted theoretical and experimental studies to identify major vulnerabilities with these standards. The test setup allows attacks to be initiated from nodes within one lab with targets in the field or in other Microgrid labs.

7 Conclusion

Research into cybersecurity is a never-ending exercise. As one delves deeper and deeper into the vulnerabilities associated with smart grid technologies, standards, protocols and architectures, one realizes that counter efforts with equal intensity and vigour are being conducted by the entities on the other side to find more exploits, manipulate more vulnerabilities and develop more potent attack scenarios on our critical infrastructure. That clearly means that we have to be in this for the long haul, deepening our understanding of the shortcomings of our defences, develop more potent mitigation solutions and conduct continuos tests, experimentation and simulation of such attacks to measure the potency of our defences and our strategies. The more investment, resources and efforts one may put in this area, the less would be the likelihood of being vulnerable to crippling cyber attacks on our critical infrastructure, way of life and economy.

Points for Discussion

- What do you think of the hierarchy of threats in the chapter? For whom does this hierarchy make most sense? Would other actors have different priorities, or even different risks?
- Cyber attacks between nations could also focus on electricity infrastructure. In the context of a roll out of smart grids, would this increase or decrease vulnerability to cyber-attacks?
- Besides technical solutions, which other means are there to make smart grids less vulnerable, i.e., the role of the government and regulators, legislation, etc.?
- Are we able to put in regulations, such that privacy is taken care of, and can this be partly implemented by software?

Further Readings

Gauci, A., Giarratano, D., Pathania, S.: A Framework for Developing and Evaluating Utility Substation Cyber Security. Schneider Electric

Hahn, A., Govindarasu, M., Liu, C.C.: Vulnerability assessment for substation automation systems. Iowa State University

Lopez, C., Sargolzaei, A., Santana, H., Huerta, C.: Smart grid cyber security: An overview of threats and countermeasures. Florida International University

Smart grid cyber security potential threats, vulnerabilities and risks. California Energy Commission, May 2012

Sridhar, S., Hahn, A., Govindarasu, M.: Cyber-physical system security for the electric power grid. Iowa State University

The Optimal Control Problem in Smart Energy Grids

D. Bao Nguyen, Desti Alkano and Jacquelien M.A. Scherpen

Abstract This chapter addresses the balancing problem that arises in smart energy grids. Because power generation from renewable energy resources is tied to environmental factors, supply is often fluctuating and decentralised. Minimising the imbalance between supply and demand is important for grid stability, as well as for economic considerations. Flexible appliances propose a means to achieve supply-demand matching by shifting their production or consumption in time. We take a distributed optimal control point of view: we formulate the problem as an optimal control problem and suggest solutions based on distributed model predictive control (MPC) methods. In particular, we aim to minimise the imbalance using demand response regulation and via Power-to-Gas facilities that offer energy storage. Furthermore, we discuss how demand response regulation can be embedded in the market structure of the Universal Smart Energy Framework. We present example simulations to demonstrate the viability of our approaches.

1 Introduction

Modern society is driven by energy, and in particular, electricity. Electronic devices, such as personal computers or mobile phones, have become an integral part of our everyday lives and the large-scale introduction of electric vehicles will only

---

D.B. Nguyen (✉) · D. Alkano · J.M.A. Scherpen
Jan C. Willems Center for Systems and Control, Engineering and Technology institute Groningen (ENTEG), Faculty of Mathematics and Natural Sciences, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands
e-mail: d.b.nguyen@rug.nl

D. Alkano
e-mail: d.alkano@rug.nl

J.M.A. Scherpen
e-mail: j.m.a.scherpen@rug.nl

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_7

further bolster the demand for electricity. Current power generation is mainly based on fossil fuel, but growing environmental awareness has triggered the transition towards renewable energy resources and smart grids.

Energy sources like wind or solar energy are characterised by intermittency: the production heavily depends on weather conditions, leading to large fluctuations in supply. Furthermore, generation from these resources is decentralised, as windmills and solar panels are often located in different geographical areas.

In existing grids a few, large power plants supply the electricity to the network, but photovoltaic cells and μCHP (micro combined heat and power) devices will allow end-users, who were traditionally consumers, to become producers themselves as well. μCHPs can produce heat and electricity simultaneously, and are small enough to fit in a household. With the introduction of the so-called prosumers, the grid will become bi-directional, however, current transmission lines were not designed to handle such demands.

The need to accommodate the fluctuating, decentralised generation while avoiding transmission line overloads creates a balancing problem between supply and demand. To overcome this challenge, smart grids utilise the power of flexible appliances that can shift their load and thus change their electricity production or consumption in time. The contribution to the balancing problem from the end-user side is generally referred to as demand response.

In this chapter we present our approach to supply-demand matching from a control theoretical perspective. We use an optimal control setting, i.e., an optimisation criterion, such as imbalance minimisation, is solved while taking the system dynamics into account. When additional constraints are imposed, and when uncertainty in the signals (for example, in the future demand signals) play an important role, the optimisation problem can be recasted as a model predictive control (MPC) problem. MPC is a real-time optimisation method in which at every time-step the signals are updated to their real values, making it possible to handle uncertain predictions and to obey the constraints. The method was originally formulated for centralised problems (Maciejowski 2002), but recently it has also been developed for distributed systems (Giselsson and Rantzer 2014). This allows us to use the framework in the decentralised generation case. Two solutions to the supply-demand matching problem are proposed, both in the distributed MPC framework: the first is demand response regulation, the second is energy storage using Power-to-Gas facilities.

The rest of the chapter is organised as follows. We review the basic concepts of optimal control theory in Sect. 2, and elaborate on the balancing problem in Sect. 3. Section 4 introduces the Universal Smart Energy Framework (USEF), a new market structure for energy grids in the Netherlands. We show how to embed demand response regulation in that structure. We end with our conclusions in Sect. 5.

2 Preliminaries

We first give a brief, conceptual overview of control systems that form the basis of our solutions to be discussed in the rest of the chapter. For a more in-depth and technical understanding, we refer to standard textbooks such as Åström and Murray (2008), Maciejowski (2002).

Control theory lies in the intersection of mathematics and engineering; it studies dynamical systems that are interconnected with their environment through appropriately defined inputs and outputs. The objective is then to design a controller that steers the output to a desired value, based on measurements on the system. Figure 1 shows the block diagram of a typical control system. The system model is either known a priori (e.g., from physical laws) or obtained through system identification methods, and is often described in the form of difference equations

$$\begin{aligned} x[k+1] &= \mathbf{A}x[k] + \mathbf{B}u[k] + w[k] \\ y[k] &= \mathbf{C}x[k], \end{aligned}$$

where $k \in \mathbb{Z}$ is the discrete time-step, $x[k]$ is the variable (vector) representing the state of the system, $u[k]$ is the control input, $y[k]$ is the output, and $w[k]$ is some external disturbance. $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{C}$ are the system, input, and output matrices, respectively. For example, let's say we want to heat up our living room in a cold evening. Assuming that the dynamics of the temperature in the room is known (i.e., the system model is given), the thermostat turns on the furnace to attain the desired temperature. The thermostat also monitors the actual temperature in the room to make any adjustments necessary.

Naturally, there can be multiple possible solutions to the problem (think of the different temperature settings the furnace can have). Different solutions are associated with different performances, so in order to choose the preferred solution, one can define a cost $L(x[k], u[k])$ that measures the performance. Furthermore, constraints (both inequality and equality) on the states and inputs can be added to

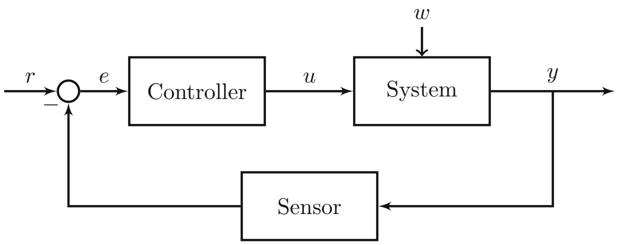


Fig. 1 Feedback control loop. The measurement of output y is subtracted from the reference signal r, resulting in the error signal e. The controller uses this error signal to determine the next control input u, with the goal of minimising the error, and consequently bringing the output to its desired value. External disturbances that act on the system are captured in w

bound the solutions to certain criteria. The so-called optimal control problem is then mathematically formulated as

$$\begin{aligned} \text{minimise} \quad & \sum_{k \in \mathcal{K}} L(x[k], u[k]) \\ \text{subject to} \quad & x[k+1] = \mathbf{A}x[k] + \mathbf{B}u[k] + w[k], \\ & F(x[k], u[k]) \leq 0, \\ & G(x[k], u[k]) = 0, \end{aligned}$$

with $\mathcal{K}$ being the time interval, and F and G are constraint functions. For simplicity, we assume that the output is the full state, $y[k] = x[k]$. Note, that we can always write the constraints in the form where the right-hand side is 0. Sometimes it is more practical to define a utility function instead of a cost, in that case the problem at hand is to maximise the utility. By introducing the cost and constraints it is possible to optimise the solution to best suit our requirements. Going back to the thermostat example, the cost can be the time span the furnace is on or its gas or electricity consumption. Accordingly, the optimal control problem is to find the fastest or the most energy efficient way to warm the room up. The maximum heat output of the furnace is a constraint (without this constraint the minimum time optimisation would require the furnace to provide infinitely hot temperature).

Model predictive control [MPC, also known as receding horizon control in the literature, (Maciejowski 2002)] is an iterative optimal control method that is widely popular in process control applications. In MPC, a prediction model (which is often the same as the system model) is used to solve the optimisation problem over a certain time period in the future, called the prediction horizon. However, from the resulting sequence of inputs, only the first one is applied to the system. The optimisation process is then repeated again with new measurements of the updated system, hence the name receding horizon (see Fig. 2). The main advantage of MPC rests in the receding horizon principle: it allows predicted future events to be taken into account. Moreover, it enables the elegant handling of constraints.

Although MPC generally yields very good results, because of the real-time calculation of the optimal control inputs, the method can become computationally expensive as the number of states grow. To avoid this, we split the system into smaller subsystems. The idea is that each subsystem only solves its own, much simpler subproblem, and by iterating and communicating the results to their peers, together they arrive to the solution of the original problem. The distributed structure conforms the decentralised nature of renewable power generation, moreover, it also improves the robustness of the system. Decentralisation is achieved via a dual decomposition technique (Boyd and Vandenberghe 2004; Rantzer 2009), which gives exact solutions under convexity assumptions. It introduces the Lagrange-multipliers that are iteratively updated by a subgradient process, and are commonly interpreted as shadow prices (Starrett 2000). Dual decomposition was developed for the MPC setting in Giselsson and Rantzer (2014), Larsen et al. (2013, 2014a).

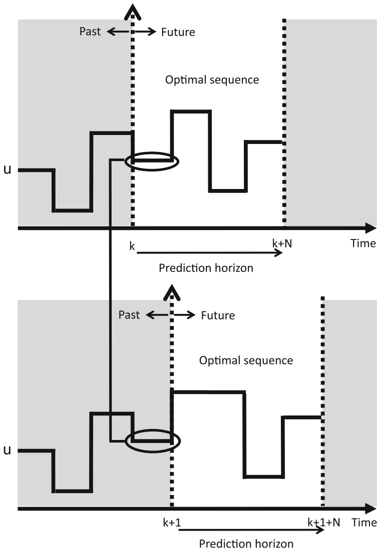


Fig. 2 The receding horizon principle. The optimal control input sequence is calculated over the prediction horizon *N*, but only the first sample is implemented. Afterwards, the optimisation process is restarted over the shifted prediction horizon

3 Supply–Demand Matching

As mentioned earlier, smart grids are facing with the supply-demand matching problem due to the nature of power production from renewable energy resources. Household devices are designed to operate at nominal frequency levels (50 Hz in the Netherlands), however, the frequency drops when power supply is lower than demand, and conversely, it rises when demand is lower than supply. Supply-demand matching is therefore crucial to ensure the stability of frequency in the grid.

Active participation of the end-users in the balancing process (demand response) is enabled by flexible appliances. Consider the case of electric vehicles. The owner typically wants to charge the vehicle at night to use it the next day, but when exactly it is charged is not important. The only concern is that the vehicle should be fully charged by morning and therefore its electricity demand can be moved around to match the available supply. If there is a large number of electric vehicles in the neighbourhood, their combined flexibility can be used to optimise the performance of the grid. Other potential flexible devices include washing machines (Larsen et al. 2013), refrigerators, and heat pumps. It is useful to distinguish between flexible consumption (e.g., the previous examples), flexible production (e.g., μCHPs—micro combined heat and power systems), fixed consumption (e.g., TVs), and fixed production (e.g., solar panels).

With the availability of new gas sources, similar flexibilities can be of interest for the gas grid. Farmers who produce biogas from agricultural wastes can utilise special household appliances that can reliably and safely consume biogas. Relying on the fact that the gas grid has a broader tolerance for fluctuation than the power grid, the flexibilities in the gas grid are not directly used to minimise the imbalance between supply and demand. The produced biogas can create as much revenue as possible by upgrading it to green gas, and then injecting the green gas into the low pressure gas grid or selling it to a gas filling station later on. In Alkano et al. (2014), we develop the optimal control problem for such setting.

3.1 Demand Response Regulation

One way to achieve demand response is to control the flexible devices of the households, both on the production and the consumption side. We thus address the problem of minimising the overall imbalance (between supply and demand) in a network of households by utilising flexibility in a cooperative manner. Because the households are assumed to be able to produce electricity on their own, we refer to them as prosumers.

Let $f_i[k]$ be the flexible, $g_i[k]$ the fixed load of prosumer $i \in I$ at discrete time-step k, I being the set of prosumers. We call load the sum of supply (production) and demand (consumption), with the convention of using positive sign for supply and negative for demand. The imbalance of a prosumer, denoted by $\tilde{x}_i[k]$, is the sum of its net flexible and net fixed load,

$$\tilde{x}_i[k] = f_i[k] + g_i[k]. \tag{1}$$

Consequently, the evolution of imbalance can be described by the equation

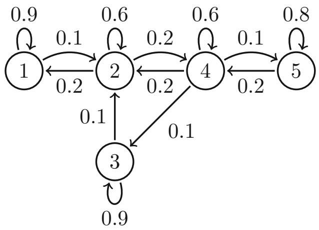
$$\tilde{x}_i[k+1] = \tilde{x}_i[k] + u_i[k] + w_i[k],$$

where $u_i[k] = f_i[k+1] - f_i[k]$ is the change in flexible, $w_i[k] = g_i[k+1] - g_i[k]$ is the change in fixed load.

The prosumers are dynamically linked in order to exchange information. We introduce an information sharing model (Larsen et al. 2014b) to provide the coupling: the network is represented by a weighted, directed graph, in which an existing edge (i,j) means that information is sent from prosumer j to prosumer i. The weight on the edge characterises the importance of the shared information. To incorporate the model, the imbalance dynamics is extended to

$$x_i[k+1] = A_{ii}x_i[k] + \sum_{j \neq i} A_{ij}x_j[k] + u_i[k] + w_i[k]. \tag{2}$$

Note, that here we omit the tilde notation, as $x_i[k]$ is no longer the physical imbalance but rather information about imbalance. The difference is that the latter is a weighted accumulation of the self-imbalance and the imbalances of the connected



$$\mathbf{A} = \begin{pmatrix} 0.9 & 0.2 & 0 & 0 & 0 \\ 0.1 & 0.6 & 0.1 & 0.2 & 0 \\ 0 & 0 & 0.9 & 0.1 & 0 \\ 0 & 0.2 & 0 & 0.6 & 0.2 \\ 0 & 0 & 0 & 0.1 & 0.8 \end{pmatrix}$$

Fig. 3 Example network consisting of 5 prosumers. The nodes represent the prosumers and outgoing edges indicate that imbalance information is shared with the given neighbour. The topology of the network can be expressed by the matrix **A**

neighbours. The total imbalance information should be equal to the total physical imbalance, i.e.,

$$\sum_{i \in I} x_i[k] = \sum_{i \in I} \tilde{x}_i[k].$$

The condition is satisfied if coefficients A_{ij} are elements of a stochastic matrix **A** with properties

- $A_{ij} \geq 0$,
- $A_{ij} = 0$, if no information is sent from agent j to i,
- $\sum_i A_{ij} = 1$.

This matrix corresponds to the graph of the network, which is required to be strongly connected, that is, there exists a directed path between every pair i and j in both directions. A simple example is given in Fig. 3.

Since the objective is to minimise the overall imbalance, we define the cost as

$$L(x[t], u[t]) = \sum_{i \in I} x_i^2[k].$$

A quadratic cost is used to account for both positive and negative imbalances. The optimal control problem is thus formulated as to minimise $\sum_{k \in K} \sum_{i \in I} x_i^2[k]$, subject to (1), (2), boundary conditions $u_i \in U_i$, $w_i \in W_i$, and additional device-specific constraints such as minimum operating time (c.f. Nguyen et al. 2015). It is solved using the distributed MPC approach discussed in Sect. 2, results, embedded in a market structure, are presented in Sect. 4.2.

3.2 Energy Storage Using Power-to-Gas Facilities

Due to the intermittent characteristics, the power output of renewable power sources is not fully dispatchable. It is therefore evident that the need for storing excess power production will increase as the penetration of renewable energy increases. A comprehensive review on available solutions for storing large amount of power sources can be found in Beaudin et al. (2010), de Boer et al. (2014). Pumped hydro storage (PHS) and compressed air energy storage (CAES) are being widely regarded as the most cost effective energy storage options for large-scale power. However, PHS requires reservoirs causing environmental damage by flooding areas up to 10–20 km^2, whereas CAES requires an underground cavern which may be difficult to find around renewable power sources (de Boer et al. 2014).

A relatively new energy storage possibility, namely Power-to-Gas (PtG), has gained in popularity. It converts a surplus of electric power into hydrogen by using electrolysis, which can then be injected into, for example, the gas grid. So far, the amount of hydrogen that is allowed to be injected in the gas grid is rather low. Alternatively, the produced hydrogen can be sold to a mobility or industry sector in order to increase the sustainability of the feedstock. In addition, the hydrogen can be stored in a hydrogen storage device. Also, the stored hydrogen can be reconverted into electrical energy at a later moment using a fuel cell when there is power shortage. Adapted from (Grond et al. 2013), the schematic illustration of a PtG facility can be seen in Fig. 4.

In Alkano et al. (2015a), we model a number of PtG facilities embedded in energy grids that consists of the gas grid, the mobility or industry sector, and the power grid. Each PtG facility $i \in I$ is equipped with a hydrogen storage device and a fuel cell. It aims at maximising its revenue $U_i(g_i[k], m_i[k], p_i[k])$ from its produced hydrogen by injecting the hydrogen to the gas grid at a level of $g_i[k]$, by selling it to the mobility or industry sector at a level of $m_i[k]$, or by reconverting the hydrogen to electrical energy (using a fuel cell) at a level of $p_i[k]$ before selling it to the power grid. However, there is a maximum allowable amount of energy that can be injected to the energy grids due to a limited capacity of the gas pipelines $G[k]$, the pipelines of the mobility or industry sector $M[k]$, and the power transmission lines $P[k]$.

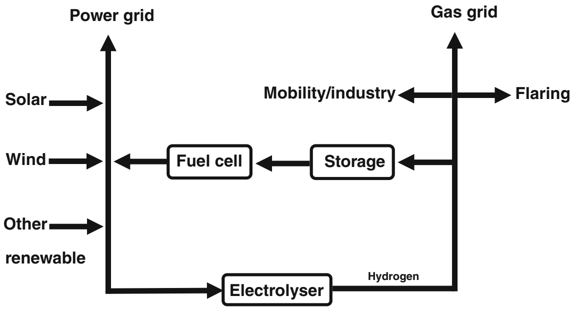


Fig. 4 Overview of the power-to-gas concept. Hydrogen produced from excess power generation can be injected to a gas grid, utilised by a mobility or industry sector, or stored in a storage device and reconverted back to electrical energy using a fuel cell. In case the surplus of hydrogen exceeds the remaining space in the storage device, it is possible that some amount of hydrogen needs to be flared

Hence, the goal is to maximise the total revenue of the produced hydrogen without overloading the energy grids. It is mathematically defined as

$$\begin{aligned} &\text{maximise} \quad \sum_{k\in\mathcal{K}}\sum_{i\in I} U_i(g_i[k], m_i[k], p_i[k]) \\ &\text{subject to} \quad z_i[k+1] = z[k] + \rho(w_i[k] - g_i[k] - m_i[k] - p_i[k]), \end{aligned} \tag{3}$$

$$\sum_{i\in I} g_i[k] \le G_i[k], \quad \sum_{i\in I} m_i[k] \le M_i[k], \quad \sum_{i\in I} p_i[k] \le P_i[k], \tag{4}$$

and boundary conditions $g_i[k] \in \mathcal{G}_i$, $m_i[k] \in \mathcal{M}_i$, $p_i[k] \in \mathcal{P}_i$, and $z_i[k] \in \mathcal{Z}_i$. Coefficient ρ refers to the efficiency of discharging and charging the storage device, $w_i[k] \in \mathcal{W}_i$ is the surplus power sources. Constraint (3) defines the dynamics of the available hydrogen $z_i(k)$ in the storage device, while constraints (4) correspond to the fact that the total energy supply from PtG facilities must be lower than the capacity of the respective grids. On intervals $\mathcal{G}_i$, $\mathcal{M}_i$, and $\mathcal{P}_i$, the revenue function $U_i(g_i[k], m_i[k], p_i[k])$ is increasing, strictly concave, and twice differentiable (Low and Lapsley 1999). Under this condition, each PtG facility i will only sell energy to a grid when it gains some revenue.

We solve the optimisation problem in the MPC framework, and as above, we develop a distributed MPC setting to allow PtG facilities to locally solve their optimisation problem using their own information, yet some coordination with the grid operators is still necessary to meet the grid capacity constraints. To develop the distributed MPC, we use dual decomposition combined with a projected gradient method explained in Sect. 2. In this way, two-layer optimisation problems are involved. The lower level consists of the individual optimisation problem solved to maximise the revenue of the PtG facilities, while the higher level is due to the requisite of coordinating the supply bids to the grid operators.

The interaction among PtG facilities and the grid operators is illustrated in Fig. 5. The PtG facilities publish their supply bids to the grid operators and based on the total supply bids from the PtG facilities, the grid operators determine whether their

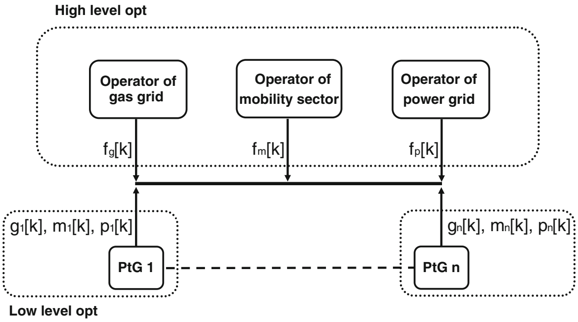


Fig. 5 Proposed interaction among PtG facilities and the grid operators. The operator of the gas grid, the mobility sector, and the power grid publish the distribution charges $f_g[k]$,$f_m[k]$, and $f_p[k]$, respectively, at each time k to activate the PtG facilities to modify their supply levels $g_i[k], m_i[k], p_i[k]$.

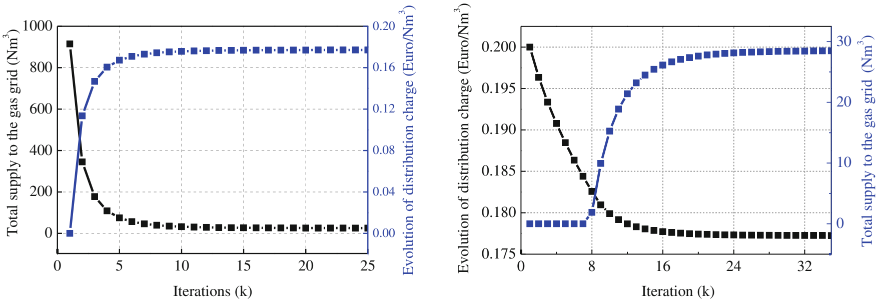


Fig. 6 The behaviour of the distribution charge. The *left figure* shows the increase of the distribution charge in the gas grid as the aggregated supply bids exceed the capacity of the grid (28 Nm^3), whereas the *right figure* presents the decrease of the distribution charge as the aggregated supply bids are still below the grid capacity

grids are overloading. Next, the grid operators introduce additional costs, which can be viewed as distribution charges for energy transport and system services utilised by the PtG facilities when the grid operators detect grid overloads. In this way, the grid operators make sure the PtG facilities modify their supply levels.

Figure 6 depicts the behaviour of the distribution charges. The distribution charges decrease from their initial values when the aggregated supply bids are below the grid capacities; the distribution charges increase otherwise. We terminate the iterations of exchanging supply bids and distribution charges among the PtG facilities and the grid operators when the grid capacity constraints are met, and when the consecutive updates of the distribution charges stay within a sufficiently small bound ξ, i.e., $|f_\alpha[k] - f_\alpha[k-1]| \leq \xi$, for all $\alpha = g, m, p$. In the simulation we set ξ at 1e−6, but with these settings the proposed algorithm has a fairly slow convergence rate. To overcome the problem, we can set the maximum allowable number of iterations while sub-optimality and stability of the optimal solutions are still guaranteed (2012).

The supply bids and distribution charges are iteratively calculated based on updated information. In other words, the iterations are done synchronously. In practice, PtG facilities and the grid operators may not have a common clock to synchronise their updates, therefore it is important to involve the asynchronous scheme in the distributed supply coordination. In Alkano et al. (2015b), distributed asynchronous supply coordination for PtG facilities is embedded in the energy grids.

4 Embedding in the Market Structure

4.1 Universal Smart Energy Framework

The Universal Smart Energy Framework (USEF) (Smart Energy Collective 2014) is an initiative in the Netherlands by the collective of top sector companies to standardise smart grids. Their aim is to create an open platform that facilitates the access to the grid for stakeholders and the development of smart energy services. The framework defines the energy market model, the roles and responsibilities of the stakeholders, and communication protocols for interaction.

USEF creates value by introducing flexibility, the time-shiftable load of smart devices, to the electricity grid. Flexibility can be invoked for grid capacity management to avoid or reduce peak loads. It allows for active balancing through optimisation between supply and demand.

Stakeholders in USEF are organised in a hierarchical tree structure, Fig. 7: suppliers, Balance Responsible Parties (BRP), aggregators, prosumers, and the Distribution System Operator (DSO). Electricity is traded between the suppliers and the BRPs over the wholesale energy market (day-ahead) or imbalance market (operation time). The BRPs dispatch the electricity to the aggregators, which in turn deliver to the prosumers. The aggregator is a new stakeholder in energy grids that groups the prosumers into clusters. Its main purpose is to accumulate and offer flexibility on behalf of the connected prosumers. The DSO acts as a supervisor for the grid—it is responsible for detecting and resolving any congestion that might occur in the distribution lines.

USEF employs a market-based control mechanism that consists of four phases: planning, validation, operation and settlement. In the planning phase a day-ahead forecast of the energy consumption is made, which then needs to be validated by the DSO. The planning and validation phases are iterated until an agreement is reached on the forecast. In the operation phase the system aims to follow the plan

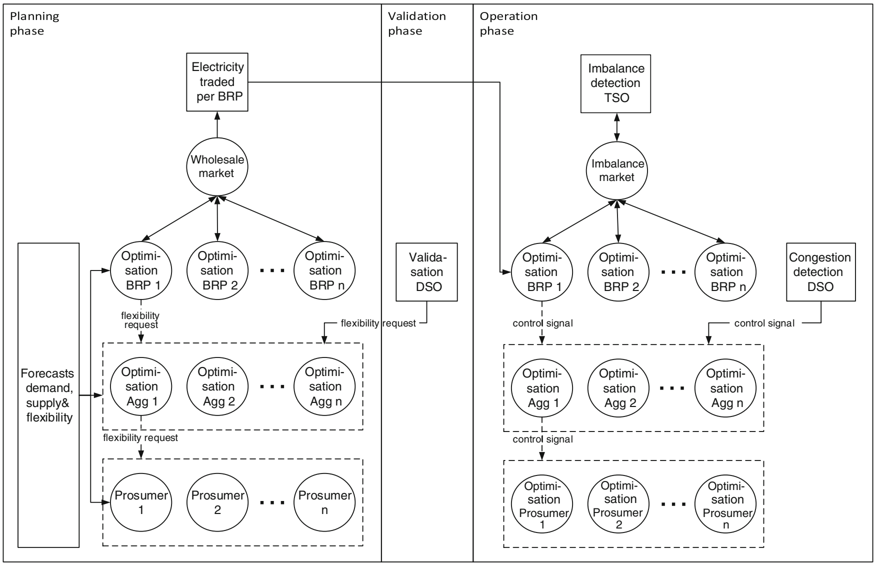


Fig. 7 The USEF structure. Interactions between stakeholders during the planning, validation, and operation phases. The settlement phase is omitted from this figure

that has been created in the first two phases and balances between the forecast and actual electricity load by procuring flexibility. Financial reconciliation is completed in the settlement phase.

4.2 Demand Response in the Universal Smart Energy Framework

We embed the distributed MPC method in the operation phase of USEF, assuming that the energy portfolio has already been forecasted and agreed on by the aggregators, BRP, and DSO. Each prosumer is equipped with one appliance, either a heat pump (representing consumption) or a μCHP (representing production).

The algorithm is implemented on both the prosumer and aggregator levels, with the aggregators accumulating the imbalance and the flexible and fixed loads of their prosumers. The objective of minimising the total imbalance is now extended to the aggregators, hence our optimal control problem is formulated as

$$\begin{aligned} \text{minimise} \quad & \sum_{k\in\mathcal{K}}\sum_{l\in\mathcal{L}}\sum_{i\in I} x_i^2[k] \\ \text{subject to} \quad & x_i[k+1] = A_{ii}x_i[k] + \sum_{j\neq i} A_{ij}x_j[k] + u_i[k] + w_i[k] - \Delta\text{goal}_i[k], \\ & \text{and the constraints from Sect.3.1,} \end{aligned}$$

where $\mathcal{L}$ is the set of aggregators. The goal function is introduced to couple the two levels and intuitively reflects the flexibility invoked by the aggregators from their prosumers (Nguyen et al. 2015).

We give an example of a small network with 3 aggregators, each with 10 connected prosumers. The prosumers are arranged in a circular topology, each one having a self-weight of 0.6 and a weight of 0.2 for the information coming from its two neighbours. The aggregators are fully connected.

The controller is first applied to a reference scenario: we choose the case where there is no heat storage, meaning the devices are not flexible. Aggregator optimisation is not required, as there is no need to accumulate flexibility. By comparing to this scenario, we will be able to see the importance of the aggregator optimisation loop. Figure 8 depicts the evolution of the total load (green line), the total imbalance (blue line), and the goal function (red line) during the simulated day of the reference scenario. We observe three large peaks in the imbalance, which have been marked.

Next, we look at the case where the appliances are flexible. The peaks are reduced by our controller, as shown in Fig. 9. This reduction results from the procurement of available flexibility, which is in line with our controller design objective: to minimise the total imbalance in the network.

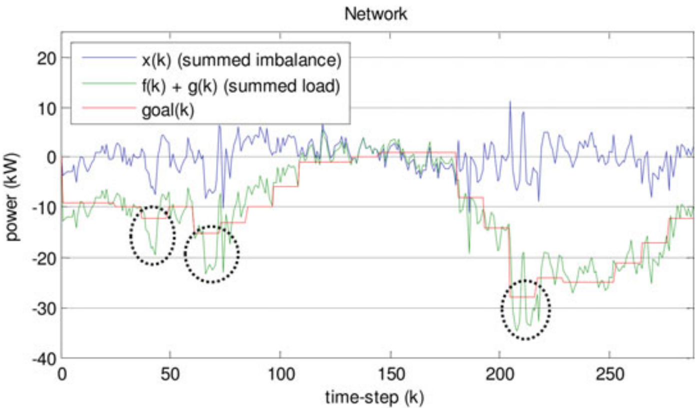


Fig. 8 Reference scenario. In the reference case no flexible appliances are considered. Three large peaks appear during the simulated day

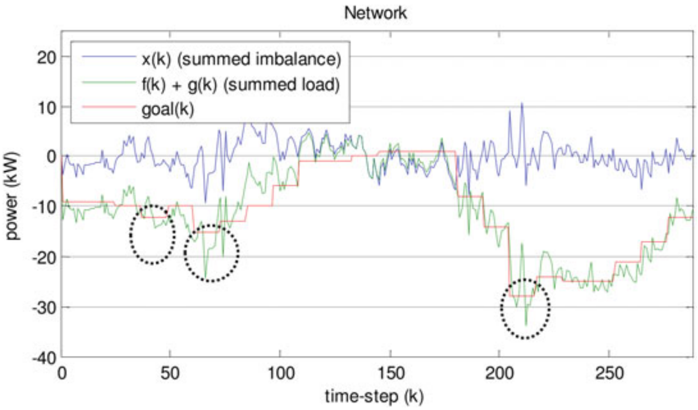


Fig. 9 Flexible scenario. When flexible appliances are present, the peaks are reduced due to efficient utilisation of flexibility

A closer examination at the imbalances of the aggregators reveals that the peaks are mainly caused by one aggregator (aggregator 2), see Fig. 10. We measure the performances of the controllers in terms of total network imbalance over time. We plot the difference between the performances in Fig. 11, the flexible scenario against the reference scenario. We observe that large performance increase happens in the flexible scenario when there are large imbalance differences between the aggregators. This is as expected, since in this scenario the aggregators cooperate and by sharing their imbalance information, they help each other to minimise the overall imbalance.

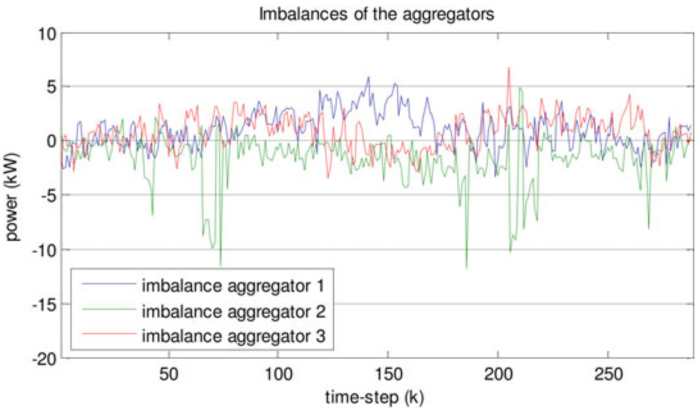


Fig. 10 Aggregator imbalances. Large imbalances appear on aggregator 2 (*green line*) during the reference scenario

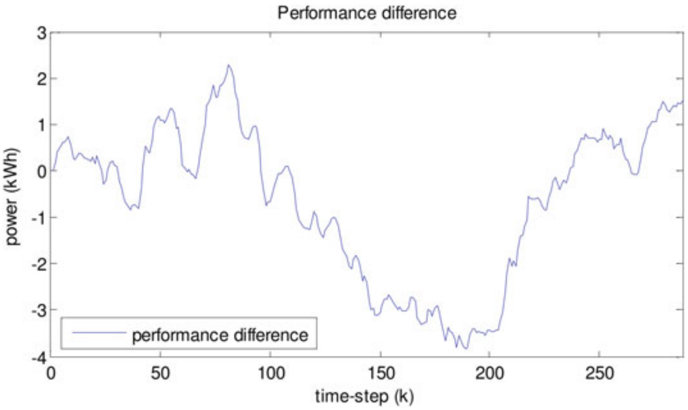


Fig. 11 Performance comparison between the two scenarios. Noticeable performance improvements occur in the flexible scenario, compared to the reference scenario, when there are large imbalances in the network

Additionally, we demonstrate the scalability of the distributed MPC formulation in a network of prosumers under one aggregator. Figure 12 shows that the distributed algorithm can well handle up to 100,000 prosumers, whereas the centralised algorithm quickly becomes intractable. In this simulation only heat pumps are considered. We expect that the inclusion of μCHPs does not make a big difference in scalability, because although additional constraints have to be introduced, the nature of how these devices are modelled is the same.

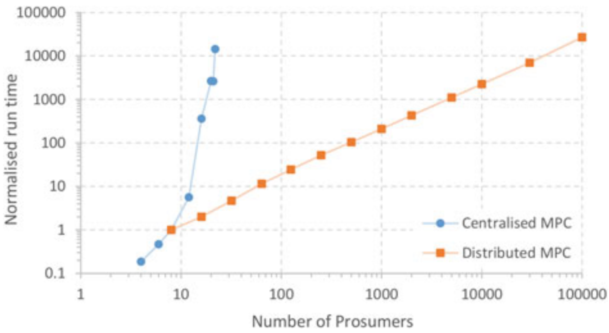


Fig. 12 Simulation run time comparison. Results indicate that the distributed formulation indeed reduces the computational complexity of the algorithm. Note that the scale is logarithmic, and the run times are normalised to the value obtained for a network of 8 prosumers

5 Concluding Remarks

The transition towards smart energy grids poses several challenges, among which we focus on balancing supply and demand. In this chapter we discuss two of our ongoing research directions: demand response regulation in relation to the Universal Smart Energy Framework, and Power-to-Gas facilities for energy storage. The topics are subject to further study and we suggest to explore the link between the electricity and the gas grids in more detail as future work. We also propose to investigate and understand how pricing mechanisms can be incorporated in the energy market structure. A technical summary of the methods covered in the chapter can be found in Scherpen (2015).

Points for Discussion

- Why must control solutions for smart grids be linked to other aspects of the energy system, such as markets, infrastructures, users, and regulatory bodies?
- Which actors are, or should be responsible for developing such control solutions, and for proper interfacing?
- Are other incentives possible, besides price? How much modulation are people willing to accept?
- As is obvious from the more technical-oriented chapters in this volume, the complex technology involved in constructing and operating smart grids requires high-tech control. This puts people and firms who understand, produce, control, and secure the technology in a special societal position. How do the technological imperatives of smart grids relate to the societal imperatives? In this context, are smart grids collective goods (which moves them into the realm of governmental responsibilities) or private goods (based on individual choices and purchasing power)?

Acknowledgements This work is supported by the TKI Switch2SmartGrids (TKISG02001) and the Energy Delta Gas Research (EDGaR) program. EDGaR is co-financed by the Northern Netherlands Provinces, the European Fund for Regional Development, the Ministry of Economics Affairs, and the Province of Groningen.

References

Alkano, D., Kuiper, I., Scherpen, J.M.A.: Distributed MPC for power-to-gas facilities embedded in the energy grids. In: Proceedings of 14th European Control Conference, Linz, Austria, July 2015 (2015a)

Alkano, D., Nefkens, W.J., Scherpen, J.M.A., Volkerts, M.: Optimal control in a micro gas grid of prosumers using model predictive control. In: Proceedings of 21st International Symposium. Mathematical Theory of Networks and Systems, pp. 592–598, Groningen, The Netherlands, July 2014

Alkano, D., Scherpen, J.M.A., Cao, M.: Distributed asynchronous supply coordination for energy producers embedded in the energy grids. Submitted (2015b)

Åström, K.J., Murray, R.M.: Feedback Systems: An Introduction for Scientists and Engineers. Princeton University Press, Princeton (2008)

Beaudin, M., Zareipour, H., Schellenberglabe, A., Rosehart, W.: Energy storage for mitigating the variability of renewable electricity sources: an updated review. Energy. Sustain. Dev. **14**(4), 302–314 (2010)

Biegel, B., Andersen, P., Stoustrup, J., Bendtsen, J.: Congestion management in a smart grid via shadow prices. In: 8th IFAC Symposium, Power Plant and Power System Control, pp. 518–523, Toulouse, France, Sept 2012

Boyd, S., Vandenberghe, L.: Convex Optimization. Cambridge University Press, Cambridge (2004)

de Boer, H.S., Grond, L., Moll, H., Benders, R.: The application of power-to-gas, pumped hydro storage and compressed air energy storage in an electricity system at different wind power penetration levels. Energy **72**, 360–370 (2014)

Giselsson, P., Rantzer, A.: On feasibility, stability and performance in distributed model predictive control. IEEE Trans. Autom. Control **59**(4), 1031–1036 (2014)

Grond, L., Schulze, P., Holstein, J.: Systems analyses power to gas: a technology review. Technical report, DNV KEMA, Groningen, The Netherlands (2013)

Larsen, G.K.H., Pons, J., Achterop, S., Scherpen, J.M.A.: Distributed MPC applied to power side control. In: Proceedings of 12th European Control Conference, pp. 3295–3300, Zürich, Switzerland, July 2013

Larsen, G.K.H., van Foreest, N.D., Scherpen, J.M.A.: Distributed mpc applied to a network of households with micro-CHP and heat storage. IEEE Trans. Smart Grid **5**(4), 2106–2114 (2014a)

Larsen, G.K.H., van Foreest, N.D., Scherpen, J.M.A.: Power supply-demand balance in a smart grid: an information sharing model for a market mechanism. Appl. Math. Model. **38**(13), 3350–3360 (2014b)

Low, S.H., Lapsley, D.E.: Optimization flow control, I: basic algorithm and convergence. IEEE/ACM Trans. Netw. **7**(6), 861–874 (1999)

Maciejowski, J.: Predictive Control with Constraints. Prentice Hall, Harlow (2002)

Nguyen, D.B., Scherpen, J.M.A., Bliek, F.: Distributed Model Predictive Control in the Universal Smart Energy Framework. Technical report, University of Groningen, Groningen, The Netherlands (2015)

Rantzer, A.: Dynamic dual decomposition for distributed control. In: Proceedings of 2009 American Control Conference, pp. 884–888, St. Louis, MO, USA, June 2009

Scherpen, J.M.A.: Distributed supply-demand balancing and the physics of smart energy systems. Eur. J. Control **24**, 63–71 (2015)

Smart Energy Collective: An Introduction to the Universal Smart Energy Framework. Arnhem, The Netherlands (2014)

Starrett, D.A.: Shadow pricing in economics. Ecosystems **3**(1), 16–20 (2000)

Economic Regulation of Energy Networks

Machiel Mulder

Abstract The growing attention for the environmental effects of using fossil energy calls for an evaluation of current regulatory regimes of energy networks. In the past, tariff regulation of energy networks was mainly meant to foster competition and to improve efficiency in order to achieve lower prices for energy users. Currently, it is generally believed that regulation also has to facilitate the process of decarbonisation. In order to deal, for instance, with the growing significance of distributed generation, distribution-network operators have to upgrade their networks. The key question now is whether the existing regulatory frameworks should be adapted in order to enable these types of developments. This chapter focuses on yardstick regulation, which is a form of tariff regulation in which the allowed revenues of network operators are based on the average costs of all operators. The chapter concludes that several mechanisms exist by which yardstick regulation fosters efficient investments directed at making the grids smarter. However, such a regulatory framework may also include mechanisms potentially hindering efficient investments. These negative effects of regulation on the development of smart grids occur if the regulated firms operate in different circumstances and when externalities exist. The chapter ends by presenting a number of options to deal with such regulatory shortcomings.

1 Introduction

The energy industry is facing major changes resulting from government policies to pursue an energy transition, which is a transformation of the current fossil-energy based economies into renewable-energy based economies. This transition affects all

---

M. Mulder (✉)
Faculty of Economics and Business, University of Groningen, Groningen, The Netherlands
e-mail: machiel.mulder@rug.nl

M. Mulder
Authority for Consumers & Markets, The Hague, The Netherlands

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_8

players in energy markets: consumers, producers as well network operators. Consumers are being incentivized to increase the efficiency of their use of energy, to produce electricity by solar cells themselves or to replace the use of primary energy carriers in cars by using electricity. These incentives are given through policy measures as subsidies and levies on energy. Producers also face financial incentives to increase the production by renewable sources, such as subsidies for onshore and offshore wind parks. As a result, the time profiles of consumption and production of electricity are changing significantly. The intermittent character of wind and solar electricity creates more volatility in the injection of electricity into the grid, resulting in higher peaks as well. Consequently, the electricity network operators have to adapt their grids (see e.g. Veldman et al. 2010). Distribution network operators, for instance, have to upgrade their network in order to deal with the growing significance of distributed generation, such as micro CHP systems and solar cells. The grids should also be able to charge huge numbers of electric cars.

In principle, operators have two technological options to tackle these developments. The first one is extending the grid, making the capacity of the grid sufficiently large to facilitate both peak load and peak supply. The other option is making the grid smarter, which basically means using information technology to stimulate network users to change the profile of their production and consumption of electricity such that it results in a more efficient utilisation of the grid (Colak et al. 2015). One example of such a change in profile is peak shaving, which means shifting the production or consumption in order to flatten the profile over a day. Both extending the grid and using the grid more efficiently call for investments by the network operators. Which option is optimal from the perspective of the network operators depends on how these options affect their financial performance. This performance, in turn, depends on the regulation of the tariffs which the network operators are allowed to charge.

The key question discussed in this chapter is whether the existing tariff-regulatory frameworks are capable of facilitating distribution-grid operators to adapt their grids to the needs of the energy transition. Various authors have stated that the existing regulatory frameworks are inadequate for facilitating this transition in the energy industry (WRR 2007; Nykamp et al. 2012; Agrell et al. 2013). They argue that the regulatory frameworks so far have focused too much on efficiency and tariff reduction at the expense of the necessary investments in adapting the network to the changing needs of the energy market. In the view of these authors, several key elements of the framework should therefore be revised in order to ensure that these investments can still be made. Instead of the current system where energy transport tariffs are based on the network operators' efficiency levels, there should, for instance be a system where the network operators have more financial certainty when they decide upon an investment.

In this chapter we analyse how a specific type of tariff regulation affects the incentives of network operators to upgrade their networks. The type of regulation analysed is yardstick regulation which is applied to, among others, the Dutch energy distribution networks. In this type of regulation, the maximum level of revenues per unit of output of the regulated firm is related to the average costs of a number of similar firms. We conclude that yardstick regulation gives incentives to operators to make their grids smarter if this contributes to a higher productivity of the grids. Yardstick regulation may, however, also hinder investments in smart grids if the operators do not operate in a similar economic environment, because not all investment costs will then be reimbursed. Yardstick regulation may also result in a suboptimal level of investments in smart grids when the network operators are not able to capture the positive externalities on the wholesale and retail energy markets.

The chapter is structured as follows. Section 2 summarizes the economic principles regarding tariff regulation, in particular focussing on methods giving incentives to network operators to make efficient investments. In Sect. 3, we describe how yardstick regulation is applied for the Dutch electricity distribution networks and what the impact has been on tariffs, investments and quality of network services. Then, we analyse in Sect. 4 how yardstick regulation may affect the incentives for network operators to adapt the grids in order facilitate the transition in the energy industry. Finally, Sect. 5 presents the conclusions on the ability of yardstick regulation to foster smart grids.

2 Theory of Economic Regulation

2.1 *Regulatory Principles*

If energy networks could operate in well-functioning markets, there would be no need for regulation at all. The functioning of the market would guarantee that the profit-maximising behaviour of individual firms together with the utility-maximising behaviour of consumers result in the optimal outcome for society. This means that the market would optimally coordinate all the individual activities of the numerous independent producers and consumers. Energy networks, however, do not operate in perfect markets. Without any form of regulation, the energy markets would suffer from a number of failures. These market failures are market power, information asymmetry, externalities and hold-up. The presence of market power is the key reason to implement tariff regulation of energy networks (Viscusi et al. 2005).

Because of the huge fixed costs of networks, competition between operators is not feasible in most network industries, which gives them a (natural) monopoly.[1] Hence, the market suffers from the existence of some firms having market power. A monopolist will not automatically produce the products which are needed by society. Moreover, it has limited incentives to innovate or to be as efficient as technically possible because of the so-called replacement effect, which is the effect that any improvement in products for society goes at the expense of reduced

---

[1] More formally, an energy network is a natural monopoly if the costs are sub additive, which means that the total costs of supplying all services needed in a market by one network are below the total costs of producing these services by more than one network.

revenues from other products. In addition, a monopolist will generally use its market position to charge relatively high prices. A monopolist set the prices at that level that maximizes its profit. These monopoly prices can be significantly above the level of competitive prices. Consequently, consumers pay too much and, because of the high prices, they may consume less than when the prices would be at the competitive level.[2] Because of the market failure of market power, regulation is needed to give network operators incentives to realise the products which are needed by society, to operate as efficiently as technically possible and to let networks users benefit from efficiency improvements within the networks.

Regulation of an industry, however, is not a perfect substitute for a competitive market because of the existence of information asymmetry between regulator and the regulated firm. This asymmetry is related to information about the precise characteristics of the firm as well as information about its precise behaviour. This first component is called hidden information and may result into adverse selection, which means that the regulator makes the wrong assumptions about, for instance, the efficient cost level. The second is called hidden behaviour and may result in moral hazard, which means that the regulated firm is less inclined to do its utmost as the regulator is unable to monitor and reward that behaviour sufficiently. Because of this information asymmetry, it is impossible (or highly expensive) for a regulator to acquire the same level of information and knowledge as regulated firms have about their activities. Therefore, regulated firms are in principle better equipped than regulators to choose the optimal production technique, including size and type of investments, and to determine the optimal level and type of production. Therefore, the regulatory frameworks are generally directed at setting constraints and giving incentives to the regulated firm.

These constraints and incentives are, theoretically, given to pursue several regulatory objectives, which can be summarised as productive efficiency, dynamic efficiency and allocative efficiency. The objective regarding productive efficiency is that the network operator should operate as efficiently as technically possible. This means that the operator needs to have incentives to look for the best technique available and to design the investment projects in such a way that maximises the utilisation per unit of costs. The dynamic-efficiency objective is that the network operator should try to innovate and to continuously improve the productive efficiency. The allocative-efficiency objective, finally, is that networks users should benefit from the above efficiency improvements within the network. This means that the tariffs which users have to pay for using the grid should reflect the efficient costs of the operator, including a market-based reward for capital, leaving no room for economic profits[3] of the network operator.

---

[2] This reduction in consumption is called the deadweight loss of a monopoly.

[3] Note that ‘economic profits’ are the profits on top of the normal profits, while the latter are defined as the reward for the opportunity costs of capital. In tariff regulation, this reward is given by including a compensation for capital costs in the revenue formula. This compensation is based on the WACC (weighted costs of capital), which is weighted sum of the costs of debt and the required return on equity.

While dealing with these objectives, the regulator faces a number of trade-offs. The most fundamental trade-off is the one between giving incentives for efficiency on the one hand and rent[4] extraction the other. In order to give incentives to the operator to increase productive and dynamic efficiency, the operator must receive a fair share in the benefits of the increased efficiency. This means that the efforts by the operator to increase the efficiency of the network need to be translated into higher profits. As a result, consumers will pay more than what is precisely needed to recoup all costs. Hence, giving incentives for efficiency improvement automatically means that consumers pay more than the actual level of costs, and the other way round: extracting all rents from the network operator for the benefits of consumers removes the incentive to improve efficiency.

Regulators can choose from different regulatory systems to deal with the above objectives. Basically, two main types of tariff regulation can be distinguished: cost-plus regulation and price-cap regulation. With cost-plus regulation, the allowed level of revenues (R) of an operator are equal to its realised costs (C), while with price-cap regulation the maximum level of revenues[5] fully depend on an external benchmark (B). The relationship between the costs of a firm and its revenues is negatively related to the so-called incentive power (α) (see Eq. 1). In case of cost-plus regulation ($\alpha = 0$), the firm has not any incentive to reduce its costs since all efficiency improvements are fully passed on to the network users. With price-cap regulation ($\alpha = 1$), however, the firm has the highest power to increase its efficiency since the revenues will remain the same independent of the size of its costs, implying that all efficiency improvements will be translated into higher profits.

$$R = (1 - \alpha)C + \alpha B \tag{1}$$

Both kinds of tariff regulation have some disadvantages. Price-cap regulation is generally seen as a disincentive for investments in new infrastructure, as investments result in higher (capital) costs while the revenues of the firm are constant and independent of the realised costs. In addition, price-cap regulation may result in positive economic profits for the operator, implying that grid users may pay more than is needed to recoup the costs. Cost-plus regulation, however, gives weak incentives to the operator to be efficient, because of the absence of the option to make an economic profit, while the incentives for investments are not necessarily high.

A specific form of cost-plus regulation is rate-of-return regulation, which gives operators ex ante certainty on the rate of return on their investments. This type of regulation is viewed to be most suited to foster investments in new infrastructure. Rate-of-return regulation may, however, result in a too high level of investments while incentives to operate productively efficient are soft.

---

[4] In economics, ‘rent’ is an alternative term for ‘economic profit’.

[5] The maximum level of revenues is translated into tariffs for the different types of services a network supplies. Operators generally may vary with these tariffs but the sum of all tariffs times the expected volumes per type of service is not allowed to exceed the maximum level of revenues.

A specific form of price-cap regulation is yardstick regulation. Here the allowed level of revenues of a firm is determined on the basis of the cost of a group of similar firms (Shleifer 1985). By relating the revenues of a firm to the average costs of other firms, the incentive power to increase efficiency can be high. The incentive power is equal to one minus the share of the regulated firm in the yardstick (i.e. the average costs of the group) (Dijkstra et al. 2015). If only the costs of other firms are included, ignoring the costs of the firm itself, this incentive power is at its maximum level.[6] This kind of yardstick regulation is called discriminatory yardstick, since the cap on revenues is firm specific. If the allowed revenues of a firm are based on the costs of all firms in the group, including the costs of the firm itself, the yardstick is called uniform, since all firms face the same cap on revenues. Now, the incentive power is lower since changes in the cost of that firm are to some extent translated into changes in revenues. To what extent this holds, depends on the share of that firm in the yardstick.[7]

A necessary condition for a proper application of yardstick regulation is that the firms are similar. Only then it makes sense to base the allowed revenues of a firm on the costs of other firms. Later on in this chapter we will see that this condition may not be satisfied when we are talking about smart grids.

2.2 Tariff Regulation, Investments and Risks

The different kinds of tariff regulation differ in the way they deal with the so-called hold-up problem. Hold-up is a market failure which means that ex ante (i.e. before taking a decision) a firm is uncertain about the ex-post conditions (e.g. the conditions affecting the revenues, such as the regulatory framework). This effect may particularly occur when investments result in sunk costs, such as in energy networks. After the network operator has made an investment in the grid, the investment costs are sunk, meaning that these cannot be undone anymore. This makes that the negotiation position of the network operator after the investment has been realised is much weaker than before. Hence, the network operator faces the risk that an investment will result in stranded assets and, as a result, it may hold up the investment. In order to reduce this risk of ex post deterioration of the financial conditions the operator may require ex ante commitments given by the counter parties or the regulator.

With rate-of-return regulation, this hold-up problem seems to be effectively solved. If investors in networks are assured they will earn a given rate of return, there is no risk of stranded assets on micro-level, i.e. on the level of the firms.

---

[6] In this case, the share of the regulated firm in the yardstick is zero, implying that the incentive power is 1.

[7] Note that if the group consist of just one firm, its market share is 1 and the incentive power is 1 − 1 = 0, which is equal to a cost-plus type of regulation.

On macro-level, however, there is still a risk that investments will appear to be socially inefficient, resulting in stranded assets from that perspective. In this type of regulation, network users pay for this risk, as the tariffs for using the network rise if the utilisation of the networks reduces. So, rate-of-return regulation seems to be an effective solution to foster investments and to reduce the risk of stranded assets for network operators, but in fact this risk is shifted to network users. In addition, rate-of-return regulation creates relatively high risks of stranded assets for users because of the relatively high likelihood of socially inefficient investments. The more the guaranteed rate of return exceeds the opportunity costs of capital (i.e. the return to be achieved in the market given the risk), the more this type of regulation will foster investments. This adverse effect of rate-of-return regulation is called the Averch-Johnson effect (Averch and Johnson 1962).

With price-cap regulation, the network operator has a high-powered incentive to reduce costs including investments ($\alpha = 1$). The operator faces, however, the risk that it will not be fully rewarded, while there is also a chance that the revenues exceed realised costs. It is therefore important to choose the optimal level of the price cap, balancing between the risk of financial distress of the regulated firm on the one hand and the risk of above-normal profits and too high tariffs for network users on the other.

The more the price cap is related to realised costs, the stronger the certainty that the operator will be fully reimbursed, and the lower its risk of stranded assets. This certainty has its price, as free lunches don't exist. The price includes reduced incentives for the operator to increase the productive efficiency. In addition, as the risk for the operator is relatively low in case of such a cost-based form of price-cap regulation (which can also be seen as a form of cost-plus regulation), the reward for capital costs should be lower as well. Hence, in return for the certainty about the profits and the resulting lower risk on stranded assets for the network operator, the compensation for costs of capital can be lower which has a downward effect on tariffs. The networks users face, however, the risk of stranded assets as their tariffs will also be related to the utilisation of the network.

2.3 Realising Optimal Investments

From the above follows that the challenge for regulators is to incentivize network operators to realise the socially optimal level of investments in a productively efficient way while network users pay no more than is needed to recoup the costs. Given the existence of the abovementioned information-asymmetry, it is highly complicated if not impossible to realise all these objectives simultaneously. Theoretically, network operators should be incentivised to conduct all those investments which are efficient from a welfare-economic point of view, but they should also be prevented from making socially inefficient investments. Taking care of the welfare effects of investment projects can generally be done in three different ways: applying menu regulation, conducting social cost-benefit analysis or applying yardstick regulation.

Incentives to operators to only develop efficient investment projects can be given through menu regulation (Joskow 2006). In this form of regulation, operators can earn a higher profit the more their investment plan is viewed to be socially efficient. In addition, the more productively efficient the investment plan is realised, the more the profit rises. The idea here is that network operators can choose between different investment plans and different types of implementation, but that the menu triggers the operators to make efficient decisions. The menu prescribes the rate of return operators can make, which means that they will not face a risk of stranded assets. The stranded-asset risk for users is mitigated through the incentives given to make only socially efficient investments.

Instead of giving the operators the freedom to choose an investment plan (regarding size, timing, etc.), the operators can be asked to submit several, alternative plans to the regulator (or government) which are analysed from a welfare-economic perspective. The standard method here is social cost-benefit analysis, in which all effects of the (proposed) investments are taken into account, preferably but not necessarily in monetary units. The investment plan with the highest, positive outcome can be approved, which means that the operator will be allowed to make the investment with the guarantee that in principle all costs will be reimbursed.

As a matter of fact, conducting social cost-benefit analysis is not an easy exercise as it is often pretty difficult to determine all social costs and benefits of a project. One of the key issues which has to be discussed is the counterfactual: what would happen if the investment project would not take place? Another difficulty often arising is that not all effects, such as that on security of supply, can be directly expressed in monetary terms because of the absence of market prices. Nevertheless, a social cost-benefit analysis enables us to think systematically about the welfare effects of an investment project.

While menu regulation and cost-benefit analysis can be applied when there is only one regulated firm (i.e. the monopolistic network operator), yardstick regulation can be applied to give incentives to firms when more regulated firm exists. If each firm is free to decide on the investment, the yardstick regulation will only reward these investment if other firms also have decided to invest. A reason to give operators freedom of operation is that ex ante neither the regulator nor the operators know for certain which technique will appear to be the most efficient one. Giving incentives to choose for a specific technique, therefore, creates the significant risk that this technique does not appear to be the best or the most efficient one at the end of the day. When each operator is able to make its own technological choice, the benefits of a decentralised organisation come to the fore, just as in normal markets (Kay 2005). This means that there is a higher chance that ex post the best technique will be chosen (or developed) by at least one of the operators. In a centralised system, without such freedom and variation on firm level, innovation would be likely less developed. Of course, such a regulatory system can only applied if sufficient number of comparable firms exists.

Concluding, to define the optimal regulatory system regarding investments, the treatment of risks is an essential component. If investments in networks are viewed to be highly important, the risk of the investment can be fully shifted to society by, for instance, giving financial support to the operator from government funds or to network users by, for instance, implementing a form of cost-plus regulation. As a result, the risk for the network operators is reduced which calls for a downward adaptation of the compensation for capital costs. The disadvantage here is that the operators only face soft (or no) incentives to be productively efficient, which likely results in higher tariffs for end-users. Therefore, in discussing rewards for risks on investments attention has also to be paid to incentives for the firm to operate efficiently.

3 Regulation of the Dutch Distribution Grids

3.1 General Principles

The Dutch regulatory framework can be characterised as output-oriented regulation. This basically means that the regulation is directed at the output of the networks instead of the inputs. The main output parameters include total revenues and the reliability of the network services. The regulation of the revenues is based on yardstick regulation. This framework determines the maximum level of revenues of an operator, giving the operator full freedom to decide upon its own costs. As a consequence, network operators are expected to have the opportunity to make all the investments that are socially profitable or desirable, while at the same time not being forced to make investments that are neither. The regulatory framework aims to provide for revenues that cover efficient costs, but it tries not to offer financial room for investments which are viewed to be inefficient or to generate revenues which result in excessive profits (Mulder 2010).

These characteristics of the framework are based on the principle that the regulator does not want to interfere with the operational and investment decisions of network operators, but that it sees to the statutory tasks being performed as efficiently as possible. The general idea is that operators have far more knowledge about efficient network management than the regulators have. Hence, the aforementioned problem of information asymmetry between regulator and network operator is treated by giving the operator the freedom as well as the incentives to choose the optimal technical options in its specific situation. In principle, the benefits of realising a more efficient solution can be reaped by the operator. In order to prevent that too many efficiency benefits remain within the network firm, however, the yardstick which determines the cap on revenues of the operator is frequently reassessed.

3.2 Regulation of Tariffs and Quality

A major component of the regulatory framework is the tariff regulation. This regulation sets the total revenues of a network operator on the level of efficient costs.

These efficient costs are based on a yardstick which is calculated as the average of the costs per unit of standardized output[8] (SO) of all operators (i). Hence, the cap on the total revenues of an operator is equal to the average costs per unit of standardized output times the expected level of standardized output for this operator (see Eq. 2).[9] Because the costs of all operators are included, this is a form of a uniform yardstick.

$$R_i = \frac{\sum C_i}{\sum SO_i} * SO_i \tag{2}$$

Since the regulatory framework only determines the cap on revenues, the operators are fully free to allocate the total revenues among capital and operational costs. Some operators having a relative capital-intensive operation may use the revenues as compensation for their relatively high depreciation costs and costs of capital. Others, having a relatively old network, may use the revenues as compensation for operational costs such as labour costs and costs of maintenance. By definition, network operators operating more efficiently than the average operator will earn higher profits, because they incur lower costs than others—and vice versa. A consequence of this form of benchmark regulation is that all the network operators' costs are incorporated into the tariffs: on industry level, aggregated revenues of all operators are equal to aggregated costs. Each individual network operator, however, is not necessarily able to cover its own costs as this depends on the relative productivity.

The regulated revenues also depend on the performance of the network with respect to quality. Although the framework does not precisely prescribe standards for quality of energy supply, it does include incentives to optimize the level of quality. These incentives comprise a bonus-malus system and a compensation mechanism. Operators receive a bonus if the quality of their network (measured by SAIDI[10]) exceeds the average quality of all operators in the previous regulatory period. And vice versa: if the quality of an operator is below the average level in the previous period, it receives a malus. Both bonus and malus are capped at the level of 5 % of total revenues in the previous period in order to prevent that a bonus or malus has a too large impact on the financial position of the regulated firm. The compensation mechanism says that the individual energy users should be financially compensated if they have experienced a serious disruption. In case of

---

[8] Network operators provide a number of different services and, hence, they have a number of different outputs. In order to be able to calculate a productivity index, these outputs needs to be standardized. This standardization can be done by using, for instance, realised average tariffs for each output category.

[9] The costs in this formula includes both capital costs (capex) and operational costs (opex), implying that the regulatory framework can be characterised as totex-regulation, i.e. the revenues are based on an estimate of the total costs.

[10] SAIDI means 'System Average Interruption Duration Index' and is calculated as the ratio between the sum of duration of interruptions in power supply for all network users during a year over the total number of network users. Hence, this ratio measures the average duration (in minutes or hours) that network users cannot make use of the power grid in a year.

failures that last for more than four hours, network operators are required to compensate customers for these interruptions in transport.

In addition to the bonus-malus scheme, the regulatory framework includes rules regarding the reliability of the network and the services to be provided to energy users. Network operators have to take care of the network in such a way that energy users have the guarantee that they will be connected as soon as possible and that the supply of energy will be disrupted as less as possible. Network operators are required to periodically inform the regulator which actions they will be taking to maintain their networks' reliability. Furthermore, the regulator set, in close consultation with network operators and users, technical codes, which stipulate how network operators are supposed to behave towards each other and towards all parties connected to the networks.

3.3 Effects on Tariffs and Network Quality

Undoubtedly, yardstick regulation has significantly reduced the tariffs consumers have to pay for using the networks. The impact of regulation on tariff can be calculated by making an assumption about the development of the tariffs in case of no regulation (the so-called 'counterfactual'). It can safely be assumed that in that case tariffs would annually increase by at least the rate of inflation (Kemp et al. 2010). Without regulation, the network operators could use their monopoly power to raise prices even above that level, but one might assume that political pressure would cap the price increases to the level of the rate of inflation. The cumulative savings since the start of the regulation of the Dutch energy-distribution networks are estimated to be several billion of euros. The reduction in tariffs reflects the reduction in total costs per unit of output. This higher efficiency results partly from higher productivity of the network operators, but it partly also results from lower capital cost which were caused by the decreased opportunity costs of capital.[11]

Economic literature includes a number of papers finding a negative effect of incentive regulation on network quality (see Granderson and Linvill 2002; Jamasb et al. 2008; Pollitt 2005; Ter-Martirosyna 2003). As a result, one might expect that the realised reduction in costs in the Dutch electricity networks has hampered the quality of the infrastructure. On the other hand, there are also several papers concluding that the negative effects of price-cap regulation can be compensated, at least partially, by quality regulation (see Ajodhia et al. 2006; Burger et al. 2008; Ter-Martirosyna and Kwoka 2010).

Movares and Kiwa (2009) and Haffner et al. (2010) did not find evidence that the quality of the Dutch energy distribution networks has deteriorated since the start of the tariff regulation in 2004. In fact, the quality of Dutch networks has hardly

---

[11] In particular the risk-free interest has declined significantly over the past years. This interest rate is a component of both the cost of debt and the required rate of return on equity.

changed since the introduction of regulation. The average consumer experienced approximately 30 min of disturbances in electricity supply per year. These disturbances were mainly caused by the high-voltage network; the low-voltage (distribution) network was responsible for no more than 5 min of disturbance on average per consumer per year. In addition, compared to other European countries, the performance of the Dutch energy networks is still at a high level. Looking at the causes of disturbances within the network, it appears that wear is only responsible for about 10 % of the disturbances (Movares and Kiwa 2009). Most disturbances appear to be caused by digging activities and external factors like accidents.

Regarding the impact of regulation on the investment behaviour of network operators, PwC (2009) and Haffner et al. (2010) concluded that there is no evidence that the regulatory framework has resulted in the necessary investments in the network being postponed or even being cancelled. The regulatory financial incentives have had no appreciably negative effect on the investments in quality and safety. There is also no evidence that operators wait for each other in making investments. This finding refutes the common statement that a system of yardstick regulation acts as an incentive to wait on each other. After all, according to that argument, firms would only invest if others would do the same, otherwise they would only be partially reimbursed for the increased costs. However, even if other operators invest, the incentive for an individual operator to reduce costs and postpone investments remains the same as investments by others do not change the (marginal) profitability of specific investments projects.

In addition, the PwC (2009) gives evidence that the regulatory framework has been an incentive for operators to adopt a more rational approach with regard to investment policy. Network operators have taken a more critical attitude towards investments, which in practice has led to the implementation of risk-based asset management, and to increased professionalization of operational processes. This finding is in line with conclusions of Jamasb et al. (2008), Pollitt (2005) and Cambini and Rondi (2010).

Concluding, the regulation of the Dutch energy networks has had a significant effect on the tariffs energy users pay for using the grid. In addition, up to now there seems to be no evidence that this pressure by the regulatory framework has negatively affected the quality of the networks.

4 Tariff Regulation and Smart Grids

The key question now is whether yardstick regulation is also able to facilitate the transition in the energy industry from a fossil-fuel based industry into a renewable-energy based industry. In principle operators have two technological options to tackle this development. The first one is extending the grid, making the grid capacity sufficiently large to facilitate both peak demand and peak supply. The other option is making the existing grid smarter, which basically means the use of information technology to optimize the use of the grid. Either way, significant investments have to be made, raising the capital costs of the network operators. How does tariff-regulatory schemes deal with these costs and the incentives for the network operators to adapt their networks? For cost-plus types of regulation, the answer to this question is relatively simple as this type of regulation gives the operator full certainty that all costs will be reimbursed, no matter whether these investments are efficient or not. For price-cap types of regulation, this question is less easy to answer as this type of tariff regulation has mixed effects on the incentives as we have seen in the previous sections. Therefore we analyse this type of regulation further, focussing on one specific form of price-cap regulation which is yardstick regulation.

With yardstick regulation, all costs made by all network operators subject to this regulation enter into the yardstick. Consequently, on group level all realised costs are reimbursed. On firm level, however, some firms may face a cap on its revenues which is below its costs, while others are able to generate an economic profit when the cap on revenues is above the realised costs. When the firms operate in a similar regulatory and economic environment, the differences in productivity among the firms result from differences in choices made by the firms. Having this kind of differences is precisely the purpose of yardstick regulation.

What happens if a network operator wants to upgrade its network because of the abovementioned changes in the energy market? First of all, because of the price-cap character, yardstick regulation gives an incentive to each operator to search for the most efficient solution. If using information technology to stimulate electricity consumers to shift their use of electricity to off peak hours, for instance, appears to increase the productivity of the distribution network, the operator has an incentive to do so. The same holds when extending the network capacity results in a higher productivity. This is not only a theoretical insight, it also follows from empirical research: price-cap regulation stimulates regulated firms to make investments which increase productivity (Cambini and Rondi 2010).

In cases where upgrading the network does not raise the productivity of the firm, the impact of yardstick regulation is less clear. This may occur when upgrading the network calls for significant capital expenditures that do not immediately result in higher revenues. As a result, the productivity, which is measured by the ratio between total costs and standardized outputs, declines. In this scenario, the network operator has an incentive to hold up the investment. This scenario occurs when only a limited number of firms decide to make the investment, while others decide not to invest. Because of the yardstick formula, the revenues of each operator only increase by the share of the costs of the former group of operators in the total costs on group level. Consequently, the operators who have made the investment are only partly being compensated for the costs they made.

Uncertainty about the investment behaviour of other operator creates uncertainty for each operator about its revenues. This uncertainty may hamper investments in smart grids or network extension, not because operators are waiting on each other, but because they are uncertain about the benefits of a specific investment. If only some of the operators make these investments, the yardstick rises by the share of these operators in the total industry, but when all network operators make comparable investments, they will all be fully reimbursed. Their revenues increase by the costs which are made to upgrade the network. In other words, the system of yardstick compensation has as a consequence that the operators together will be fully reimbursed for all projects, no matter whether they are welfare enhancing or not, as long as all other operators conduct the same type of projects.

If all operators believe that a specific technique, like smart grids, is the most efficient technique to solve the future challenges they are facing, this view on the future technological challenges will likely appear to be true. In that case, rewarding all costs of smart grids seems also to be the optimal approach, even if the future benefits of these investments are still uncertain. If, however, some operators believe that investing in smart grids is the optimal approach, while others are more sceptical about the efficiency of such an investment, a different case appears. The efficiency of the investments then becomes unclear ex ante. If the investments appear to be efficient, operators having chosen for this technology will reap the benefits while others, who were hesitant to invest in the uncertain technology, will have higher costs.

Seen from this perspective, yardstick regulation effectively deals with investments with uncertain benefits. The higher the number of operators believing that this technique will have positive net benefits, the higher the number of operators that will actually make the upfront costs and the more the costs will be rewarded by the yardstick regulation. Despite the uncertainty operators have about the investment behaviour of other operators, they will always invest if they expect that the investment will create benefits within the operator itself, such as savings on network extension.

A system of yardstick regulation may hamper investments if network operators face significant differences in economic circumstances. After all, the system of yardstick regulation presumes that all operators operate in a level playing field. Whether this assumption holds has to be continuously checked. It is conceivable that network operators have in varying degrees, depending on regional circumstances, to deal with energy developments, such as distributed generation, or requests for electric-car charging stations, which will likely force them to adopt different investments patterns. Network operators that need to make substantial investments therefore incur more costs that are not sufficiently covered through the current tariff regulation. Such a development would call for flexibility in applying the yardstick regulation, meaning that raising the yardstick in specific cases may be efficient.

In addition, the regulatory framework may also result in a suboptimal level of investments in smart grids if these investments create positive externalities, i.e. if other participants benefit from the investments without sufficiently rewarding the network operator. The consequence of positive externalities is that the operators invest too less. This may occur when a new technology (or infrastructure) creates new products in the retail market, such as energy-saving services or charging options for electric cars, for which no tariff products have been defined. This externality or inefficiency in the framework can be solved by defining the appropriate products in the tariff structure of the networks.

Investments in smart grids may also generate positive benefits for the wholesale market. If the network operators are effective in realising peak shaving, the demand for peak generation capacity in the wholesale market declines which results in lower wholesale energy prices. If distribution-network operators are not integrated with companies on the wholesale market, as is the case in many countries, the operators are not able to include this benefit in their investment decision. Consequently, the operators may suboptimally invest in peak shaving. Because of the separation of network activities and wholesale activities, this market failure cannot be dealt with by tariff regulation. A policy measure to correct such a positive externality is to give the network operators public funding for activities directed at peak shaving.

5 Conclusion

Empirical evidence shows that yardstick regulation is able to foster productive efficiency of electricity networks without an adverse effect on the performance of these networks. The central question discussed in this chapter is whether yardstick regulation is also adequate to facilitate the transition in the energy industry from a fossil-fuel based industry into a renewable-energy based industry. We conclude that yardstick regulation gives incentives to operators to make their grids smarter if this contributes to a higher productivity of the grids. Yardstick regulation may, however, also hinder investments in smart grids if the operators do not operate in a similar economic environment, because not all investment costs will then be reimbursed. Yardstick regulation may also result in a suboptimal level of investments in smart grids when the network operators are not able to capture the positive externalities on the wholesale and retail energy markets.

These shortcomings can partly be minimized by introducing specific tariff categories to capture all benefits directly related to the network. External benefits which occur in the wholesale market, such as a positive effect of peak shaving measures by the network operators on the need for peak generation capacity, cannot be internalized through other tariff categories if network operation and wholesale activity are conducted in separated companies. In such cases, specific public funding may be an efficient solution to give the network operators the optimal incentives to realise the optimal level of investments in upgrading their networks in order to facilitate the energy transition.

Points for Discussion

- Does current regulation steer operators towards making the right investments in the grids to enable the energy transition?
- If decentralised energy production were to become a major trend, what effect would greater diversity of firms have on yardstick types of regulation?
- Would dynamic tariffs help in any way?
- Are tariffs the only way to shape the investments?

References

Agrell, P.J., Bogetoft, P., Mikkers, M.: Smart-grid investments, regulation and organization. Energy Policy **52**, 656–666 (2013)

Ajodhia, V., Lo Schiavo, L., et al.: Quality regulation of electricity distribution in Italy: an evaluation study. Energy Policy **34**, 1478–1486 (2006)

Averch, H., Johnson, L.: Behavior of the firm under regulatory constraint. Am. Econ. Rev. **52**(5), 1052–1069 (1962)

Burger, A., Geymueller, P.: Can We Measure Welfare? Dynamic Comparisons of Allocative Efficiency Before and After the Introduction of Quality Regulation for Norwegian Electricity Distributors. Vienna University of Economics and Business Administration (2008)

Cambini, C., Rondi, L.: Incentive regulation and investment: evidence from European energy utilities. J. Regul. Econ. **38**, 1–26 (2010)

Colak, I., Fulli, G., Sagiroglu, S., Yesilbudak, M., Covrig, C.-F.: Smart grid projects in Europe: Current status, maturity and future scenarios. Appl. Energy **152**, 58–70 (2015)

Dijkstra, P., Haan, M., Mulder, M.: Design of yardstick competition and consumer prices: experimental evidence. SOM Research Reports, vol. 15004-EEF. University of Groningen, SOM research school, Groningen (2015)

Granderson, G., Linvill, C.: Regulation, efficiency, and Granger causality. Int. J. Ind. Organ. **20**(9), 1225–1245 (2002)

Haffner, R., Helmer, D., van Til, H.: Investments and regulation: the Dutch experience. Electr. J. **23**(5), 34–46 (2010)

Jamasb, T., Pollitt, M., et al.: Productivity and efficiency of US gas transmission companies: a European regulatory perspective. Energy Policy **36**(9), 3398–3412 (2008)

Joskow, P.: Incentive regulation of electricity distribution networks: lessons of experience from Britain. Energy Policy **35**, 6163–6187 (2006)

Kay, J.: Culture and Prosperity: Why Some Nations Are Rich but Most Remain Poor. Harper Paperbacks (2005)

Kemp, R., Mulder, M., van Sinderen, J.: Outcome van NMa-optreden: een beschrijving van de berekeningsmethode. Netherlands Competition Authority, Working Papers 1 (2010)

Mulder, M.: Tariff regulation and profitability of energy networks. Netherlands Competition Authority, Working Paper 3 (2010)

Movares & Kiwa: Technisch onderzoek vervangingsinvesteringen netbeheerders. Utrecht (2009)

Nykamp, S., Andor, M., Hurink, J.L.: 'Standard' incentive regulation hinders the integration of renewable energy generation. Energy Policy **47**, 222–237 (2012)

Pollitt, M.: The role of efficiency estimates in regulatory price reviews: Ofgem's approach to benchmarking electricity networks. Utilities Policy **13**(4), 279–288 (2005)

PwC: Investeringen in energienetwerken onder druk? Een beoordeling van het reguleringskader. Amsterdam (2009)

Shleifer, A.: A theory of yardstick competition. Rand J. Econ. **16**(3), 319–327 (1985)

Ter-Martirosyna, A.: The Effects of Incentive Regulation on Quality of Service in Electricity Markets. George Washington University (2003)

Ter-Martirosyna, A., Kwoka, J.: Incentive regulation, service quality, and standards in U.S. electricity distribution. J. Regul. Econ. **38**(3), 258–273 (2010)

Veldman, E., Geldtmeijer, D.A.M., Knigge, J.D., Slootweg, J.G.: Smart grids put into practice: technological and regulatory aspects. Competition Regul. Netw. Indus. **11**(3), 287–306 (2010)

Viscusi, W.K., Vernon, J.M., Harrington, J.E.: Economics of Regulation and Antitrust (2005)

WRR: Infrastructures: time to invest. Amsterdam University Press (2007)

Frequency Regulation in Power Grids by Optimal Load and Generation Control

Sebastian Trip and Claudio De Persis

Abstract This chapter studies the problem of frequency regulation in power grids in the presence of unknown and uncontrollable generation and demand. We propose distributed controllers such that frequency regulation is achieved, while maximising the 'social welfare', i.e. maximising the utility of consuming power minus the cost of producing power. The controllable generation and loads are modeled as the output of a first-order system, which includes a widely used model describing the turbine-governor dynamics. We formulate the problem of frequency regulation as an output agreement problem for distribution networks and address it using incremental passivity, enabling a systematic approach to study convergence to the steady state with zero frequency deviation. In order to achieve optimality, the distributed controllers are utilising a communication network to exchange relevant information. The academic case study provides evidence that the performance of the controllers is good.

This work was partially supported by the Danish Council for Strategic Research (contract no. 11-116843) within the 'Programme Sustainable Energy and Environment', under the EDGE (Efficient Distribution of Green Energy) research project. Part of this work has appeared previously in Bürger et al. (2014), Trip et al. (2015).

S. Trip (✉) · C. De Persis
Engineering and Technology Institute Groningen (ENTEG), Faculty of Mathematics
and Natural Sciences, University of Groningen, Nijenborgh 4, 9747 AG Groningen
The Netherlands
e-mail: s.trip@rug.nl

C. De Persis
e-mail: c.de.persis@rug.nl

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_9

1 Introduction

Maintaining the frequency of the power grid close to its nominal value (e.g. 50 Hz.) is of great importance to guarantee a reliable operation. This is traditionally achieved by primary proportional control (droop-control) and a secondary PI-control at the different generators in the network. In this secondary control, commonly known as automatic generation control (AGC), each control area determines its 'Area Control Error' (ACE) and changes its production accordingly to compensate for local load changes to regulate the frequency back to its nominal value and to maintain the scheduled power flows between different areas. An increased penetration of renewable energy and technological advances have created a renewed interest in this frequency regulation. The use of smart grids, computer-based control and communication networks offer various economic and environmental advantages by lowering operational costs and reducing greenhouse gas emissions, while maintaining a high reliability. In this work we focus on two possibilities to improve the current approach to frequency regulation.

First, the requirement of each control area to compensate for their local load changes prevents the achievement of economic efficiency. To be economically efficient an accurate prediction of (renewable) generation and power demand is necessary in order to schedule the generation in advance. The large scale introduction of volatile renewable energy sources makes this however difficult. The net-load (uncontrolled demand minus uncontrolled generation) will change faster and by larger amounts. For this reason, the economic efficiency of AGC has attracted considerable attention (Ibraheem et al. 2005), removing the requirement of local compensation. Distributed controllers to achieve efficient frequency regulation can e.g. be found in Andreasson et al. (2013), where a linearised model of the power grid is analysed or in Apostolopoulou et al. (2014) where a discrete time model is investigated numerically. In Li et al. (2014) distributed controllers are developed by formulating a suitable optimisation problem. Similar studies have appeared for microgrids as well, see e.g. Trip et al. (2014), Simpson-Porco et al. (2013), Guerrero et al. (2011), Schiffer et al. (2013), Dörfler et al. (2014).

Second, demand side or load control presents a novel way for providing the desired frequency response. Load control can reduce the overall costs, since the reserve capacity of generators can be reduced (Aunedi et al. 2013). Additionally, load control provides the possibility of faster response times reducing frequency deviations. Work relating frequency regulation and distributed optimal load control has appeared e.g. in Zhao et al. (2013), Chen et al. (2012), Zhao and Low (2014), where primal-dual algorithms are investigated. Load control also paves the way to adjust demand by financial incentives, such as real-time pricing of electricity (Alvarado 1999; Kiani and Annaswamy 2011).

In order to control the power grid towards a desired state it is important to take into account the physical properties of the network. Over the last centuries mathematics has proven itself to be the most suitable language to describe the physics and it is for this reason that mathematics (control theory) also plays a central role in this work. We adapt our previous results in Bürger et al. (2014), where we proposed distributed controllers that minimise the generation costs, and extend it by including optimal load control and widely used first-order dynamics describing the controllable generation (e.g. turbine-governor dynamics) and the controllable loads. Remarkably, the used *nonlinear* dynamic model describing the power grid, is an incrementally passive system with respect to a steady state that is of interest (a steady state for which the frequency deviation is zero). Here we provide a systematic method, exploiting the incremental passivity property, to design distributed controllers that are able to achieve frequency regulation while maximising the so called 'social welfare' (Kiani and Annaswamy 2011), i.e. maximising the utility of consuming power minus the cost of producing power. Although we restrict ourselves in the present work to unknown but constant net-loads, the framework presented in Bürger and De Persis (2015) provides clear guidelines, based on the internal model principle (De Persis and Jayawardhana 2014), how controllers can be designed in more complex settings (Bürger 2014; Trip et al. 2015).

This chapter is organized as follows. In Sect. 2, we introduce the dynamic model describing the power grid. In Sect. 3, we analyse the dynamic model assuming constant generation and load, and show that it leads in general to a nonzero frequency deviation. In Sect. 4, we characterize the optimal generation and load that maximises the social welfare. In Sect. 5, a distributed controller is proposed which ensures frequency regulation and at the same time achieves this maximum social welfare. In Sect. 6, we test our controllers in an academic case study using simulations. In Sect. 7, conclusions are given and an outline for future research is provided.

2 Dynamic Model of the Power Grid

Before we can address the problem of designing controllers that adjust generation and demand to obtain frequency regulation, it is of great importance to be able to predict the response of the system to various inputs. In this section we introduce therefore a model (a set of differential equations) describing the dynamic behaviour of the frequency. The power grid can be regarded as a large interconnected network of smaller (control) areas, which can independently be represented by an equivalent single generator. In this work we model such an equivalent generator by the so called 'swing equation'. These 'swing equations' play a major role in stability studies of the power grid and describe the dynamic behaviour of the frequencies within the network. Its derivation is provided in the vast majority of books on power systems (see e.g. Machowski et al. 2008; Sauer and Pai 2007). How such equivalent models can be obtained for a specific area by e.g. coherency and aggregation techniques can be found in Chakrabortty et al. (2011), Ourari et al. (2006).

To make the network structure of the power grid more precise let us consider a network consisting of n control areas. The network is represented by a connected and undirected graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where the nodes, $\mathcal{V} = \{1, \ldots, n\}$, represent control areas and the edges, $\mathcal{E} \subset \mathcal{V} \times \mathcal{V} = \{1, \ldots, m\}$, represent the transmission lines connecting the areas. An example of such a graph is given in Fig. 1. The network structure can also be represented by a single matrix known as the incidence matrix $D \in \mathbb{R}^{n \times m}$. The elements of the matrix are defined as follows. The ends of edge k are arbitrary labeled with a '+' and a '−'. Then

$$d_{ik} = \begin{cases} +1 & \text{if } i \text{ is the positive end of } k \\ -1 & \text{if } i \text{ is the negative end of } k \\ 0 & \text{otherwise.} \end{cases}$$

Example 1 A possible incidence matrix for the network given in Fig. 1 is

$$D = \begin{pmatrix} 1 & 0 & 0 & -1 \\ -1 & 1 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & -1 & 1 \end{pmatrix}.$$

Every control area represents an aggregated amount of controllable generation P_i^G, controllable loads P_i^L and an *uncontrollable* net-load P_i^N. The uncontrollable net-load is the sum of all the uncontrollable loads and generation in an area and can be either positive or negative. It is important to notice that we do *not* assume that P_i^N is measured, which is important for the practical applicability. The dynamics of the voltage angle δ_i and the frequency ω_i^b of control area i are given by

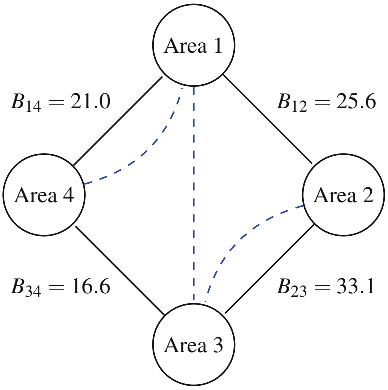


Fig. 1 A four area equivalent network of the power grid, where B_{ij} denotes the susceptance of the transmission line connecting two areas. The *dashed lines* represent the communication links

$$\begin{aligned}\dot{\delta}_i &= \omega_i^b - \omega^n \\ M_i \dot{\omega}_i^b &= P_i^G - \sum_{j \in \mathcal{N}_i} V_i V_j B_{ij} \sin(\delta_i - \delta_j) - A_i(\omega_i^b - \omega^n) - P_i^L - P_i^N.\end{aligned} \tag{1}$$

An overview of the used symbols is provided in Table 1.

Assumption 1 By using system model (1) following assumptions are made, which are standard in a broad range of literature on power grid dynamics and are generally valid for interconnected control areas by high voltage transmission lines.

1. Transmission lines are lossless, i.e. the conductance is zero.
2. Nodal voltages V_i are constant.
3. Reactive power flows are ignored.
4. A balanced load condition is assumed, such that the three phase network can be analysed by a single phase.

Due to physical constraints it is often not possible to change the generation instantaneously. In generators, the turbines and governors react e.g. gradually to a changed control signal. Similarly, consumers generally react slowly to e.g. price changes. The generation P_i^G and the load P_i^L are therefore modelled as the output of a first-order system,

$$\begin{aligned}\tau_{G_i} \dot{P}_i^G &= -P_i^G + u_i^G \\ \tau_{L_i} \dot{P}_i^L &= -P_i^L + u_i^L,\end{aligned} \tag{2}$$

Table 1 Overview of variables, inputs and parameters

Variables	
δ	Voltage angle
ω^b	Frequency
ω^n	Nominal frequency (e.g. 50 Hz)
P^G	Controllable generation at the control area
P^L	Controllable load at the control area
Controllable inputs	
u^G	Input to adjust generation
u^L	Input to adjust loads
Uncontrollable input	
P^N	Net-load at the control area
Parameters	
M	Inertia of the control area
A	Damping of the control area
V	Voltage of the control area
B	Susceptance of the transmission line
τ_G	Time delay of generation control
τ_L	Time delay of load control

where u_i^P and u_i^L are additional control inputs to be designed later in order to regulate the frequency in an optimal manner. The constants τ_{G_i} and τ_{L_i} represent the speed of which respectively generation and load can be altered. Although simplistic, these first-order dynamics are commonly used to model turbine-governor dynamics (Li et al. 2014; Zhang and Papachristodoulou 2014) or load dynamics (Alvarado 1999; Kiani and Annaswamy 2011. A more detailed discussion on (2) is postponed to Sect. 5, where we focus on the design of u_i^G and u_i^L to obtain frequency regulation and economic efficiency.

For the analysis in the following sections it is convenient to write system (1) compactly for all areas $i \in \mathcal{V}$ as

$$\begin{aligned} \dot{\eta} &= D^T \omega \\ M\dot{\omega} &= P^G - D\Gamma \sin(\eta) - A\omega - P^L - P^N \\ y &= \omega, \end{aligned} \tag{3}$$

where ω is the frequency deviation $\omega^b - \omega^n$, D is the incidence matrix corresponding to the network topology, $\Gamma = \operatorname{diag}\{\gamma_1, \ldots, \gamma_m\}$ with $\gamma_k = V_iV_jB_{ij} = V_jV_iB_{ji}$ where k denotes the line $\{i, j\}$ and $\eta = D^T\delta$. We write explicitly $y = \omega$ to stress that we only measure the frequency and not e.g. the power flows.

3 Stability and Incremental Passivity of the System

During the design of controllers it is useful if the system at hand has some nice (mathematical) properties that we can exploit. A given system can have many properties and a key question is which one is most useful for the controller design. In this section we establish an incremental passivity property of system (3) that turns out the be very useful in the subsequent sections, where we propose distributed controllers that optimally regulate the frequencies. Additionally, it is helpful for inferring asymptotic stability (i.e. the frequency converges to a constant when time approaches infinity) under constant[1] generation and load, i.e. $P^G = \overline{P}^G$ and $P^L = \overline{P}^L$. A similar analysis has also been carried out in our papers (Bürger et al. 2014; Trip et al. 2015). We recall the following definition of incremental passivity (Pavlov and Marconi 2008), which is well known in the control theory community, and enables to compare different trajectories of the system. In particular, it allows to compare the actual state of the system with its steady state.

---

[1] A variable which is constant is denoted with a bar.

Definition 1 Consider the system

$$\begin{aligned} \dot{x} &= f(x,u,t) \\ y &= h(x,t), \end{aligned} \tag{4}$$

with state $x \in \mathbb{R}^n$, input $u \in \mathbb{R}^l$ and output $y \in \mathbb{R}^l$. We say that system (4) is incrementally passive if there exists a storage function $Z(t,x,x')\colon \mathbb{R}_+ \times \mathbb{R}^{2n} \to \mathbb{R}^n$ such that for any two inputs $u(t)$ and $u'(t)$ and any two solutions to system (4) $x(t)$, $x'(t)$ corresponding to these inputs, the respective outputs $y(t) = h(x(t),t)$ and $y'(t) = h(x'(t),t)$ satisfy the inequality

$$\dot{Z} \leq (y - y')^T (u - u'). \tag{5}$$

Furthermore system (4) is *output strictly* incrementally passive when

$$\dot{Z} \leq -\rho(y - y') + (y - y')^T (u - u'), \tag{6}$$

where ρ is a positive definite function, i.e. a function that is positive for every nonzero value of $y - y'$, and zero when $y - y' = 0$.

In this work we are interested in proving asymptotic stability to some (desired) steady state. It is therefore useful to restrict the definition above to incremental passivity with respect to a steady state solution with constant input $(x', u') = (\overline{x}, \overline{u})$, where $(\overline{x}, \overline{u})$ satisfies

$$\begin{aligned} \mathbf{0} &= f(\overline{x}, \overline{u}, t) \\ \overline{y} &= h(\overline{x}, t). \end{aligned} \tag{7}$$

For system (3) this steady state solution necessarily satisfies

$$\begin{aligned} \mathbf{0} &= D^T \overline{\varpi} \\ \mathbf{0} &= \overline{P}^G - D\Gamma \sin(\overline{\eta}) - A\overline{\varpi} - \overline{P}^L - P^N \\ \overline{y} &= \overline{\varpi}. \end{aligned} \tag{8}$$

Notice that $\mathbf{0} = D^T \overline{\varpi}$ implies that at a steady state, the frequency deviations at all control areas are equal. The value of $\overline{\varpi}$ can be made specific by characterizing the solution to (8) and we do so in the following lemma.

Lemma 1 *If there exists* $(\overline{\eta}, \overline{\varpi}) \in \mathcal{R}(D^T) \times \mathbb{R}^n$ *such that* (8) *holds, then necessarily* $\overline{\varpi} = \mathbf{1}_n \omega_*$, *with*

$$\omega_* = \frac{\mathbf{1}_n^T(\overline{P}^G - \overline{P}^L - P^N)}{\mathbf{1}_n^T A \mathbf{1}_n} = \frac{\sum_{i \in \mathcal{V}}(\overline{P}_i^G - \overline{P}_i^L - P_i^N)}{\sum_{i \in \mathcal{V}} A_i}, \tag{9}$$

where $\mathbf{1}_n$ *is the vector of all ones. The vector* $\overline{P}^G - \overline{P}^L - P^N$ *must satisfy*

$$\left(I - \frac{A\mathbf{1}_n\mathbf{1}_n^T}{\mathbf{1}_n^T A \mathbf{1}_n}\right)(\overline{P}^G - \overline{P}^L - P^N) \in \mathcal{D}, \tag{10}$$

where

$$\mathcal{D} = \{v \in \mathcal{R}(D) : v = D\Gamma \sin(\overline{\eta}),\ \overline{\eta} \in \mathcal{R}(D^T)\}. \tag{11}$$

The proof of the lemma follows from algebraic manipulations of (8). One can notice that a surplus of generation will lead to a positive frequency deviation and a shortage of generation will lead to a negative frequency deviation. A characterization of the equilibria for related systems has been similarly discussed in and Simpson-Porco et al. (2013), Schiffer et al. (2013), Bergenand Hill (1981). Motivated by the result above, (10) is introduced as a feasibility condition that formalizes the physical intuition that the network is capable of transferring the electrical power at its steady state solution.

Assumption 2 For a given $\overline{P}^G, \overline{P}^L$ and P^N there exist $\overline{\eta} \in \mathcal{R}(D^T)$ for which (10) is satisfied.

Additionally, we need the following assumption, also referred to as a security constraint (Dörfler et al. 2014), to guarantee that all trajectories that start sufficiently close to an equilibrium remain bounded.

Assumption 3 The differences in voltage angles η satisfies at steady state $\overline{\eta} \in (\frac{-\pi}{2}, \frac{\pi}{2})^m$.

Having characterized the steady state solution of system (3) and having assumed that such a steady state solution exists, we are ready to state the main result of this section concerning the incremental passivity of the system with respect to the steady state solution.

Theorem 1 *Let* Assumptions 2 *and* 3 *hold. System* (3) *with input* $P^G - P^L$ *and output* $y = \omega$ *is an output strictly incrementally passive system, with respect to the constant equilibrium* $(\overline{\eta}, \overline{\omega})$ *satisfying* (8). *Namely, there exists a storage function* $Z_1(\omega, \overline{\omega}, \eta, \overline{\eta})$ *which satisfies the following incremental dissipation inequality*

$$\dot{Z}_1(\omega, \overline{\omega}, \eta, \overline{\eta}) = -\rho(y - \overline{y}) + (y - \overline{y})^T((P^G - P^L) - (\overline{P}^G - \overline{P}^L)), \tag{12}$$

where $\dot{Z}_1$ *represents the directional derivative of* Z_1 *along the solutions to* (3) *and* ρ *is a positive definite function.*

The proof is provided in the appendix. Having established this key property of incremental passivity of system (3), we can use this to infer other properties of the power grid. One consequence is that system (3) converges to an equilibrium when $P^G = \overline{P}^G$ and $P^L = \overline{P}^L$ are constant.

Corollary 1 *Let* Assumptions 2 *and* 3 *hold and let* P^G *and* P^L *be constant. Then there exists a neighbourhood of initial conditions around the equilibrium* $(\overline{\eta}, \overline{\varpi})$*, such that the solutions to* (3) *starting from this neighborhood converge asymptotically to an equilibrium as characterized in* Lemma 1.

The proof is provided in the appendix. The interpretation of Corollary 1 is that under Assumptions 2 and 3 system (3) converges to a steady state with a frequency deviation $\overline{\varpi}$ that is generally nonzero when $\overline{P}^G$ and $\overline{P}^L$ are not carefully chosen. This is the main motivation to design a controller that dynamically adjusts the generation and load.

4 Maximising Social Welfare

In the previous section we noticed that the *total* generation needs to be equal to the *total* load in the network, in order to achieve a zero frequency deviation. We have therefore the freedom to distribute the generation and load over the various areas. It is natural to wonder what desired optimality properties $\overline{P}^G$ and $\overline{P}^L$ should have. For this we recall again that it follows from Lemma 1 that the steady state frequency deviation only depends on the sum of generation and load, i.e. $\overline{\varpi}$ depends on $\mathbf{1}_n^T(\overline{P}^G - \overline{P}^L - P^N)$. Especially we have that $\overline{\varpi} = \mathbf{0}$ if and only if $\mathbf{1}_n^T(\overline{P}^G - \overline{P}^L - P^N) = 0$. In order to characterize the optimal distribution of generation and load, we assign to each controllable load a utility function $U_i(P_i^L)$, which characterizes the utility an area obtains from consuming P_i^L. Similarly, the controllable generation has an associated cost function $C_i(P_i^G)$ which characterizes the costs of generating P_i^G. An optimal control of generation and load is required to maximise the so called 'social welfare' S_W, which has been used as an optimality measure before in e.g. Chen et al. (2012), Kiani and Annaswamy (2011).

$$\begin{aligned} &\max_{P^L, P^G} S_W(P^L, P^G) = \max_{P^L, P^G}\left(\sum_{i\in\mathcal{V}} U_i(P_i^L) - \sum_{i\in\mathcal{V}} C_i(P_i^G)\right) \\ &\text{s.t. } 0 = \mathbf{1}_n^T(P^G - P^L - P^N). \end{aligned} \tag{13}$$

Comparing the equality constraint above to (9), we can see that the solution to (13) implies a zero frequency deviation at steady state ($0 = \mathbf{1}_n^T(P^G - P^L - P^N)$ implies a zero frequency deviation at steady state). We assume in the remainder that $U_i(P_i^L)$ and $C_i(P_i^G)$ are linear-quadratic functions (Kiani and Annaswamy 2011), i.e.

$$\begin{aligned} U_i(P_i^L) &= \frac{1}{2} q_i^L (P_i^L)^2 + r_i^L P_i^L + s_i^L \\ C_i(P_i^G) &= \frac{1}{2} q_i^G (P_i^G)^2 + r_i^L P_i^G + s_i^G, \end{aligned} \tag{14}$$

where $q_i^L < 0$ and $q_i^G > 0$. The total social welfare $S_W(P^L, P^G)$ can now be expressed as

$$S_W(P^L, P^G) = \frac{1}{2}(P^L)^T Q_L P^L + R_L^T P^L + S_L - \frac{1}{2}(P^G)^T Q_G P^G - R_G^T P^G - S_G, \tag{15}$$

with $Q_L = \text{diag}(q_1^L \ldots q_n^L)$, $R_L^T = (r_1^L, \ldots, r_n^L)$ and $S_L = (s_1^L, \ldots, s_n^L)^T$. The entries Q_G, R_G, S_G are defined similarly. In the following lemma we characterize the solution to the optimisation problem (13).

Lemma 2 *The solution* $(\overline{P}^L, \overline{P}^G)$ *to* (13) *is optimal if*

$$\begin{aligned} \overline{P}^L &= Q_L^{-1}(\mathbf{1}_n \overline{\lambda} - R_L) \\ \overline{P}^G &= Q_G^{-1}(\mathbf{1}_n \overline{\lambda} - R_G), \end{aligned} \tag{16}$$

where

$$\overline{\lambda} = \left(\frac{\mathbf{1}_n^T (P^N + Q_G^{-1} R_G - Q_L^{-1} R_L)}{\mathbf{1}_n^T (Q_G^{-1} - Q_L^{-1}) \mathbf{1}_n} \right). \tag{17}$$

Observing that λ is a scalar it is immediate to see that at the solution, all marginal utilities $q_i^L \overline{P}_i^L + r_i^L$ and marginal costs $q_i^G \overline{P}_i^G + r_i^G$ are equal. For the optimal control characterized above to guarantee a zero frequency deviation, the equalities (8) should now be satisfied with $\overline{P}^G - \overline{P}^L$ as in (16) and $\overline{\omega} = \mathbf{0}$. In this case, the second equality in Lemma 1 becomes

$$D\Gamma \sin(\overline{\eta}) = Q_G^{-1}(\mathbf{1}_n \overline{\lambda} - R_G) - Q_L^{-1}(\mathbf{1}_n \overline{\lambda} - R_L) - P^N, \tag{18}$$

with $\overline{\lambda}$ as in (17). Motivated by Lemma 2 and the remark that led to (18), we introduce the following condition that replaces the previous Assumption 2.

Assumption 4 For a given $\overline{P}^G - \overline{P}^L - P^N$, $\overline{\lambda}$ as in (17), there exist $\overline{\eta} \in \mathcal{R}(D^T)$ for which

$$Q_G^{-1}(\mathbf{1}_n \overline{\lambda} - R_G) - Q_L^{-1}(\mathbf{1}_n \overline{\lambda} - R_L) - P^N \in \mathcal{D}, \tag{19}$$

with $\mathcal{D}$ defined as in Lemma 1, is satisfied.

In this section we characterized the optimal generation and load such that the social welfare is maximised and that the steady state frequency deviation is zero. Notice that in this characterization the actual value of P^N is required, which hampers the possibility to calculate the optimal values for P^G and P^L. In the next section we address this issue by designing dynamic controllers that are able to converge to these optimal values without knowledge of P^N, using only frequency measurements.

5 Optimal Generation and Load Control

We now discuss what in our opinion makes the power grid intelligent, namely the presence of a provable correct algorithm that keeps the power grid stable and maximises the social welfare, despite unknown changes in e.g. renewable generation. We propose autonomous controllers for u^G and u^L, such that generation and load converge to an optimum as discussed in the previous section and at the same time ensure asymptotic convergence of the frequency deviation to zero. Consider therefore the first-order dynamics (2) for P_i^G and P_i^L. We can write them compactly for all nodes as

$$\begin{aligned} \tau_G \dot{P}^G &= -P^G + u^G \\ \tau_L \dot{P}^L &= -P^L + u^L. \end{aligned} \tag{20}$$

For notational convenience we also concatenate P^G and P^L to obtain

$$\tau \dot{P} = -P + u, \tag{21}$$

where $P = (P^G, P^L)^T$, $\tau = \text{diag}(\tau_G, \tau_L)$ and $u = (u^G, u^L)^T$. It is important that local controllers exchange information with their neighbours via a communication network. The underlying reason is that different parts of the network need to compare their marginal costs and utilities, in order to reach a situation where all marginal costs and utilities are equal. To ensure this optimality we require that every pair of controllers is directly, or indirectly via other controllers, connected with each other. This leads to the following assumption.

Assumption 5 The undirected graph reflecting the topology of information exchange among the nodes is connected.

We note that the proposed control architecture is completely distributed without the requirement of a centralized control unit, increasing its robustness and scalability. We can now state the main result, that is, the design of u^G and u^L, such that the frequencies in the network are regulated optimally. The proposed controller has two main components. First, the local frequency deviations ω are measured. Second, information (Q and R) about the marginal costs and utilities are exchanged via a communication network (represented by L_{comm}).

Theorem 2 *Consider system* (3) *interconnected with system* (21). *Let* Assumptions 3, 4 *and* 5 *hold. Let controllers at the nodes be*

$$\begin{pmatrix} u^G \\ u^L \end{pmatrix} = (I_{2n} - QL_{comm}Q)P - QL_{comm}QR - \left(\begin{pmatrix} 1 \\ -1 \end{pmatrix} \otimes I_n \right) \omega, \tag{22}$$

where $Q = \operatorname{diag}(Q_G, Q_L)$, $R = (R_G, R_L)^T$ *and* $L_{comm} \in \mathbb{R}^{2n \times 2n}$ *is the Laplacian matrix associated with a graph that describes the exchange of information among the controllers. Then* (22) *guarantees the solutions to the closed-loop system that start in a neighborhood of* $(\overline{\eta}, \overline{\omega}, \overline{P})$ *to converge asymptotically to the largest invariant set where* $\omega_i = 0$ *for all* $i = 1, 2, \ldots, n$ *and where the social welfare as in* (13) *is maximised.*

The proof is provided in the appendix and exploits the incremental passivity properties of the system and the controller. We can see from (22) that every area exchanges information with their neighbouring areas, indicating that a communication network is fundamental part of an intelligent power grid. Furthermore, the frequency deviation ω is measured in order to decide if the overall generation is too high or too low. This remarkable feature enables the optimal control without direct measurements of the uncontrollable net-load P^N. We can conclude that the designed control inputs u^G and u^L regulate the frequency deviation asymptotically to zero such that the power generation and load converge to a steady state that maximises the social welfare.

6 Case Study

We illustrate the performance of the controllers on an academic example of the electricity grid. Consider a 4-area interconnected system, as shown in Fig. 1. An overview of the numerical values used in the simulations can be found in Table 2. The system is initially at steady state with a constant net-load $P^N(t) = (10, 10, 10, 10)^T$, $t \in [0, 5)$ and according to their cost and utility functions generators and loads take a different share in the frequency regulation such that the total social welfare is maximised. At timestep 5 the net-load is changed to $P^N(t) = (12, 8, 20, 14)^T$, $t \geq 5$. The frequency response to the control input is given in Fig. 2. From Fig. 2 we can see how the frequency drops due to the increased net-load. Furthermore we note that the controllers regulate the power generation

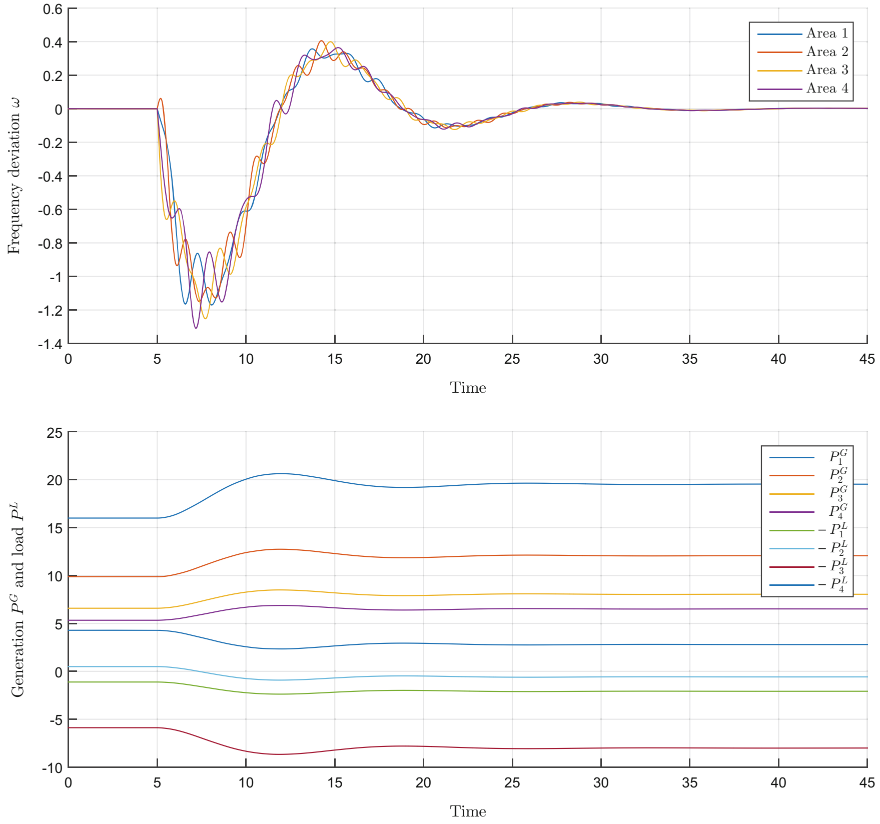


Fig. 2 Frequency response ω, generation P^G and load control P^L using the controller of Theorem 5. The constant net-load P^N is increased at timestep 5, whereafter the frequency deviation is regulated back to zero and the social welfare is maximised. For clarity reasons we show the value of $-P^L$

Table 2 An overview of the numerical values used in the simulation

	Area 1	Area 2	Area 3	Area 4
M_i	5.22	3.98	4.49	4.22
A_i	1.60	1.22	1.38	1.42
V_i	1.00	1.00	1.00	1.00
τ_i^G	2.00	3.00	2.00	2.00
τ_i^L	1.00	0.50	0.40	0.10
q_i^G	2.10	3.40	5.10	6.30
r_i^G	0.00	0.00	0.00	0.00
s_i^G	6.00	5.00	4.00	6.00
q_i^L	−7.70	−6.90	−3.50	−5.00
R_i^L	25.0	37.0	13.0	55.0
s_i^L	0.00	0.00	0.00	0.00

and demand such that a new steady state condition is obtained where the frequency deviation is again zero and the social welfare is maximised.

7 Conclusions and Future Research

We have investigated the use of incremental passivity to design distributed controllers that regulate the frequency and maximise the social welfare by carefully sharing generation and load control among different control areas in the power network. Based on first-order dynamics for generation and load control, commonly found in literature, we adjusted the way how generation and loads are modified as a response to changing frequencies. An important aspect to achieve optimality is the existence of an underlying communication network, that is used to share information between the different areas.

In a future research direction we will include for the present setting time-varying changes in the uncontrollable net-load and the extension to higher order models for the control areas, as we have done in Trip et al. (2015). Extending the first-order dynamics of the generation control to a second order system (Zhao and Low 2014) will also be investigated. Including dynamic pricing of electricity is an exciting open research area, as well as the inclusion of more realistic constraints of the physics and the economic market.

Appendix

Proof of Theorem 1

Proof. Consider the regular storage function

$$
\begin{aligned}
Z_1(\omega,\varpi,\eta\overline{\eta}) = {} & \frac{1}{2}(\omega-\varpi)^T M(\omega-\varpi) \\
& - \mathbf{1}^T \Gamma \cos(\eta) + \mathbf{1}^T \Gamma \cos(\overline{\eta}) - (\Gamma \sin(\overline{\eta}))^T(\eta-\overline{\eta}).
\end{aligned}
\tag{23}
$$

We have that

$$
\begin{aligned}
\dot{Z}_1 &= (\omega-\varpi)^T \Big(-A(\omega-\varpi) - D\Gamma(\sin(\eta)-\sin(\overline{\eta})) + ((P^G-P^L)-(\overline{P}^G-\overline{P}^L))\Big) \\
&\quad + (\Gamma(\sin(\eta)-\sin(\overline{\eta})))^T D^T(\omega-\varpi) \\
&= -(\omega-\varpi)^T A(\omega-\varpi) - (\omega-\varpi)^T((P^G-P^L)-(\overline{P}^G-\overline{P}^L)),
\end{aligned}
\tag{24}
$$

which proves the claim. □

Proof of Corollary 1

Proof. Bearing in mind Theorem 1 and setting $P^G - P^L = \overline{P}^G - \overline{P}^L$, the overall storage function $Z_1(\omega, \overline{\omega}, \eta, \overline{\eta})$ satisfies along the solutions to (3)

$$\dot{Z}_1 = -(\omega - \overline{\omega})^T A(\omega - \overline{\omega}). \tag{25}$$

As $\dot{Z}_1 \leq 0$ and $(\overline{\omega}, \overline{\eta})$ is a strict local minimum of Z_1 as a consequence of Assumption 3, there exists a compact level set Υ around the equilibrium $(\overline{\omega}, \overline{\eta})$, which is forward invariant. By LaSalle's invariance principle the solution starting in Υ asymptotically converges to the largest invariant set contained in $\Upsilon \cap \{(\omega, \overline{\eta})\colon \omega = \overline{\omega}\}$. On such invariant set the system is

$$\begin{aligned} \dot{\eta} &= \mathbf{0} \\ \mathbf{0} &= -D\Gamma(\sin(\eta) - \sin(\overline{\eta})). \end{aligned} \tag{26}$$

From $\dot{\eta} = \mathbf{0}$ it follows that on the invariant set η is a constant and from the second line it follows that $\eta = \overline{\eta}$. One can conclude that the system indeed converges to an equilibrium as characterized in Lemma 1. ☐

Proof of Theorem 2

Proof. Bearing in mind Theorem 1, we have that the incremental storage function Z_1 satisfies along the solutions to (3)

$$\dot{Z}_1 = -(\omega - \overline{\omega})^T A(\omega - \overline{\omega}) + (\omega - \overline{\omega})^T ((\, 1 \quad -1\,) \otimes I_n)(P - \overline{P}), \tag{27}$$

showing that the system is output strictly incrementally passive. This equality holds in particular for $\overline{\omega} = \mathbf{0}$, with $\overline{P}^G$ and $\overline{P}^L$ as given in (16), and we restrict the subsequent analysis to this solution of interest. The dynamics for P are with u is in (22), given by

$$\tau \dot{P} = -QL_{comm}(QP + R) - \left(\begin{pmatrix} 1 \\ -1 \end{pmatrix} \otimes I_n \right) \omega. \tag{28}$$

Consider the incremental storage function

$$Z_2(P, \overline{P}) = \frac{1}{2}(P - \overline{P})^T \tau^{-1} (P - \overline{P}), \tag{29}$$

which satisfies along the solutions to (22)

$$\begin{aligned} \dot{Z}_2 &= -(P - \overline{P})^T QL_{comm}(QP + R) + (P - \overline{P})^T \left(\begin{pmatrix} 1 \\ -1 \end{pmatrix} \otimes I_n \right) \omega \\ &= -(P - \overline{P})^T QL_{comm}Q(P - \overline{P}) + (P - \overline{P})^T \left(\begin{pmatrix} 1 \\ -1 \end{pmatrix} \otimes I_n \right) \omega, \end{aligned} \tag{30}$$

where we use that $\mathbf{0} = -QL_{comm}(Q\overline{P} + R)$. Notice that $Z = Z_1 + Z_2$ satisfies now along the solutions to the closed loop system of (3) and (22)

$$\dot{Z} = \dot{Z}_1 + \dot{Z}_2 = -\omega^T A\omega - (P - \overline{P})^T QLQ(P - \overline{P}), \tag{31}$$

where we have set $\overline{\omega} = \mathbf{0}$. As $\dot{Z} \le 0$, there exists a compact level set Υ around the equilibrium $(\overline{\eta}, \overline{\omega}, \overline{P})$ which is forward invariant. By LaSalle's invariance principle the solution starting in Υ asymptotically converges to the largest invariant set contained in $\Upsilon \cap \{(\overline{\eta}, \overline{\omega}, \overline{P}) : \overline{\omega} = \mathbf{0}, QP = Q\overline{P} + \mathbf{1}_{2n}\alpha(t)\}$, where $\alpha(t)$ is a scalar function and $QP = Q\overline{P} + \mathbf{1}_{2n}\alpha(t)$ follows from the communication graph being connected. On such invariant set the system is

$$\begin{aligned} \dot{\eta} &= \mathbf{0} \\ \mathbf{0} &= -D\Gamma(\sin(\eta) - \sin(\overline{\eta})) + (1 - 1) \otimes I_n)Q^{-1}\mathbf{1}_{2n}\alpha(t). \\ \mathbf{1}_{2n}\dot{\alpha}(t) &= -QL_{comm}(Q\overline{P} + \mathbf{1}_{2n}\alpha(t) + R). \end{aligned} \tag{32}$$

By pre-multiplying the second equation by $\mathbf{1}_n^T$ it follows that necessary $\alpha(t) = 0$. From $\dot{\eta} = 0$ it follows that on the invariant set η is a constant and from the second line it follows that $\eta = \overline{\eta}$. By invertibility of Q we furthermore have that $P = \overline{P}$. We conclude that the dynamical controller guarantees asymptotic regulation to a frequency deviation of zero and convergence to the optimal generation $\overline{P}^G$ and the optimal load $\overline{P}^L$. □

Points for Discussion

- Do the swing equations studied here capture the relevant dynamics of the grid to study the frequency deviation?
- Is the name “social welfare” function the appropriate name for the cost function used? How does economic optimization relate to the concept of social welfare? Is it possible to capture other terms into this function?
- How important are general delays in the network, and can they jeopardize the stability or optimality?
- Is this framework useful for further generalization and for coupling to layered structures of the physical grid, as well as to layered (currently different from the physical layers) market structures? How does it combine with market structures?

References

Alvarado, F.: The stability of power system markets. IEEE Trans. Power Syst. **14**(2), 505–511 (1999)

Andreasson, M., Dimarogonas, D.V., Johansson, K.H., Sandberg, H.: Distributed vs. centralized power systems frequency control under unknown load changes. In: Proceedings of the 12th European Control Conference (ECC), Zurich, Switzerland, pp. 3524–3529 (2013)

Apostolopoulou, D., Sauer, P., Dominguez-Garcia, A.: Automatic generation control and its implementation in real time. In: Proceedings of the 47th Hawaii International Conference on System Sciences (HICSS), Waikoloa, HI, USA, pp. 2444–2452 (2014)

Aunedi, M., Kountouriotis, P.-A., Calderon, J., Angeli, D., Strbac, G.: Economic and environmental benefits of dynamic demand in providing frequency regulation. IEEE Trans. Smart Grid **4**(4), 2036–2048 (2013)

Bergen, A., Hill, D.: A structure preserving model for power system stability analysis. IEEE Trans. Power Apparatus Syst. **PAS-100**, 25–35 (1981)

Bürger, M., De Persis, C.: Dynamic coupling design for nonlinear output agreement and time-varying flow control. Automatica **51**, 210–222 (2015)

Bürger, M., De Persis, C., Trip, S.: An internal model approach to (optimal) frequency regulation in power grids. In: Proceedings of the 21st International Symposium on Mathematical Theory of Networks and Systems (MTNS), Groningen, the Netherlands, pp. 577–583 (2014)

Chakrabortty, A., Chow, J.H., Salazar, A.: A measurement-based framework for dynamic equivalencing of large power systems using wide-area phasor measurements. IEEE Trans. Smart Grid **2**(1), 68–81 (2011)

Chen, L., Li, N., Jiang, L., Low, S.: Optimal demand response: problem formulation and deterministic case. In: Control and Optimization Methods for Electric Smart Grids, vol. 3, pp. 63–85. Springer, New York (2012)

De Persis, C., Jayawardhana, B.: On the internal model principle in the coordination of nonlinear systems. IEEE Trans. Control Netw. Syst. **1**(3), 272–282 (2014)

Dörfler, F., Simpson-Porco, J.W., Bullo, F.: Breaking the hierarchy: distributed control & economic optimality in microgrids. arXiv preprint arXiv:1401.1767 [math.OC] (2014)

Guerrero, J.M., Vasquez, J.C., Matas, J., de Vicuña, L.G., Castilla, M.: Hierarchical control of droop-controlled ac and dc microgrids, a general approach toward standardization. IEEE Trans. Industr. Electron. **58**(1), 158–172 (2011)

Ibraheem, I., Kumar, P., Kothari, D.: Recent philosophies of automatic generation control strategies in power systems. IEEE Trans. Power Syst. **20**(1), 346–357 (2005)

Kiani, A., Annaswamy, A.: Wholesale energy market in a smart grid: dynamic modeling and stability. In: Proceedings of the IEEE 50th Conference on Decision and Control (CDC), Orlando, FL, USA, pp. 2202–2207 (2011)

Li, N., Chen, L., Zhao, C., Low, S.: Connecting automatic generation control and economic dispatch from an optimization view. In: Proceedings of the 2014 American Control Conference (ACC), Portland, OR, USA, pp. 735–740 (2014)

Machowski, J., Bialek, J., Bumby, D.J.: Power System Dynamics: Stability and Control, 2nd edn. Wiley, New York (2008)

Ourari, M., Dessaint, L.-A., Do, V.-Q.: Dynamic equivalent modeling of large power systems using structure preservation technique. IEEE Trans. Power Syst. **21**(3), 1284–1295 (2006)

Pavlov, A., Marconi, L.: Incremental passivity and output regulation. Syst. Control Lett. **57**, 400–409 (2008)

Sauer, P., Pai, M.: Power System Dynamics and Stability. Stipes Publishing Co. (2007)

Schiffer, J., Ortega, R., Astolfi, A., Raisch, J., Sezi, T.: Synchronization of droop-controlled microgrids with distributed rotational and electronic generation. In: Proceedings of the IEEE 52nd Conference on Decision and Control (CDC), Florence, Italy, pp. 2334–2339 (2013)

Simpson-Porco, J.W., Dörfler, F., Bullo, F.: Synchronization and power sharing for droop-controlled inverters in islanded microgrids. Automatica **49**(9), 2603–2611 (2013)

Trip, S., Bürger, M., De Persis, C.: An internal model approach to frequency regulation in inverter-based microgrids with time-varying voltages. In: Proceedings of the IEEE 53rd Conference on Decision and Control (CDC), Los Angeles, CA, USA (2014)

Trip, S., Bürger, M., De Persis, C.: An internal model approach to (optimal) frequency regulation in power grids. Automatica (2015), regular paper, to appear. Preprint available at arXiv:1403.7019

Zhang, X., Papachristodoulou, A.: Redesigning generation control in power systems: methodology, stability and delay robustness. In: Proceedings of the IEEE 53rd Conference on Decision and Control (CDC), Los Angeles, CA, USA, pp. 953–958 (2014)

Zhao, C., Low, S.: Optimal decentralized primary frequency control in power networks. In: Proceedings of the IEEE 53rd Conference on Decision and Control (CDC), Los Angeles, CA, USA, pp. 2467–2473 (2014)

Zhao, C., Topcu, U., Low, S.: Power system dynamics as primal-dual algorithm for optimal load control. Submitted to IEEE Trans. Autom. Control (2013)

Charging Electric Vehicles in the Smart Grid

Chris Develder, Matthias Strobbe, Klaas De Craemer and Geert Deconinck

Abstract High level challenges that motivate the evolution towards smart grids include (i) the anticipated electrification of transportation, including electrical vehicles (EVs), and (ii) the increasing penetration of distributed renewable energy sources (DRES). This chapter will discuss how the extra grid load stemming from the EVs can be handled, including the context of reduced control over power generation in light of DRES adoption (especially solar and wind power). After a basic introduction to common EV charging technology, we give two illustrative examples of controlling EV charging: avoiding peaks, and balancing against renewable generation. We then qualitatively present possible demand response (DR) strategies to realize such control. Finally, we highlight the need for, and underlying principles of, (smart grid) simulation tools, e.g., to study the effectiveness of such DR mechanisms.

1 Introduction

The transition of today's electricity grid towards a *smart grid* is driven by the need to make electricity delivery more reliable, economical and sustainable. The challenges ahead stem from (i) increased electrification, as well as (ii) higher penetration of

---

C. Develder (✉) · M. Strobbe
Ghent University—iMinds, Ghent, Belgium
e-mail: chris.develder@intec.ugent.be

M. Strobbe
e-mail: matthias.strobbe@intec.ugent.be

K. De Craemer
Vito—EnergyVille, Antwerp, Belgium
e-mail: klaas.decraemer@vito.be

G. Deconinck
KULeuven—EnergyVille, Leuven, Belgium
e-mail: geert.deconinck@kuleuven.be

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_10

renewable energy sources (RES). Examples of (i) include the electrification of the electrical vehicle fleet, or heat pumps.

One challenge of (ii), i.e., RES such as wind turbines and solar panels, is their location: they are very much distributed (DRES), and typically connected in the distribution grid (low or medium voltage). This is in sharp contrast to more classical generation such as hydro plants, or the less environmentally friendly coal, gas or nuclear plants. These distribution grids (especially the low voltage portions) however have not been designed for the resulting power flows, which are potentially bidirectional. The power injection at the points of connection of the DRES may lead to voltage variations and even violation of the admissible voltage boundaries (e.g., beyond the maximal voltage limit). Further, when a feeder is disconnected from the grid, the generation within the islanded feeder may still be there, thus leading to unsafe scenarios both for equipment and people.

Another challenge obviously is the intermittent, uncontrollable generation from DRES: we have no influence on how hard the wind blows, or the sun shines, and thus we note a paradigm shift from steering generation to controlling the load. This calls for scalable algorithms to achieve demand response (DR), e.g., by assessing the possible flexibility that can be exploited by shifting (a portion of the total) consumption in time. Another option would be to decouple production and consumption of power in time, through storage. Still, the latter for now is not cost effective yet for a massive rollout, e.g., in the distribution grid at each household or even aggregated per feeder.

Thus, some major challenges for the transition to smart grids are (i) the development of scalable control algorithms (potentially ranging from fully distributed to more centralized), (ii) the introduction of and reliance on information and communication technology (ICT) infrastructure and its interworking with the power grid, and (iii) the creation and implementation of new business and market models. It is clear that these challenges are not only technical, but also may require adaptation of regulatory frameworks.

The focus of this chapter will be on electrical vehicles (EVs), in terms of how to cope with the additional load on the power grid they entail, as well as how their charging can be optimized to maximally exploit RES power. Section 2 will first provide an overview of EV technology, the charging process, and the communication options for exchanging the charging control information. Next, we present two illustrative case studies: Sect. 3 considers controlling EV charging to avoid peaks in a residential distribution feeder, while Sect. 4 studies balancing the wind power generation with a fleet of EVs. In Sect. 5, we then give a more general overview of possible strategies for demand response algorithms. Lastly, Sect. 6 indicates the main ideas of smart grid simulation tools to study such cases. Section 7 then summarizes the conclusions.

2 Electrical Vehicle Charging

Electric vehicles (EVs) can be implemented as *hybrid electric vehicles (HEVs)* or *Battery Electric Vehicles (BEVs)*. Both contain a battery to power an electric motor, but a Hybrid Electric Vehicle also contains an internal combustion engine (ICE) that can recharge the battery or operate as a range extender. BEVs and *Plugin HEVs (PHEVs)* are charged through the electric power system, which can lead to increased congestion of the grid. Especially the impact on the low voltage grid can be significant, if the peak of arriving EVs that plug into charge at home corresponds to the residential load peak (Clement-Nyns et al. 2010; Gomez and Morcos 2003; see also Sect. 3).

At the same time, while the charging of EVs requires a large amount of energy, vehicles tend to be stationary during long periods, for example during the night or working hours. This creates the opportunity to spread the charging of the batteries in time and thereby limit their impact on the distribution grid. Coordinated charging of electric cars in a smart grid is an excellent application of large-scale demand response of (domestic) appliances, and is the focus of a lot of current research. Before moving to some illustrative case studies, this section summarizes the typical charging process.

2.1 *Battery Charging and State of Charge*

The charging process of an EV is primarily determined by the properties of its battery pack (NiMH, Li-ion variants, etc.). The battery capacity of contemporary PHEVs varies from 4 to 20 kWh, while that of EV batteries rather lies between 15 and 35 kWh.

Because of concerns of accelerated degradation, battery cells are not used between 0 and 100 % of their potential energy storage capacity: state-of-charge (SOC) levels close to empty and full put the highest strain on the cells. During charging, and at high SOC states, the amount of current that can be “sinked” into the pack is limited by the maximum voltage that can safely be applied over the cells (Panasonic 2007). If a cell is overvolted, chemical reactions occur that can permanently damage the cell. As a consequence, a high SOC also hinders brake energy recuperation. Similarly, too low a cell voltage leads to a progressive breakdown of its electrodes.

Because of the aforementioned risks, the charging process is controlled and guarded by a Battery Management System (BMS). During charging, a BMS will vary power depending on the SOC (Seljeseth et al. 2013; Kapoor 2012). Typically, there is a constant current (CC) and a constant voltage (CV) phase, pictured conceptually in Fig. 1a. During the CV mode, charging power decreases quickly and the amount of energy that is stored into the cell during this phase is relatively small.

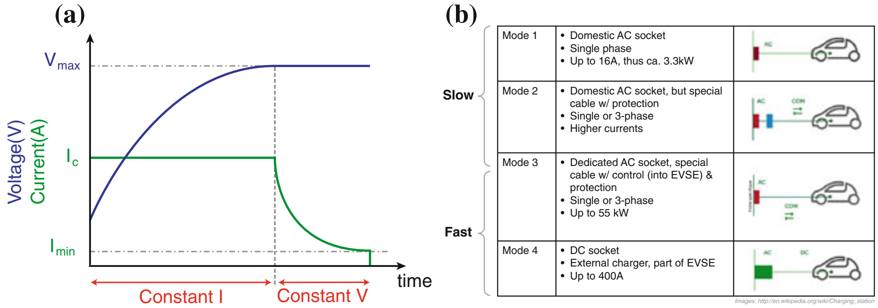


Fig. 1 Electrical vehicle charging. **a** Charging process. **b** Charging modes

2.2 *IEC Charging Modes*

IEC 62196 (IEC Technical Committee 23 2011) defines plugs, socket outlets, vehicle connectors and vehicle inlets. The charging modes, as summarized in Fig. 1b, are referenced in IEC 61851-1:

- Mode 1 provides basic charging capabilities for domestic use, such that standard electrical plugs and outlets can be used (e.g., the CEE “Schuko” plug in Europe). The current in this mode is at most 16 A, meaning that for a single phase connection, charge power is limited to ~3.3 kW.
- Mode 2 allows for higher charge currents, but imposes additional safety measures on the vehicle port and charging cable. A *control pilot* (CP) pin in the charging cable or in-line control box and the vehicle’s charge connector is used to indicate the maximum charge current supported by the cable. Detection for proper earthing is also required.
- Mode 3 defines (fast) charging using an AC connection up to 55 kW and requires the use of dedicated EVSE (Electric Vehicle Supply Equipment), such as a wallbox. The requirement of a *proximity pin* (PP) with a shorter length ensures that a sudden disconnection or interruption is detected and the cable becomes unpowered.
- Mode 4 describes fast charging using DC, with an external charger. Work on standardization of DC charging is underway in IEC 62196-3.

2.3 *Communication*

All plugs and sockets, with the exception of the residential CEE “Schuko” plug (Mode 1), are designed to allow communication between the EV and the grid equipment (i.e., electrical vehicle supply equipment, EVSE), transferring charge power settings and schedules, as indicated in the right part of Fig. 1b. An overview using early standards can be found in Ruthe et al. (2011).

- *EVSE to EV:* IEC 61851-1 defines a low level signaling protocol over the control pin (CP). Signaling from the EVSE to the vehicle is performed using a 1 kHz PWM signal, from which the duty cycle is varied to indicate the current capabilities of the charging station.
- *EV to EVSE:* The EV can also send state information to the EVSE by switching load impedances between CP-PE [Control pin, Protected Earth; see Lewandowski et al. (2011)]. The EV's charger can indicate whether it is ready for charging or that ventilation is required during the charging process.

Also higher layer protocols exist (such as specified in IEC 15118), which allow applications related to identification, payment, load leveling and value-added services. The Open Charge Point Protocol (OCPP) and IEEE P2030.1 allow communication between the EVSE or charge pole and a back office (e.g., an aggregator that coordinates the charging of a whole fleet).

2.4 Alternative Charging Solutions

Besides conductive charging (via a cable), alternative solutions exist, such as battery swapping or inductive charging. These solutions are not widely spread in the market yet, but provide similar opportunities for demand response as in case of conductive charging.

3 Sample Case Study 1: Load Flattening

Now that we have outlined the main EV charging approaches, we venture into a first analysis of the impact of EV charging on the grid, in terms of total power consumption in a residential low voltage grid. In particular, we address the following high level questions:

1. What is the impact of uncontrolled EV charging in a residential environment?
2. What is the minimal impact on peak load that we could *theoretically* achieve?
3. How can we minimize the impact of EV charging in practice?

We explore these questions in a case study, detailed by Mets et al. (2012a), in a three-phase distribution feeder comprising 63 households, which each have a single phase connection. The base load of the houses—that is, the total power consumption minus the EV—is set to that of a typical winter day in Flanders (which is the time of year with maximal electricity consumption), as taken from actual measurements. As for the EVs, we consider three scenarios: *light*, *medium* and *heavy*, that represent increasing EV adoption.

To answer the first question, we define a “*business-as-usual*” *scenario (BAU)*, where drivers plug in their EVs when they arrive at home, and then the charging immediately starts. This scenario clearly needs no additional infrastructure beyond the charging equipment: no communication or control is needed. Yet, without any such control, power consumption from EV charging after arrival at home adds to the already existing peak in the base load profile, related to other human activities (cooking, appliance usage, hot water, etc.). In the particular case assumed by Mets et al. (2012a), the increase in peak load due to EV charging amounts to between 1.5× and over 3× the original base load peak, i.e., an increase in the same order of magnitude as the original peak. We note that also in terms of total yearly power consumption, the energy used for charging a full EV is in the same range of a typical household’s energy from the non-EV base load. Clearly, to avoid the need to reinforce the grid with extra generation (to meet the peak load), spreading the EV charging in time is needed—as to minimize coincidence with the already existing peak load. We note that apart from peak load reduction, spreading the EV charging in time also may help to avoid, e.g., over voltages. Indeed, when excessive power is being drawn at certain connection points, the voltage may drop to levels outside (i.e., below) the tolerable bounds around the nominal voltage. [We will not dwell on the latter point here; see Mets et al. (2012a).]

Now, we investigate the *theoretical bounds* in terms of minimizing peak load by shifting/spreading the EV charging in time: since most cars will stay connected all night before leaving in the morning, we do not need to start charging immediately upon arrival. We adopt *quadratic programming (QP)* to formulate an optimization problem that tries to shift around (EV charging) power consumption as to obtain a flat power consumption over time. The approach is theoretical, in the sense that it assumes all events (cars arriving and departing, the base load of households) are fully and correctly known. We consider two fundamentally different variants:

(i) *local control* only uses knowledge of the household itself (in terms of both base load and EV), while
(ii) *global control* relies on knowing also the state of other households (load and EVs).

Note that these fundamentally different assumptions also imply distinct infrastructure need to enable them in practice, as illustrated in Fig. 2a. Indeed, the *local*

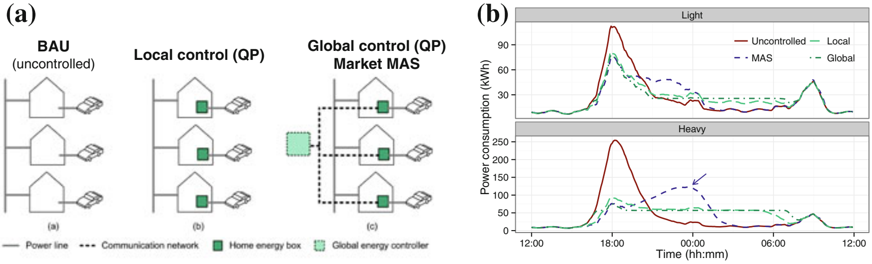


Fig. 2 Sample case study 1: load flattening. **a** Charging scenarios. **b** Results

approach only needs local technology to gather the data (e.g., arrival of the EV, and when it will leave again): no communication with other entities is strictly necessary. The *global control* approach needs at least a channel to reach other subscribers, either directly or through a centralized control entity—the latter depends on whether we realize the global control either as a fully distributed coordination strategy, or rather as a centralized one (see Sect. 5 for a discussion of the types of DR algorithms).

To move away from such bounds on what is achievable when we would be all-knowing (i.e., have perfect knowledge of past/present/(short) future EV and base load behavior), and rather get an idea of what is realistically achievable, we consider a market-based coordination mechanism, based on *multi-agent systems (MAS)*. In particular we consider a single-shot, multi-unit auction market mechanism (see Mets et al. 2012b). This means that the control signal that will steer power consumption, is a price signal. (That control price signal may be directly tied to actual monetary prices to be paid by consumers, but it could equally be purely virtual, i.e., just a means of control that could be completely decoupled from the billing of energy usage.) The general principle of the market-based MAS is that participating consumer entities, i.e., the EV chargers in our case, have a price response function, also known as a bidding function. Such bidding function determines what the power consumed will be for a given price. This function may change over time: e.g., for EVs, as the deadline for completing the charging approaches, the willingness to use power will increase and even for high(er) price signals charging will happen. The advantage of such a market based system is that the control signal is very simple, and the approach scales very well. Still, the design of the bidding curves is not a trivial exercise, and in our EV case it still assumes that the state-of-charge of the battery is perfectly known.

An illustrative comparison between the various cases is given in Fig. 2b. First, we note that all control approaches, both the theoretical (Local QP, Global QP) and more realistic ones (MAS) succeed in moving away the peak from that of the base load: the peak around 18:00 is entirely caused by the base load. Second, comparing Local versus Global, we note that in theory, even with just local knowledge (i.e., no communication beyond the household) the charging process can be controlled to successfully flatten the resulting total load profile of the entire feeder. Yet, we note that in our experiment the correlation between various households was quite high–whether in reality that will mostly be the case (or to the same extent as in our limited experiment) is debatable. Third, we note that depending on the EV penetration, the MAS system with the chosen linear bidding curves manages quite well in approaching the theoretical Local/Global QP boundary. Still, in case of the "heavy" scenario, we note the appearance of a new peak around midnight (indicated with the arrow): this illustrates that the design of the bidding functions can/should be tuned to the particular (amount of) interacting entities.

4 Sample Case Study 2: Balancing Renewable Generation

In the previous section we focused on dealing with the additional load stemming from EV charging, as to not aggravate the consumption peaks. Realizing that EV charging can be spread in time, now we investigate how well we can exploit that time shifting of charging to try and meet the intermittent production from renewable energy sources (over which we clearly have no full control). Apart from ecological motivations (i.e., to maximally exploit RES and avoid less environmentally friendly sources), there are also technical incentives to try and balance the RES production. For example, if RES generation is dispersed along a distribution feeder, the injection may raise the voltage level at the point of connection beyond the admissible limit, and thus create over-voltage problems.

In the illustrative case study (taken from Mets et al. 2012a) that we will now summarize, we consider balancing power supplied by a small scale wind turbine. In particular, we propose a distributed algorithm to balance renewable energy from wind turbines with the charging demand of electric vehicles, thereby increasing renewable energy consumption, and reducing emissions of greenhouse gasses. We approach this problem from the viewpoint of a balance responsible party (BRP), also known as access responsible party (ARP), that is responsible to ensure that energy supply matches energy consumption during a given time period: if the balance is not maintained, the BRP is required to pay imbalance costs. Therefore, the objective of the BRP is to minimize the imbalance costs. Nevertheless, the wishes and preferences of subscribers have to be respected, and are therefore accounted for in our approach, while maintaining privacy by not sharing their detailed consumption information directly (e.g., they do not share arrival and departure times, vehicle properties, nor the willingness to participate in balancing demand and supply).

We consider the following participants in our distributed coordination algorithm: (i) *subscribers* represent the EV charging spots, (ii) the *BRP* knows the wind generation (i.e., its predicted output), and thus the target consumption profile required to achieve balancing, (iii) the *coordinator* is the core component that will communicate with all previous parties and align them. Note that our case study here assumes only a single coordinator, but to further scale up, we can deploy also multiple coordinators, each managing their own set of subscribers. Similarly, one can introduce intermediate *aggregator* components, grouping together a set of subscribers and thus form an intermediate level (between subscribers and coordinator) in a hierarchical constellation. We will not discuss such more advanced setups here.

The algorithm we propose is an example of a receding horizon control algorithm. We assume a time slotted approach, say with 15 min timeslots. Every timeslot t, a control algorithm is executed considering the next T timeslots. As in our load flattening case, the control signal again is a *virtual* price signal. The steps are summarized as:

1. Initialization:
    (a) The BRP updates the wind power generation forecast $\mathbf{w} = [w_t, \ldots w_{t+T}]$ for the next T time slots.
    (b) The coordinator initializes a (virtual) price vector $\mathbf{p} = [p_t, \ldots p_{t+T}]$ used to steer demand and supply.
2. The coordinator sends the price vector **p** to the subscribers and the BRP.
3. Each subscriber calculates an power consumption schedule based on **p** and its own requirements and preferences, and sends that schedule to the coordinator.
4. The BRP determines an energy production schedule based on the wind power generation forecast and **p**, and sends it to the coordinator.
5. The coordinator collects the consumption schedules from the subscribers and production schedules from the BRP, and compares them:
    (a) If the discrepancy between supply and demand is below a predefined acceptance level, or the maximum number of iterations is reached, the algorithm terminates: subscribers and BRP are notified that the schedules are final.
    (b) Else, the coordinator updates the price vector **p** and iterates from step 2.

The mathematical materialization of this algorithm relies on dual decomposition to split the overall optimization problem in sub-problems that can be solved independently (and thus in parallel, distributed over multiple participants). We refer to Mets et al. (2012a) for details.

We applied that algorithm to a case study comprising 100 electric vehicles (with arrivals, departures and state-of-charge of the battery upon arrival that are derived from a statistical model of real-life vehicle usage data), and a small wind turbine with peak power output of 30 kW (whose the total power production over time slightly exceeds the required charging power aggregated over time). Illustrative results are shown in Fig. 3.

We compare the above distributed algorithm with two baselines (see Fig. 3): (i) a *business as usual (BAU)* scenario, where EVs are charged at full power as soon as they arrive, and (ii) an "ideal world" *benchmark* that fully minimizes imbalance,[1] which is all-knowing. The latter implies that the benchmark approach has full and exact knowledge of both wind power production and EV arrivals, departures and state-of-charge. Comparing our algorithm's results to the BAU scenario, we note that it clearly succeeds in avoiding the peaks in consumption, while reasonably matching the wind power generation profile. Whether we could in theory do much better can be seen by comparing to the benchmark: we note that the match is pretty good. The result of applying our algorithm is that the fraction of power supplied from the renewable source increases from 40 % in the BAU case to 68 % (while the theoretical benchmark reaches 73 %). This means that we can reduce the CO_2

---

[1] This imbalance is formulated as sum of squared differences between generation and consumption, summed over all timeslots.

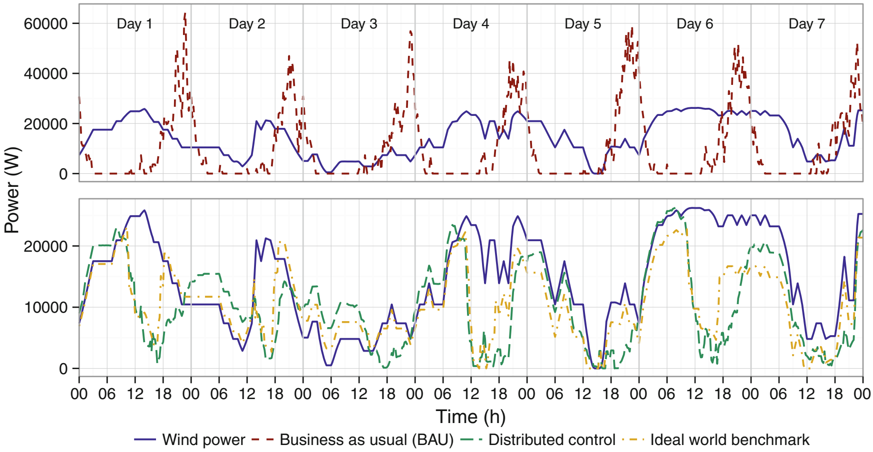


Fig. 3 Sample case study 2: balancing renewable generation. Note that the wind power curves in both plots are the same: controlled charging scenarios are shown with a different Y-axis scale to better distinguish them

emissions of the BAU case with about 45 %. Thus, we note that distributed coordination is a viable approach to tackle the challenge of shaping the consumption to renewable production. The next section will give a broader overview of possible strategies for such so-called demand response (DR) implementations.

5 Demand Response Strategies

Current research regarding the optimization and coordination of clusters of DR participants can roughly be divided according to the way the optimization is performed: distributed, centralized and aggregate and dispatch algorithms, as illustrated in Fig. 4a.

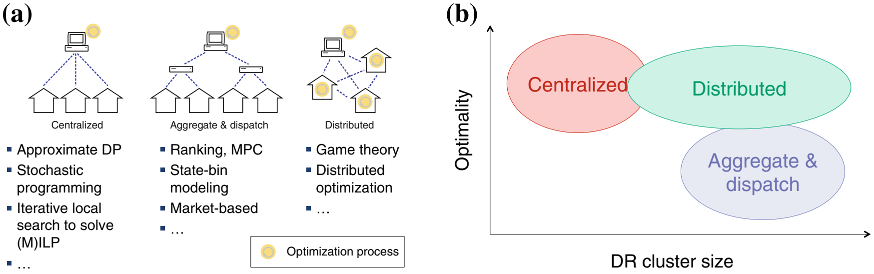


Fig. 4 Demand side management strategies. **a** Taxonomy. **b** Performance tradeoffs

Distributed algorithms perform a significant part of the optimization process of allocating energy over the cluster at the participating devices themselves. This way, the computational complexity of finding a suitable solution is spread out over the demand response cluster, typically using an iterative process where information is communicated between the participants. However, the distributed aspect does not exclude the existence of an entity responsible for initiating or coordinating the convergence over the iterations. Additionally, while possible, the implementation of a distributed algorithm is not necessarily in a peer-to-peer-style fashion, as would be suggested by Fig. 4a.

Centralized algorithms are entirely the opposite. A central actor collects information that is sent to it from the DR devices. This information can consist of individual constraints and deadlines or comfort settings. Using the collected knowledge, and possibly including its own additional information such as predictions or stochastic functions, the central coordinator can perform a single optimization that returns an optimal schedule satisfying all the constraints at once. Inherently, this makes centralized algorithms the least scalable, as the optimization process quickly becomes intractable with an increasing number of participating devices. Furthermore, the communication towards and from a single point poses a potential bottleneck. Several solutions are proposed that help to overcome the tractability issue.

In between distributed and centralized mechanism are the **aggregate and dispatch** algorithms. They decouple the optimization of the objective and the dispatch of its outcome, thus alternatively the term *dispatching mechanism* is equally fitting. An aggregate and dispatch mechanism allows information (such as constraints) from and to the central entity to be aggregated, reducing the complexity of the optimization and improving scalability, but carrying certain compromises or constraints regarding the optimality of the results.

Centralized algorithms provide a way to incorporate a large amount of diverse information and constraints in the DR scheduling problem, which can then be solved by well-established mathematical techniques. This guarantees that the outcome is optimal with respect to the problem's constraints. However, due the complexity involved, the time needed for solving quickly spirals out of control when scaling to large clusters of devices or when more advanced scenarios are taken into account. This is referred to as the curse of dimensionality, and can be partly addressed by the use of approximation and search techniques.

As an alternative, the DR scheduling problem can be broken down so that it can be distributed over multiple participants in the DR cluster (e.g., De Craemer et al. 2014). A method such as dual decomposition works by iteratively exchanging demand information and coordination signals between a central entity and the cluster's autonomous devices until convergence is reached. Alternatively, the use of game theory can provide proofs regarding the fairness of the scheduling process. The downside of the distributed algorithms is related to the need to exchange additional messages between the devices (since either multiple iterations are required or they communicate directly with each other) and the additional complexity involved due to the requirements for the communication system.

The division of the algorithms into centralized and distributed is also loosely tied to the control architecture in which they would be implemented. A centralized algorithm will have a single entity where all data for the optimization is collected and coordination signals to the individual DR devices is sent out from. In the distributed case, devices are more autonomous and may even communicate in peer-to-peer fashion.

An alternative to the centralized and distributed algorithms is provided by aggregate and dispatch algorithms. These methods use an aggregated model to represent or approximate the collective state of the DR cluster. The model is updated with state information from the individual devices. Scheduling then takes place using the aggregated model and the result is dispatched to the DR devices through, e.g., heuristic methods. Because the aggregated model fails to capture some of the details of the individual devices' state and heuristics are not perfect, aggregate and dispatch methods do not achieve the most optimal schedule. However, they obtain results that are close to the centralized or distributed algorithms, but at much lower complexity, and scale well to DR clusters containing large amounts of devices. They constitute a good trade-off, as they can achieve most of the benefits of DR at a large scale, but at low complexity and consequently cost.

In light of the above description, Fig. 4b positions the three classes of DR algorithms in terms of scalability and optimality.

6 Simulation Tools

Simulation tools offer a cost effective and safe approach to assess the performance of demand response control strategies and other smart grid use cases (such as the ones presented in Sects. 3 and 4). Different solutions can be evaluated under varying conditions before actually deploying them in the field, as to study the complex interactions between communication networks and power systems, and the monitoring and control elements on top of them.

Within smart grid research three groups of applicable tools can be distinguished:

(i) power system simulators,
(ii) communication network simulators, and
(iii) smart grid simulators, where the last category combines the simulation of both the power grid and communication infrastructure.

Power simulation tools can be largely divided into two classes: they are either targeted at steady state analysis (typically power flow studies), or at transient dynamics simulations (typically upon disturbances or sudden system changes). They typically adopt a continuous time model, studying the system state at fixed points, regularly spaced over time.

Communication network simulators on the other hand typically adopt a discrete event simulation approach, where time intervals between successive events (i.e., system changes) can greatly vary. Depending on the focus of the study at hand,

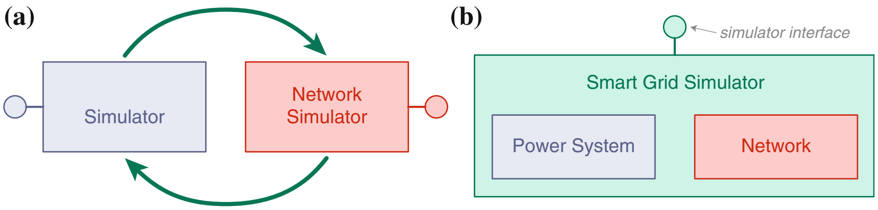


Fig. 5 Conceptual approaches to combining power and communication network simulation. **a** Co-simulation. **b** Integrated simulation

communication network can be modeled as (i) a black box model, a simplified and abstract model of the simulated communication network with only a few parameters (e.g., delay, packet loss, bandwidth) or (ii) as a detailed communication network model with an accurate topology containing hosts, switches, routers, etc., and models for the full networking stack (from application to physical layer).

Two high level approaches to combine both power and communication simulators are illustrated in Fig. 5. In case of *co-simulation* distinct simulators are used for the communication network and power grid, each having their own interface for data input, configuration, result output, control, etc. This approach requires careful synchronization of data and interactions between both simulators, especially with respect to time management, because each simulator manages its simulation time individually. This can be realized using predefined synchronization points where both simulators pause and information is exchanged. An advantage of this approach is that existing simulation models, algorithms, etc. can be reused. In this approach typically one simulator is selected as a master for the synchronization logic. This master usually also contains the control logic for the simulated use case.

In *integrated* or *comprehensive* simulation, both the power system and communication network are simulated in one environment. A single interface is provided and the management of time, data, and power/communication system interactions can be shared among the simulator constituents. Hence, no performance penalty due to synchronization is expected. The main challenge is the combination of both models in one environment and to provide a simulation interface that provides sufficient level of detail for the different aspects of the smart grid simulation model.

Other important requirements for smart grid simulators are the need for new models to characterize for example renewable energy sources, to correctly deal with their intermittent and stochastic behavior. For DR approaches, the correct modeling of the user behavior, and especially the flexibility of his load (e.g., charging deadlines for EVs) is crucial. Simulators should be open, user-friendly and flexible environments, that support user defined models, and easy reuse of already established and validated models.

Most smart grid simulation tools are purely software-based solutions. Yet, other approaches aim for more realism. *Emulated* components more closely mimic the real world in hardware, e.g., a communication network in a lab consisting of real hosts, routers and network cables. In *real-time simulation* the simulation clock is synchronized with the real-time clock, which might be necessary to assess the timeliness with which the model interacts with external components (e.g., for protection), e.g., for *Hardware-in-the loop (HIL) simulation*, which combines real hardware with simulated components.

Many of the currently available smart grid simulators focus on specific use cases, providing answers to specific research questions. Still, a few more generic simulation environments that support a wide range of use cases and are much more extensible. In this respect, federated simulators are a promising approach for co-simulation as they allow the easy addition of extra components (e.g., external data sources with weather or traffic information) and support distributed simulation. For a more detailed discussion of simulation for smart grid applications, we refer to Mets et al. (2014).

7 Conclusions

Current electrical vehicles (EVs) relay on a charging process to replenish the power of batteries. While alternatives have been proposed (e.g., battery swapping), the majority of EVs today rely on charging by wire, either using a standard household plug, or dedicated special-purpose EV plugs and charging infrastructure. The power consumption associated with a single EV on a yearly basis lies in the same range as that of a complete household. Besides the overall larger volume of energy required, uncontrolled charging (e.g., in a residential scenario, starting the charging as soon as the user with his EV arrives at home) would also add on to the typical consumption peak in the evening. This can be solved by peak flattening through demand response (DR) approaches; similar algorithms can also be used for balancing. We advocate for the use of distributed algorithms, since these form a good tradeoff between optimality (e.g., in attaining the balancing objective) and scalability (over very large user populations). To bring these algorithms (from mostly theoretical studies) to the real world, careful validation is still required. Further development (e.g., scaling up) of simulation tools that combine both the power grid, the communication network and the actual smart grid applications is required before moving to proof-of-concept trials, but also or to complement them with larger scale experiments.

Points for Discussion

- The case study on load flattening is based on the assumption of a peak at 18.00. What is this assumption based on? How could such an assumption be grounded?
- Can ICT prevent the need to make greater investments to strengthen grid to deal with peaks?

- The chapter studies the loading of EVs in the context of households connected to a smart grid partly characterized by distributed renewable energy sources. What are the consequences of installing this practice for (a) the households at stake (differentiate where people live), and (b) people working in the traditional automobile and oil industries?

Acknowledgements The work presented in this chapter has been supported in part by the European Commission through the project *P2P-Smartest: Peer to Peer Smart Energy Distribution Networks* (H2020-LCE-2014-3, project 646469).

References

Clement-Nyns, K., Haesen, E., Driesen, J.: The impact of charging plug-in hybrid electric vehicles on a residential distribution grid. IEEE Trans. Power Sys. **25**(1), 371–380 (2010). doi:10.1109/TPWRS.2009.2036481

De Craemer, K., Vandael, S., Claessens, B., Deconinck, G.: An event-driven dual coordination mechanism for demand side management of PHEVs. IEEE Trans. Smart Grid **5**(2), 751–760 (2014). doi:10.1109/TSG.2013.2272197

Gomez, J., Morcos, M.: Impact of EV battery chargers on the power quality of distribution systems. IEEE Trans. Power Deliv. **18**(3), 975–981 (2003). doi:10.1109/TPWRD.2003.813873

IEC Technical Committee 23: IEC 62196 ed2.0: plugs, socket-outlets, vehicle connectors and vehicle inlets—conductive charging of electric vehicles (2011)

Kapoor, A. Charging algorithms of lithium-ion batteries: an overview. In: 7th IEEE Conference on Industrial Electronics and Applications (ICIEA 2012), Singapore, pp. 1567–1572 (2012). doi:10.1109/ICIEA.2012.6360973

Lewandowski, C., Gröning, S., Schmutzler, J., Wietfeld, C.: Performance evaluation of PLC over the IEC 61851 control pilot signal. In: 5th Workshop on Power Line Communications (WSPLC 2011), Arnhem, The Netherlands (2011)

Mets, K., De Turck, F., Develder, C.: Distributed smart charging of electric vehicles for balancing wind energy. In: Proceedings of 3rd IEEE International Conference on Smart Grid Communications (SmartGridComm 2012), Tainan City, Taiwan, pp. 133–138 (2012a). doi:10.1109/SmartGridComm.2012.6485972

Mets, K., D'hulst, R., Develder, C.: Comparison of intelligent charging algorithms for electric vehicles to reduce peak load and demand variability in a distribution grid. J. Commun. Netw. **14**(6), 672–681 (2012b). doi:10.1109/JCN.2012.00033

Mets, K., Aparicio, J., Develder, C.: Combining power and communication network simulation for cost-effective smart grid analysis. IEEE Commun. Surv. Tutorials **16**(3), 1771–1796 (2014). doi:10.1109/SURV.2014.021414.00116

Panasonic: Lithium Ion Batteries Technical Handbook (2007). url http://industrial.panasonic.com/www-data/pdf/ACI4000/ACI4000PE5.pdf

Ruthe, S., Schmutzler, J., Rehtanz, C., Wietfeld, C.: Study on V2G protocols against the background of demand side management. Int. J. Bus. Inform. Sys. 33–44 (2011)

Seljeseth, H., Henning, T., Solvang, T. Measurements of network impact from electric vehicles during slow and fast charging. In: Proceedings of 22nd International Conference on Electricity Distribution (CIRED 2013), Stockholm, Sweden (2013). doi:10.1049/cp.2013.1197

Demand Side and Dispatchable Power Plants with Electric Mobility

Zofia Lukszo and Esther H. Park Lee

Abstract The variable energy sources drive the need for flexibility to restore a system's energy balance. The flexibility sources, i.e. demand side response, dispatchable power plants, storage and interconnection, can respond to restore that balance. Electric vehicles, including plug-in EVs and fuel cell electric vehicles (FCEVs), have a huge potential to play an important role in future energy systems. EVs and FCEVs can be used to discharge electricity to the grid, and when aggregating the power of a large number of vehicles, they can function as dispatchable power plants. Plug-in EVs can adapt their charging behaviour to the needs of the power system operator, and similarly they can act as storage by charging their batteries for example, when there is a surplus of renewable energy. Fuel cell cars (FCEVs), while parked, can produce electricity more efficiently than the present electricity system and with useful 'waste' products, heat and fresh water. In terms of technology, the energy production system "*Car as Power Plant*" can be envisaged as a fleet of fuel cell vehicles, where cars, while parked (over 90 % of the time), can produce with the fuel cell electricity, heat and fresh water that can be feed into the respective grids. The Car as Power Plant system with FCEVs has the potential to replace all electricity production power plants, creating a flexible detachable decentralized multi-modal energy system. This chapter will address the role of electric mobility in the future energy systems in general and its role in demand response and in flexible generation.

1 Introduction

With the 2009/28/EC Directive, the European Union defined three objectives by 2020: 20 % reductions in greenhouse gases emissions, 20 % share of renewable energy and 20 % improvement of energy efficiency. The ambition is also that by

---

Z. Lukszo (✉) · E.H. Park Lee
Faculty of Technology Policy and Management, Delft University of Technology,
Delft, The Netherlands
e-mail: z.lukszo@tudelft.nl

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_11

2020, at least 80 % of all households are equipped with intelligent metering systems.

At the same time it is known that electric power sector has experienced continuous growth in all the three major parts of the power system, i.e. generation, transmission and distribution. The growth of the technical system is only one part of the complexity of the whole system. The power sector is a complex socio-technical system with a social network of many players that together develop, operate and maintain the technical infrastructure, which is developed over the course of years or decades, and when the risks associated with incorrect operational decisions are large. No single player controls the system, but their actions are coordinated through a range of institutions—informal and formal rules—and regulation. The role of customer is also changing. They install distributed energy resources, mostly solar photovoltaic (PV) systems, with different characteristics than those of the central energy resources that dominated the electric power system in the past. The power produced in not only for self-consumption, but it can be sold into the grid. As the control is distributed among actors, including the consumers, the overall system behavior (at different time scales) emerges from operating practices and from (dis)investment decisions and other aspects of the players' strategies.

In such a complex power system, the development of renewable energy sources, creates new challenges. Generally, the intermittent nature of renewable sources leads to more variability in the electrical supply. This variability as well as uncertainty of renewable source availability drive a need for greater flexibility in the power sector.

This flexibility can come either from flexible generation technologies with efficient ramping, or from flexible demand, storage and/or interconnection. It is essential to manage the supply-demand balance in a more flexible way. Moreover, when the power system as a whole is not flexible enough, negative electricity prices are likely to emerge and hence it can be hard and costly to adapt to changing conditions on the demand and/or on the supply side.

A negative price indicates that power generation companies are willing to pay the consumer when they buy energy. This is mostly due to a combination of high production from renewable energy sources, which are generally characterized by very low or zero marginal generation costs and due to low demand. Negative prices generally occur on very sunny and/or windy, non-working days with low demand. They were firstly introduced on the German market, followed by France and Austria.

It should be stressed, that negative prices create an economic incentive for consumers to shift their consumption patterns to capture the opportunity of being paid. At the same time, the emergence of negative prices shows that the generating fleet has too little "flexibility" and/or that grid interconnections are insufficient within a market area.

In this chapter we will discuss the flexibility needs forthcoming from variable generation and we will discuss the role of electric mobility to support the needed flexibility of the power system.

Electric vehicles (EV) are meant to make mobility and the energy use of the future sustainable and green. Electric vehicles are greener than gasoline cars as they do not use fossil fuels themselves. EVs use electricity from the grid and the emissions of electric vehicles are therefore dependent on the source of electricity production. With the current Dutch electricity production portfolio, EVs produce less CO_2 and improve air quality, as they produce no local emissions (Kleiwegt and Lukszo 2012).

A necessary condition for a successful breakthrough of electric mobility is the availability of a charging infrastructure. Increasing efforts to eliminate barriers led to technology for fast charging, quick battery change and driving ranges of over 600 kilometres. However, a plug-in EV uses a relatively large amount of electricity. For comparison: an entire household uses on average about 10 kWh per day; an electric vehicle (based on the current average travel distance per day) uses about 6 kWh per day. In addition, it is expected that, when left to consumers' convenience, this increased demand will occur mostly during existing peak demand hours.

The real impact of electric mobility is uncertain and difficult to predict, for instance due to the market potential uncertainty. Policy makers are already taking measures to stimulate the energy innovations as they benefit from the sustainable character of such innovations.

2 Sources of Variability and Flexibility

As explained in the introduction energy systems have been undergoing major transitions throughout the world over the last decade, triggered by environmental concerns and new geopolitical realities. A consistent principle in managing the transitions, where variable renewable power generation as well as demand fluctuation are present, is to increase flexibility of the power system, which calls for an adequate intelligent grid, power market and a novel mode of operation, see Fig. 1.

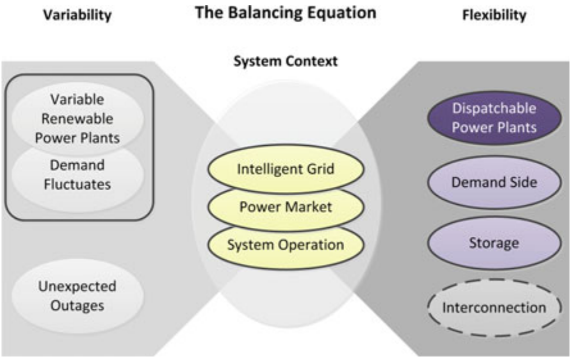


Fig. 1 Variability and flexibility sources in the electric power system. Adapted from Holttinen et al. (2013)

Smart grids have been identified as an infrastructural innovation that can enable system-wide flexibility. They are also viewed as enablers for integrating unconventional distributed energy resources in a sustainable and efficient way. At present in many countries much effort is put into enhancing the basic infrastructure of distribution networks, for instance deploying Advanced Metering Infrastructure (smart metering) and executing many pilot projects with distributed generation and demand side response. The pilot projects investigate the interplay of new ways of operation, new market structures and technical solutions offered by the intelligent grid. However, when consumers actively respond to instantaneous real prices, for example by demand response of charging electric cars, the profiles used for forecasting energy demand are no longer correct. This can be seen as a paradoxical situation in which increased flexibility in the system could lead to greater imbalance costs for power generators.

To balance the system, besides demand side response, dispatchable power and storage, as well as increased interconnection capacity between different power systems are needed. The challenge is to steer the evolutionary transition to future energy systems in such a way that significant changes in the power system and its operating philosophy are accomplished at the lowest societal costs, both at present and in the future.

3 Electric Mobility

Electric vehicles have the potential to play a significant role in future energy systems, especially to support demand side and dispatchable power plant production. Before explaining this potential we will shortly introduce the main types of electric drive vehicles.

Electric drives have some form of electric propulsion, either alone or combined with an internal combustion engine (ICE). The main types of electric drive vehicles are battery electric vehicles (BEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and fuel cell vehicles (FCEV)—see Table 1. In the

Table 1 Electric drive vehicle types, adapted from Kempton and Letendre (1997)

Type	Characteristics			
	Motive force	Energy storage and conversion	Fuel source	Interaction with electricity system
BEV	Electric	Battery	Electricity	Load
HEV	Mechanical and electric	Hybrid	Liquid	None
PHEV	Mechanical and electric	Hybrid	Liquid/electricity	Load
FCEV	Electric	Fuel cell	Gas	None

literature, the term Electric Vehicles (EV) is normally used to refer to the plug-in electric vehicles (BEVs, PHEVs).

- BEVs: They are all-electric vehicles that have an electric motor, a controller and a battery that stores electricity and can be charged from the grid. Regenerative braking is also used to store extra energy.
- HEVs and PHEVs: Hybrid electric vehicles consist of both a conventional ICE and an electric propulsion system. There are different configurations and degrees of hybridization, but we make a distinction between the gasoline-electric hybrid vehicle and the plug-in hybrid vehicle. The first type has a small electric motor and is powered using liquid fuels. The small battery is recharged via regenerative braking, but cannot be charged from the grid. PHEVs, on the other hand, have a bigger electrical motor and battery, and can either use liquid fuels or charge their battery by connecting the car to the grid. They are also called extended range electric vehicles (EREV).
- FCEVs: They are all-electric vehicles that are powered using electricity generated on-board from a gaseous fuel, using a fuel cell stack. A small battery is used to store energy with regenerative braking—although it can be designed to have a bigger battery and a smaller fuel cell, as a HEV or PHEV. The fuel source can be natural gas or hydrogen, but the FCEVs currently being commercialised or under development use hydrogen. Although they are all-electric as the BEVs, they are often considered a rival technology and their characteristics are often compared (Thomas 2009) due to the different power source and storage system they have and the infrastructure they rely on.

The idea of using electric drive vehicles to provide electricity and services directly to the grid was put forward through the concept of Vehicle-to-Grid (V2G) power (Kempton and Letendre 1997; Letendre and Kempton 2002; Kempton and Tomić 2005a, b). In 2005, it was estimated that by replacing 25 % of the US light vehicle fleet with V2G-capable electric drive vehicles, it would be sufficient to compete with the capacity of the electricity generation system (Kempton and Tomić 2005b). More recent research involving V2G is about plug-in electric vehicles, i.e. vehicles that charge their batteries from the grid (Peças Lopes et al. 2011; Verzijlbergh et al. 2012a; Druitt and Früh 2012; Mwasilu et al. 2014). In these studies, V2G is proposed as a solution to the congestion problems that can arise from uncontrolled charging, for a better integration of electric vehicles in the electricity system and for a higher penetration of variable renewable energy sources in the electricity system. Although not yet fully commercialized, the fuel cell vehicle is the only one that truly "*represents a new source of power generation*" (Letendre and Kempton 2002).

In this chapter, we will consider the potential role of EVs and FCEVs in future energy systems.

4 Electric Mobility and Demand Side Management

As already mentioned, electric mobility has the potential to play an important role in the future power systems by adjusting demand of the electric vehicles to the variable generation, i.e. by demand side management. There are many types of demand side management; manipulations of load shape can be done for example by delaying a peak or spreading it, which can be realized by delaying charging or spreading it. Therefore, the impact of electric mobility on the grid and the electricity demand will heavily depend upon the time and duration at which consumers charge their vehicles. The impact depends also on several other factors, namely: grid characteristics, developments in the existing energy system, type of charging stations and charging behaviour of vehicle users. But how can the controlled charging for demand response be done taking into account the different interests of the relevant actors? Controlled charging does not mean the same for car owners or aggregators representing them, for distribution network operators and for wind power producers. All of them think differently about intelligent charging, see Fig. 2

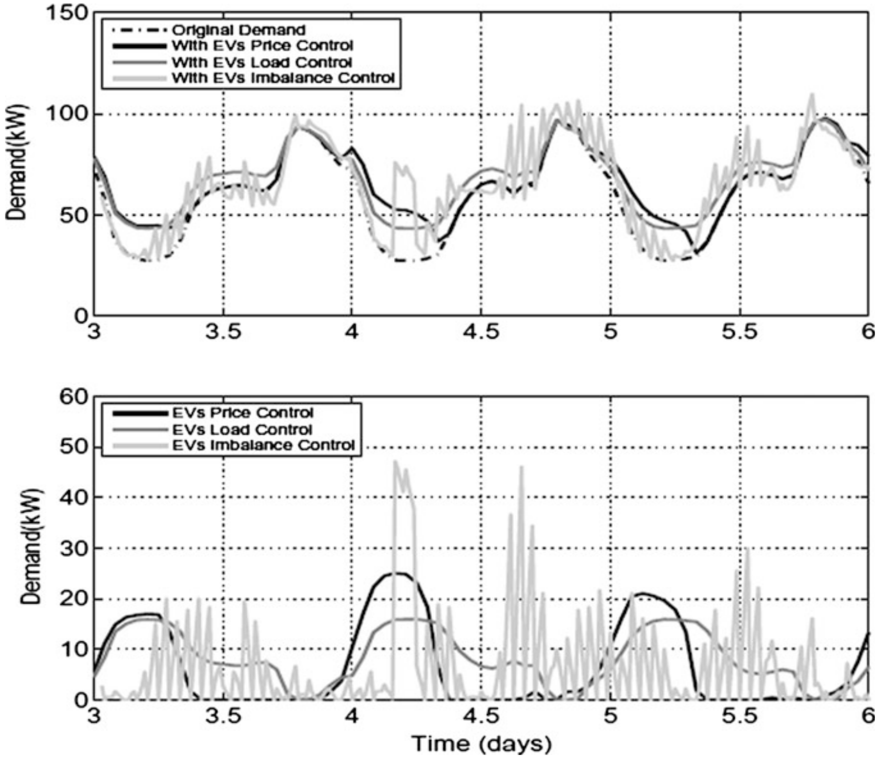


Fig. 2 Different optimal charging strategies for three actors (consumers represented by an aggregator, distribution network operators and wind producers) in a system with 100 houses and 50 plug-in EVs (Verzijlbergh et al. 2012a)

(Verzijlbergh et al. 2012b); car owners aim at minimizing charge costs, network operators at minimizing network losses by load control and producers at maximizing profits by imbalance control.

The demand response potential of electric vehicles is large due to the flexibility in the charging process by shifting it in time. Many others types of loads have this ability, too. As an example of another type of responsive demand a cold storage warehouse can be given (Verzijlbergh and Lukszo 2013).

To conclude, demand side management is going to be increasingly important for the future power systems. By developing controlled demand systems, for example using electric mobility and cold storage, the capacity problems around peak demand hours can be challenged and an efficient integration of renewable energy sources in the power system can be realized. It should be stressed that the potential value of demand response strongly depends on the tariff structure and incentives formulated by policy makers and regulators.

5 Fuel Cell Electric Vehicles as Dispatchable Power Plants

While plug-in EVs play important role in demand side management, fuel cell electric vehicles have the potential to operate as highly flexible dispatchable power plants. As mentioned earlier, FCEVs are the only type of electric vehicle that represent a new electricity generation source (Letendre and Kempton 2002). Like stationary fuel cell systems, fuel cell electric vehicles can be used to provide electricity when they are in stationary mode. Thus, FCEV fleets that are parked can become dispatchable power plants and serve local loads or the electric grid. Both possibilities have been investigated and are considered to be economically feasible under certain circumstances (Kissock 1998; Lipman et al. 2004; Kempton and Tomić 2005a).

FCEVs can be used to provide electricity to homes, offices or other demanding systems. In a study on the economics of fuel cell power, the authors compare stationary and motor vehicle PEM fuel cell systems by estimating their potential costs for distributed power, for the period 2010–2015 (Lipman et al. 2004). In this case, FCEV were considered to be connected to a house/building to serve the load and only feed the excess electricity to the grid. Therefore FCEV power is used to replace the power that would be otherwise used from the grid, especially during peak hours. The net revenues from FCEV-based power are represented by the net savings incurred through the use of FCEV power instead of grid power. Taking into account the capacity and revenues, the authors claim that by using stationary and vehicle fuel cells as distributed generation systems, it would be possible to "*reduce the need to operate peak power plants and to construct new ones to meet peak demand growth*" (Lipman et al. 2004). The results showed that annual revenues are highest when providing electricity to offices, and under a net metering program and time-of-use tariffs. However, for FCEV power to be competitive, natural gas prices need to be low. Moreover, it is considered that the durability of a fuel cell system must be in the order of 10,000 h to be able to use it both for transport and power generation.

The heat produced by the fuel cell stack can also be used when using FCEVs to serve the energy requirements of buildings. Kissock (1998) investigated the feasibility of using both the electricity and the heat generated in FCEVs to provide energy to commercial and residential buildings. As opposed to Lipman et al. (2004) the lifetime of the fuel cells is not considered to be a limitation. The author used simulation model to compare the performance of FCEV cogeneration in residential and commercial settings in states with different climates. The results show that annual savings in the range of $1000–8000 can be generated in residential and commercial settings by using FCEV for cogeneration. Electricity purchased from the utilities can be greatly reduced, by 47–65 % in residences and by 86–93 % at workplaces, and heat from FCEVs can replace more than 96 % of thermal energy requirements. The study concludes that FCEV cogeneration is feasible and that it "*merits consideration as an innovative element in the portfolio of options for the distributed utility of the future*" (Kissock 1998). It should be noted that this is the only study that considers cogeneration from FCEVs. Lipman et al. (2004) emphasize that cogeneration is not suitable for vehicle fuel cell systems due to overheating and the need of a heat exchange connection results in more cost and complexity. Given the different assumptions made by Lipman et al. (2004) and Kissock (1998), further research is needed to study in which particular configurations cogeneration from FCEVs could be feasible.

In conclusion, FCEVs can be used as dispatchable power plants to serve the grid or local loads. This type of use of fuel cell vehicle is technically feasible and economically sound under certain circumstances. The challenge lies in the implementation of a system based on distributed power from FCEVs.

6 FCEVs as Dispatchable Power Plants: Implementation Aspects

Based on the literature regarding the implementation aspects of V2G systems, we can expect similar challenges in relation to the implementation of the Car as Power Plant. In this chapter we will briefly discuss the technical and institutional considerations, frameworks for implementation and barriers for V2G.

6.1 Technical and Institutional Considerations

6.1.1 Power Capacity of V2G

According to Kempton and Tomić (2005a) there are three limiting factors in V2G power capacity: (1) current-carrying capacity of wires and other circuits connecting the vehicle through the building to the grid, (2) the energy stored in the vehicle (divided by the time it will be used), and (3) the rated maximum power of vehicle's electronics. Therefore, the maximum power capability of a vehicle for providing V2G is the lowest value of the three limiting factors.

The line capacity depends on the type of connection: residential, commercial, or DC charger. In the case of FCEVs, which do not require charging connectors, the output will also depend on the line capacity of the connectors (Kempton and Tomić 2005b). Concerning the output from FCEVs, fuel cell efficiency increases and wear decreases at low power levels, and therefore it is considered better to operate fuel cells at partial load.

6.1.2 Institutions and Business Models

In the current system, generators make contracts with operators to provide spinning reserves or regulation in blocks of 1 MW (Letendre and Kempton 2002; Kempton and Tomić 2005b; Tomić and Kempton 2007). A signal is sent when the service is needed, and the operator pays one entity for the contract and for the power generated. Therefore, it makes sense to aggregate the power from several electric drive vehicles instead of having a contract with each individual vehicle owner. The grid operator would request for ancillary services by sending a signal to individual vehicles or to a parking lot where a fleet is located. The number of cars that would be needed in a parking lot to generate 1 MW of power would be roughly about 100, considering FCEVs with a power capacity of 15 kW, and taking into account different states of charge (Kempton and Tomić 2005b).

Some business models proposed for the management of V2G power in Kempton and Tomić (2005b) are:

1. Fleet management: Management of availability for V2G with a single fleet in one same location, e.g. in a parking garage. It is the fleet operator who has an ancillary service contract with the grid operator. An example of how fleets can be used for grid support is described in Tomić and Kempton (2007).
2. Dispersed vehicles: Retail power companies have a contract with individual electric drive vehicle owners, and 1 MW blocks are sold to the regional power market. The aggregator has no direct control over the operation of vehicles, but there are financial incentives to stay plugged when possible. This would allow for a high power availability.
3. An independent party acting as aggregator, e.g. a car manufacturer, automotive service organization, etc.

6.2 Frameworks for Implementation

To address the practical aspects in the implementation of V2G, Guille and Gross (2009) proposed a framework to integrate BEVs with the grid. In this study, BEVs are aggregated and can provide two types of services: (1) demand response and (2) storage and flexible generation (to some extent). Therefore, it is not only about V2G services but also about levelising the load during off-peak periods. Although BEVs cannot provide baseload power, the authors argue that when aggregated, they can provide reserves to the grid. Moreover, since they have a fast response, they can be used when peaking units are starting up.

In this study, the central actor and key enabler is considered to be the aggregator, which can be the TSO or an energy service company that has contracts with households of BEV owners. The main advantage of having an aggregator is that it has a large purchasing power that a single BEV owner could not have. The authors describe their conceptual implementation framework in two parts: (1) a communication framework and (2) an incentive plan. The first one describes a communication and information flow that shows how the aggregator communicates with both the TSO and the BEV owners. The incentive plan is based on a package deal in which the aggregator provides services that BEV owners could need: preferential rates for batteries, maintenance of the battery, discounts for charging and parking. With such services, BEV owners are obliged to plug the vehicle to the grid at times indicated in the contract. Compliance with the contract requirements leads to rewards in the form of discounted tariffs, and the opposite leads to penalization, which includes the discontinuation of discounts. The authors claim that this package deal would help aggregators attract a large number of BEV owners.

In another study, Williams and Kurani (2007) propose a "Mobile electricity (Me-)" framework, which integrates plug-in and plug-out (V2G) opportunities for PHEVs and FCEVs. There are three types of plug-out opportunities considered for FCEVs: (1) plug-out "*on the go*" mobile power for leisure activities, (2) plug-out "*in need*" emergency power—even for buildings and hospitals, and (3) plug out "*for profit*" vehicular distributed generation, i.e. providing V2G power. An economic assessment is made based largely on the work of Letendre and Kempton (2002) and Kempton and Tomić (2005a). The authors also address aggregation as one of the key steps for implementation. They propose a conceptual example of spatial aggregation that can be useful to promote V2G aggregation and other business opportunities: "*parking-lot power plants*", which could be used by airport rental car companies. Such aggregation is seen not only as an opportunity to aggregate capacity but also to distributed infrastructure costs, facilitate coordination, and aggregate V2G benefits.

6.3 Barriers for V2G Implementation

As mentioned in the previous section, Tomić and Kempton (2007) assess the potential of using electric drive vehicle fleets to support the grid through V2G services. Although it is considered to be economically feasible, the authors address a few implementation barriers, both technical and institutional. On the technical side, EV battery optimization and battery and fuel cell life cycle are considered to be major barriers. These technical aspects are expected to be addressed and solved by battery and fuel cell developers. On the other hand, some institutional barriers that should be addressed are: (1) lack of vehicle aggregators, (2) broadcasting of regulation signal, (3) regulation service rates not available at the retail level, (4) no mass production of V2G-ready vehicles, (5) need for new standards, to cover the quality of V2G power. This shows that in order to implement successfully a new application or a novel use of a technology, not only it has to be technically and economically feasible, but it also needs new standards, regulations, markets, and actors in place.

Sovacool and Hirsh (2009) analysed the benefits and barriers for V2G implementation. The authors claim that even if it were technically feasible, it could not be widely accepted. More importantly, they emphasize that there is a "*host of socio-technical considerations*" to take into account for a successful V2G transition. By reflecting on the history of the Zero Emission Vehicle (ZEV) policy in California and the California Air Resources Board (CARB) mandate in the 1990s, the authors make an analysis of the barriers that could also hamper the V2G transition. The CARB mandate had to be stopped for 5 years due to pressures from the automakers association and the oil consortium. For V2G to be implemented, different roles and new actors would be needed (new suppliers, technicians, aggregator role), and its success could drive some of the actors in the current regimes out of business (gas station owners, ICEV mechanics, etc.). In short, there are important institutional obstacles related to changing the current infrastructure, systems, and the related actors, who are resistant to such system-wide changes. It is not mentioned, however, how to overcome such barriers.

To conclude, the implementation aspects of V2G derived from the literature show some technical and institutional considerations that can be useful for the implementation of distributed FCEVs as power plants. The aggregation of power from vehicles and the need for an aggregating are important lessons that can facilitate the integration of electric mobility and the electricity system.

7 Car-Park Power Plant

Based on the use of FCEVs as dispatchable power plants, The Green Village proposed the Car as Power Plant (CaPP) as an "*integrated, efficient, reliable, flexible, clean, smart and personalized transport-, energy- and water system*" (Wijk and Verhoef 2014). The concept is based on the potential of using FCEVs to replace centralized power plants, and this can be achieved in different ways:

- Using a parking garage to physically aggregate large numbers of FCEVs
- Using several FCEVs to become part of an energy community system
- Using aggregated vehicles to act as back-up power in hospitals

7.1 Car-Park Power Plant

Wijk and Verhoef (2014) present in their book one of the ways the Car as Power Plant could be applied: using a parking garage. The *Car-Park Power Plant (CPPP)* is a parking facility where parking is combined with energy generation to create distributed and flexible power plants. FCEV drivers can cover their needs for parking and also become electricity producers. On-site production of hydrogen would allow a large number of cars to be connected to a hydrogen source at all times, making it possible for the vehicles to operate continuously (Lipman et al. 2004) without depleting the level of fuel in the car. Furthermore, drivers could also refill their hydrogen tanks before leaving, facilitating the refilling possibilities for parking users. The authors estimate that with a car park with 500 FCEVs it would be possible to generate up to 50,000 kWh at full capacity. With such capacity, a CPPP full of FCEVs can become a flexible power plant that can be ramped up or shut down in very little time (Wijk and Verhoef 2014). The authors also claim that such flexible power plant would be "*able to operate as a base-load, intermediate-load or peak-load power plant*" as well as a spinning reserve.

Like all energy systems, the CaPP system consists of a technical subsystem formed by the equipment, infrastructure and physical processes, and a social subsystem consisting of the relevant stakeholders and users, such as the car park operator, the transmission and distribution system operators, natural gas provider. Considering the system to be implemented in a *Car-Park Power Plant*, it could be described as shown in Fig. 3. In the physical subsystem, the elements that would be inside of the CPPP are enclosed by the box with dashed lines. Hydrogen production could also happen off-site, but the idea is to connect the required sources (e.g. natural gas) for hydrogen generation, to produce and store in the CPPP, and to supply FCEVs that are parked in the CPPP with hydrogen (Fig. 3).

7.2 Operation of a Car-Park Power Plant

The operation of CaPP through a CPPP involves activities happening on a daily basis. We believe that addressing the operational aspects will help get more insight into some requirements for integrating CaPP in the current electricity and transport systems. As mentioned previously, the electricity generated in the Car-Park Power Plant could be used to serve local loads or to serve the grid.

Aggregators can sell/buy electricity at more competitive prices on behalf of their customers. In the CaPP system, the aggregator will play an important role—just like in a system with BEVs providing V2G (Guille and Gross 2009)—by aggregating and controlling the operation of FCEVs in several parking facilities.

The daily operation of the CPPP is centred on the driving and electricity generating behaviour of the FCEV users and their interaction with the aggregator. One way of organising the operation of this system could be through the following actions:

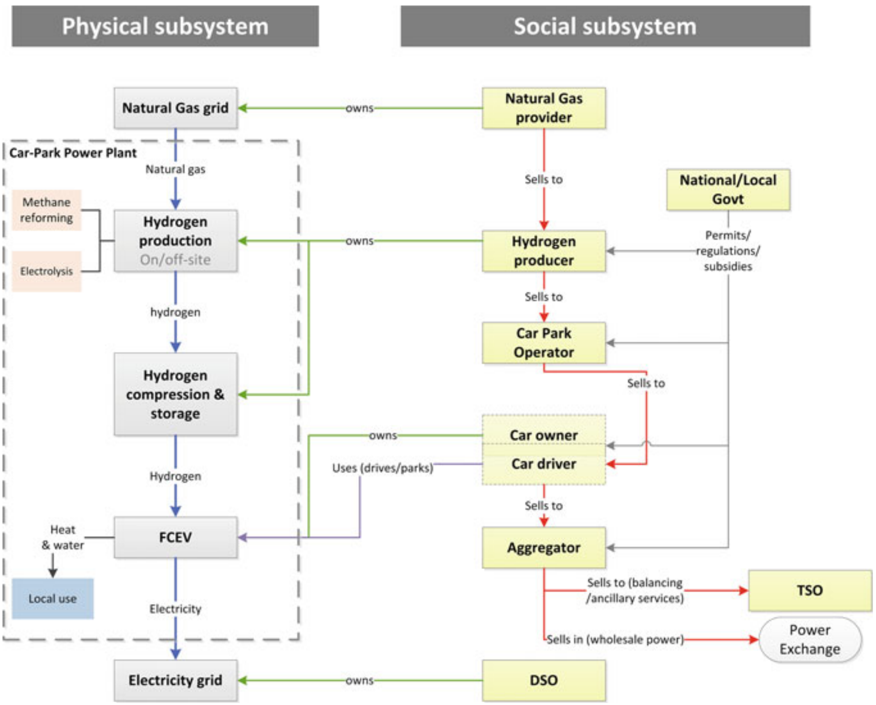


Fig. 3 Description of the socio-technical system of the Car as Power Plant using a parking garage

1. Every day before 12 h FCEV drivers send their preferences and plans for the following day to the aggregator
2. FCEV drivers park their car in a CPPP according to the schedule determined the day before
3. FCEVs are connected to the control system
4. Aggregator starts generation and stops according to vehicle preferences and dispatch schedule
5. FCEV drivers leave—paying for hydrogen consumed and getting remunerated for electricity generated.

For the Car-Park Power Plant we can consider the role of an aggregator selling electricity in the *Day-Ahead* and *Intraday* markets, as well as providing balancing and ancillary services to the transmission system operator.

To sum up, the potential benefit of realizing and using the system would be achieving a more sustainable passenger transport system and at the same time a more flexible power system. Such a power system can function as a flexible dispatchable power plant with a very short time needed to shut it down or to bring it to maximum capacity (Wijk and Verhoef 2014). CPPP is able to operate not only as a base-load, intermediate-load or peak-load power plant, but also as spinning reserve or backup power plant. Whether these benefits can be materialized depends on a large variety of developments and design choices: the novelty of the technology, the new infrastructure required, the behaviour of potential users and the constantly changing environment, among other issues, represent large uncertainties on how this system should be implemented and be best operated.

8 Final Remarks

The value of electric vehicles on balancing an (increasingly intermittent) power grid can be significant and could amount to several billions of euros (European Climate Foundation 2015). This applies to electric vehicles (charging when power supply is available) as well as hydrogen cars (using stored hydrogen to produce power when supply is short (McKinsey and Company 2010).

The question is how such an integrated and connected transport and electricity production system can be realized. Of course there are many technological, environmental, economic, social and political challenges. In all of these areas research and development is necessary, as well as demonstration projects.

One can imagine that success would not happen overnight, or even over years, but rather over decades. Environmental and regulatory drivers such as EU directives on low-emission and zero-emission requirements will create near-term opportunities.

The transport sector is key in the transition to a sustainable energy system. If the diffusion of electric cars is hampered, the climate policy of the EU and the Netherlands will be in danger, or will incur higher societal and mitigation costs. A future energy system supported by electric mobility will lead to an increasingly reliable, sustainable, flexible and affordable power system.

Points for Discussion

- How are mobility and power are linked in the vision of ‘car as power plant’? How does this differ from our usual oppositional thinking, that pits energy efficiency against car use?
- Do these developments require additional investments in the grid infrastructure?
- The role of storage is likely to be important for the future grid. Batteries can serve as storage, as well as other options such as Power-to-Gas (see the chapter of Nguyen et al.), where fuel cells may be needed again for production. How does this impact technological development, and how does this impact legislation?

Acknowledgments The results presented in this chapter are part of the project Car as Power Plant (number: 408-13-001), financially supported by the *Nederlandse Organisatie voor Wetenschappelijk Onderzoek* (NWO).

References

Druitt, J., Früh, W.-G.: Simulation of demand management and grid balancing with electric vehicles. J. Power Sources **216**, 104–116 (2012). doi:10.1016/j.jpowsour.2012.05.033

European Climate Foundation (2015) Roadmap 2050. http://www.roadmap2050.eu/. Accessed 25 June 2015

Guille, C., Gross, G.: A conceptual framework for the vehicle-to-grid (V2G) implementation. Energy Policy **37**, 4379–4390 (2009)

Holttinen, H., Tuohy, A., Milligan, M., et al.: The flexibility workout. IEEE Power Energy Mag. **11**, 53–62 (2013)

Kempton, W., Letendre, S.E.: Electric vehicles as a new power source for electric utilities. Transp. Res. Part D Transp. Environ. **2**, 157–175 (1997)

Kempton, W., Tomić, J.: Vehicle-to-grid power fundamentals: calculating capacity and net revenue. J. Power Sources **144**, 268–279 (2005a)

Kempton, W., Tomić, J.: Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy. J. Power Sources **144**, 280–294 (2005b)

Kissock, J.: Combined heat and power for buildings using fuel-cell cars. In: ASME International Solar Energy Conference, Albuquerque, NM, pp. 121–132 (1998)

Kleiwegt, E., Lukszo, Z.: Grid impact analysis of electric mobility on a local electricity grid. In: 2012 9th IEEE International Conference on Networking, Sensing and Control (ICNSC), pp. 316–321 (2012)

Letendre, S.E., Kempton, W.: The V2G concept: a new model for power? Connecting utility infrastructure and automobiles (2002)

Lipman, T.E., Edwards, J.L., Kammen, D.M.: Fuel cell system economics: comparing the costs of generating power with stationary and motor vehicle PEM fuel cell systems. Energy Policy **32**, 101–125 (2004). doi:10.1016/S0301-4215(02)00286-0

McKinsey & Company: A portfolio of power-trains for Europe : a fact-based analysis—the Role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles. Brussels (2010)

Mwasilu, F., Justo, J.J., Kim, E.-K., et al.: Electric vehicles and smart grid interaction: a review on vehicle to grid and renewable energy sources integration. Renew. Sustain. Energy Rev. **34**, 501–516 (2014). doi:10.1016/j.rser.2014.03.031

Peças Lopes, J.A., Soares, F.J., Almeida, P.M.R.: Integration of electric vehicles in the electric power system. Proc. IEEE **99**, 168–183 (2011). doi:10.1109/JPROC.2010.2066250

Sovacool, B.K., Hirsh, R.F.: Beyond batteries: an examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition. Energy Policy **37**, 1095–1103 (2009). doi:10.1016/j.enpol.2008.10.005

Thomas, C.E.: Fuel cell and battery electric vehicles compared. Int. J. Hydrogen Energy **34**, 6005–6020 (2009). doi:10.1016/j.ijhydene.2009.06.003

Tomić, J., Kempton, W.: Using fleets of electric-drive vehicles for grid support. J. Power Sources **168**, 459–468 (2007). doi:10.1016/j.jpowsour.2007.03.010

Verzijlbergh, R.A., Grond, M.O.W., Lukszo, Z, et al.: Network impacts and cost savings of controlled EV charging. Smart Grid IEEE Trans. **3**, 1203–1212 (2012a)

Verzijlbergh, R.A., Lukszo, Z, Ilic, M.D.: Comparing different EV charging strategies in liberalized power systems. In: 2012 9th International Conference on the European Energy Market (EEM), pp. 1–8 (2012b)

Verzijlbergh, R.A., Lukszo, Z.: Conceptual model of a cold storage warehouse with PV generation in a smart grid setting. In: 2013 10th IEEE International Conference on Networking, Sensing and Control (ICNSC), pp. 889–894 (2013)

Wijk, A.J.M. van, Verhoef, L.: Our Car as Power Plant (2014)

Williams, B.D., Kurani, K.S.: Commercializing light-duty plug-in/plug-out hydrogen-fuel-cell vehicles: "Mobile Electricity" technologies and opportunities. J. Power Sources **166**, 549–566 (2007). doi:10.1016/j.jpowsour.2006.12.097

Privacy Issues in the Use of Smart Meters—Law Enforcement Use of Smart Meter Data

Jonida Milaj and Jeanne Pia Mifsud Bonnici

Abstract This chapter assesses the challenges that the introduction of smart meters in the European Union creates for the right to privacy and data protection of individuals in those situations in which the transmitted data are used by law enforcement authorities for surveillance purposes. In presenting the potential risks and the limitations of the existing safeguards for the protection of the individuals by State interferences, this analysis takes a human rights approach based on the existing European legal framework, case law and doctrine. The legal analysis is augmented by evidence collected from technical/engineering studies that show the interest that smart meter data has for law enforcement authorities. It is argued that the current legal framework is not adequate for addressing the challenges that surveillance via smart meter data creates for the rights of the individuals and that the existing legal gap must be taken into account and used in favour of the protection of the fundamental rights of the individuals.

1 Introduction

Smart meters were introduced in the European Union because of the contributions they are expected to make towards the energy saving targets adopted by the Member States (Directive 2006/32/EC, art. 13). A key feature of smart meters is the collection of data for energy[1] usage and their almost real time communication

---

[1] For the scope of our study we consider only smart meters that measure the consumption of electricity and not of water or gas. In addition, also our usage of the term "energy" is limited to electric energy and does not cover gas or other forms of energy.

J. Milaj (✉) · J.P. Mifsud Bonnici
Department of European and Economic Law, Faculty of Law,
University of Groningen, Groningen, The Netherlands
e-mail: j.milaj-weishaar@rug.nl

J.P. Mifsud Bonnici
e-mail: g.p.mifsud.bonnici@rug.nl

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_12

between the meter and service providers.[2] The detailed data communication is said to benefit not only the service providers (learning about the specific energy demand and enabling energy companies to enhance the accuracy of their long term predictions which would impact their production and purchasing strategy) but also the consumers (allowing them to have an accurate overview on their consumption which might impact their consumption behavior in accordance with electricity fees) (Faraqui et al. 2010).

The European legislator has set the target of substituting at least 80 % of the electricity meters in the EU with smart ones by the year 2020 (Directive 2009/72/EC, annex I, para. 2). After a high speed start in some countries (for example Sweden, Finland and Italy) (Covrig et al. 2014; Lo Schiavo et al. 2011) the introduction of smart meters has faced in other countries concerns that were not considered before, among which privacy and data protection challenges (for example in the Netherlands and in Germany) (Cuijpers and Koops 2012; Pallas 2012).

A number of studies have shown the interest of actors other than energy suppliers for accessing smart meter data. This interest might be for engaging in illegal, commercial, law enforcement or other activities. Smart meter data for illegal activities can be used for example by burglars who are interested to learn when a residence is unoccupied, or by stalkers seeking to track the movements of their victim (Lisovich et al. 2010; Cavoukian et al. 2010; McDaniel 2009; Lerner and Mulligan 2008; Subrahmanyan 2005). Other actors might have a commercial interest in the use of smart meter data to target advertising of special products or services (e.g. more efficient energy saving devices) to identified households or individual inhabitants (McKenna et al. 2012; Anderson and Fuloria 2010; Bohli et al. 2010). Among the other interested actors are included law enforcement authorities, insurance companies, parties in a civil litigation, landlords, the press, or also simply the cohabitants of a household spying on each other (Quinn 2008; Hargreaves et al. 2010).

The use of data from electricity measuring devices for law enforcement purposes is not a new phenomenon. The so-called “dumb” meters[3] give information on the total consumption of energy in the households and the possibility for readings of the data in monthly or longer time intervals. Law enforcement authorities have been using these data and regarded very high electricity consumptions as an indicator that certain illegal activities (such as the cultivation of illegal narcotic plants) are performed in the household. Smart meters, in contrast, transfer not only final energy consumption data but also detailed data related with the use of the electricity in a household. These data might give the possibility to law enforcement authorities to check on other activities taking place within the walls of a private residence.

---

[2] With this term in this chapter are understood distribution system operators, transmission system operators, electricity supply undertakings or other parties that receive the data directly from the meter in accordance with the electricity distribution system.

[3] Analog meters that are still present in those households that have not yet installed smart ones.

This chapter contributes to the literature developed on privacy and data protection issues of smart meters (Knyrim and Trieb 2011; Savirimuthu 2013; Zeadalli et al. 2013, etc.) by focusing on the challenges that the use of smart meter data for surveillance purposes by law enforcement authorities would create for safeguarding the right to privacy of individuals in the current European legal framework (covering both EU and Council of Europe relevant legal provisions). After this short introduction Sect. 2 analyses the nature of smart meter data and qualifies them under the framework of data protection and privacy rules in Europe. Section 3 presents examples of data and information that can be retrieved by smart meters on the basis of scientific studies. The aim of this section is to identify why smart meter data are potentially relevant for law enforcement authorities and surveillance. It further discusses the risks to the protection of the right to privacy that are created by surveillance with smart meter data. Section 4 analyses the applicable European legal framework and provides practical suggestions to safeguard the right to privacy of individuals in the presence of surveillance via smart meters. The concluding remarks are presented in Sect. 5.

2 Smart Meter Data Under European Data Protection and Privacy Rules

To assess the effects that surveillance via smart meters has for the right to privacy and data protection of individuals, it is important to first establish whether smart meter data qualifies as personal data and fall under the protection offered by the applicable European rules. The aim of this section is to analyse the nature of smart meter data and to examine if they could be qualified under the framework of data protection and privacy rules. We will first give a short introduction of the rights to privacy and data protection in Europe and then will analyse smart meter data in the light of these rights.

2.1 Privacy and Data Protection in Europe

The right to privacy in Europe was first introduced in article 8 ECHR. Its aim is to protect the private life of the individuals from arbitrary interferences of State actors. Even though there is not a clear definition of what the term ‘private life’ means and this is to be established on a case by case basis,[4] the term includes many aspects such as: (i) privacy of the person, (ii) privacy of personal behaviour (Kalogridis and

---

[4] Niemietz v. Germany, ECHR application no. 13710/88, 16 December 1992, para. 29; Peck v. The United Kingdom, ECHR application no. 44647/98, 28 January 2003, para. 57; Pretty v. The United Kingdom, ECHR application no. 2346/02, 29 April 2002, para. 61.

Denic 2011), (iii) privacy of personal communication, (iv) privacy of personal data, (v) privacy of location and space, (vi) privacy of thoughts and feelings (Borton et al. 2013), and (vii) privacy of association.

Privacy is recognized as a fundamental right also in the Charter of Fundamental Rights of the EU (art. 7). The right is however designed as not having an absolute nature since State intervention with the right can be justified if done in accordance with the laws, is considered as necessary in a democratic society and is counterbalanced by one of the following interests: national security, public safety, economic well-being of the country, prevention of disorder or crime, protection of health or morals, or the protection of rights and freedoms of others (Kleining et al. 2011, 43).

The right to data protection on the other side focuses on the fair and legitimate collection and processing of personal data.[5] It was recognised as a separate right from the one to privacy only recently due to the fact that development of technology and increased exposure of personal information raised the awareness that the right to privacy had certain limitations. It applies in both vertical (that is between the state and individuals) and horizontal (between individuals) situations and is established in article 8 of the Charter of Fundamental Rights of the EU. Data protection is often seen in the literature as a tool that ensures the transparency of the operation of different institutions (public or private) since its regulation aims at the creation of a regulatory framework for collection, storage and use of personal information and facilitates data processing activities while providing a set of safeguards for the individuals (Gutwirth and De Hert 2006).

Even though from the Charter articles the separation between the rights to privacy and data protection seems normatively clearly defined, one has to keep in mind that due to the historical emergence of the right to data protection from the one to privacy (Mayer-Schoenberger 1997), their distinction is not always clear in the doctrine and the case law of the Court of Justice of the EU. This confusion is also due to the fact that despite being separate rights,[6] data protection and privacy often overlap with each other. This can be seen, for example, in the invalidation of the Data Retention Directive[7] case were the Court of Justice of the EU stated that the retention of personal (meta)data from electronic communications translates to an interference with the private sphere of the individuals, therefore with the right to

---

[5] Personal data are defined in Directive 95/46/EC (article 2(a)) as any information relating to an identified or identifiable natural person. An identifiable person is further defined as him who can be identified, directly or indirectly, in particular by reference to an identification number or to one or more factors specific to his physical, physiological, mental, economic, cultural or social identity.

[6] Friedl v. Austria, ECHR application 15225/89, 31 January 1995, para. 14.

[7] The aim of the Data Retention Directive (Directive 2006/24/EC) was to allow the retention of data generated or processed in connection with the provision of publicly available electronic communications services or of public communications networks for possible use by law enforcement authorities. It was invalidated by the Court of Justice of the EU because of infringing the proportionality principle as well as the rights to privacy and data protection.

privacy.[8] The private information obtained and the interference with the private life due to retention of communication metadata was the result of the processing of these personal data.

Interference with personal data might therefore interfere both with the right to data protection and the right to privacy of the individuals. To be able to analyse the effects of the data collected by smart meters under the rights of privacy and data protection, we will assess in the following section if these data qualify as personal data.

2.2 Smart Meter Data as Personal Data

The current EU legal framework for smart meters is composed of Directive 2009/72/EC (Energy Internal Market Directive), and Directive 2004/22/EC (Measuring Instrument Directive). These directives focus on the operation of the system and do not regulate privacy and personal data issues. Other provisions in the field have the form of soft law recommending rather than requiring the application of safeguards for the protection of the rights to privacy and data protection (Commission Recommendation 2012/148/EU, para. 4–9; Commission Recommendation 2014/724/EU). They suggest however the respect of the general legal regime in the field.

Smart meter data give information that is not limited to energy consumption but reveal also domestic activities on the basis of the usage of electric appliances in a household (Weiss et al. 2012). Electricity consumption might give also more direct information on the habits of the members of the household—when they are at home, if they have healthy habits (e.g. cooking regularly or using largely the microwave for convenience food), if they spend time together or in separate rooms, the activities they perform, and even sensitive information (e.g. the use of medical devices) (Kalogridis and Denic 2011).

There has been no reluctance to qualify smart meter data as personal data (EDPS 2012; Cuijpers and Koops 2012) even though different ideas have been presented as to whom these data belong. As potential data subjects have been targeted: (a) the member of the household that is the signatory of the electricity supply contract; (b) all the members of the household as a group; or (c) each individual member of the household.

For the Article 29 Working Party (2011) a domestic consumer of energy is associated with unique identifiers that are inextricably linked with the member of the household who is responsible for the account. The data would therefore belong to him. This qualification would, however, attribute to one member of the household all the generated electricity data, even in periods of time when it is clear that he is not present at the location.

---

[8] Joint cases C-293/12 and C-594/12 Digital Rights Ireland and Seitlinger and others [2014] nyr, para. 27.

In contrast, Knyrim and Trieb (2011) suggest that the definition of personal data should be interpreted broadly in line with some national data protection laws. They present the example of the Austrian law that refers to personal data as belonging not only to a single person but also to a 'community of persons' [Datenschutzgesetz 2000, para. 4(3)]. With this broad interpretation smart meter data would qualify as personal data belonging to all the inhabitants of the household as a community. This idea is supported also by King and Jessen (2014) that plead for the adoption of a more inclusive definition of the data subject which would cover a group of natural persons living together in a household, including temporary guests.

It is easy and automatic to link smart meter data just to the person that has signed the contract with the electricity supply company or to refer to a community of persons instead, even though the latter might create problems with regards to the consent needed for the usage of the data by third parties. But as stated by the European Data Protection Supervisor (EDPS 2012) the long period of retention and the possibility of profiling while linking different databases gives the possibility to separate the data and link them to the right identified or identifiable members of the household: "*Profiles can thus be developed, and then applied back to individual households and individual members of these households*". We would agree with this view and consider smart meter data as personal data belonging to individual household members.

Qualifying smart meter data as personal data brings them into the realm of application of the European data protection legislation with regards to the collection and processing of the personal data. As already seen in the Data Retention Directive case, the collected and processed personal data create the possibility to interfere at the same time also with the private sphere of the individuals concerned (Savirimuthu 2013). Just from the few examples mentioned above smart meter data give information on different aspects of the private life of the citizens as for example: privacy of behaviour, privacy of data, privacy of association (learning about the presence of guests and how often) and even privacy of the individuals´ body (since it is possible to detect sensitive information as for example medical appliances at home and how often they are used).

3 Smart Meters and Law Enforcement Authorities

As already stated in the introduction, this chapter focuses on the use of smart meter data by law enforcement authorities for surveillance purposes. The aim of this section is to present a number of possibilities that smart meters offer for collecting data and information on the activities that individuals perform inside their homes and the relevance that these data might have for law enforcement authorities. In the following sub-sections, the challenges that surveillance via smart meter data creates for the protection of the right to privacy of the citizens are identified and discussed.

The possibilities of smart meters for detecting activities and collecting data from the households are broad and detailed. They give the possibility for detecting illegal activities that might take place inside a household as well as give the possibility to verify defendants' claims (Lisovich et al. 2010), suspects' claims or even create and verify profiles of certain criminals as for example sex offenders (e.g. pedophiles).

Smart meters enable frequent communications between the meter and the service provider giving accurate and timely information. The regularity and frequency of the data communication discloses what members of a household do within the privacy of their home. It shows the electric devices present and if they are turned on or off. Energy usage over long periods of time may show patterns of use and even distinguish situations that are outside the normal, as for example the presence of guests (Kim et al. 2009). Data can assess the routine of a household, sleeping times, working times, if someone is at home and when the members are on holidays.

Some studies present the possibility of identifying, on the basis of the analyses of the smart meter data, the television programmes watched (Mills 2012) and the copyright protection or its absence of a DVD that is played (Enev et al. 2011). In addition data from charging of electric cars would give information on the kilometers traveled and combined with other information also the destinations reached (Smart Grid Coordination Group 2014).

From the above abilities of smart meter data, one might imagine all the interesting information that law enforcement authorities would be able to deduce. This information would facilitate the creation of detailed profiles of the members of a household—since lots of data shows their behavior and their preferences. The frequent communication between the smart meter and the service provider would also give the possibility to use this feature of the device for direct surveillance of the members of the household—their presence at home, their TV preferences (that might reveal interesting information for example for pedophiles or other sexual offenders), if they use the electricity for illegal activities (as in the case of cultivation of narcotic plants, unlicensed commercial activities, sweatshops, or infringing the copyright laws and watching copyright protected DVDs, etc.).

3.1 Risks for the Protection of Privacy of Individuals Deriving from Surveillance via Smart Meter Data

Surveillance via smart meter data can be performed by law enforcement authorities themselves, or via service providers that are under a duty to refer suspicious situations and therefore operate in such situations as an arm of the State (Chalmers et al. 2014, 312).[9] The very detailed and timely way smart meters transfer the data might give the possibility for direct surveillance as well as for dataveillance (Clarke 1997).

---

[9] C-180/04 Vassallo v. Azienda Ospedaliera Ospedale San Martino di Genova e Cliniche Universitarie Convenzionate [2006] ECR I-7251, para. 26; M.M. v. The Netherlands, ECHR application no. 39339/98, 8 April 2003, para. 42; A. v. France, ECHR application no. 14838/89, 23 November 1993, paras. 38–39.

Even though there is not yet any legislation requiring smart meter data retention for law enforcement purposes, service providers might keep data for long periods of time for other reasons than surveillance. The Measuring Instruments Directive [Annex MI-003, para. 5(3)], for example, establishes that smart meter data shall remain available for reading for a period of at least 4 months. These period of retention might change from one Member State to another in relation with the electricity payment intervals. In UK for example the customer is sent a bill every 1–3 months, but this might be an estimate bill while an accurate bill is sent every two years. In Poland the system is similar but the invoice is issued every 6 months (Essential regulatory requirements 2011, para. 100). Meter data, even if not detailed, may be retained also for other purposes as for example taxation (3 years in the UK, 5 years in Poland, 7 years in the Netherlands, 10 years in France) (Essential regulatory requirements 2011, para. 105). The data might be kept also from the electricity companies for ensuring an accurate forecasting of energy use.

Apart the retention of data and the possibility thereof to access them at a different moment in time, smart meters are supposed to send the information in short time intervals of 15 min, even though shorter time intervals are not excluded allowing for direct surveillance. When deciding on surveillance with smart meters one has to keep in mind the level of intrusion of this device that has a 24 h presence within the household. That is the reason why the need for a warrant similar with the one needed for searching a home has been advised, when smart meter data is asked for (EDPS 2012). In the following sections the effects of surveillance via smart meter data in cases of individual surveillance and mass surveillance are discussed.

3.1.1 Individual Surveillance

Individual surveillance targets well identified individuals. In the case of use of smart meter data the level of intrusion into the individual's private life might be quite high. A personal search warrant with the strict requirements and safeguards as in the case of home searches is suggested. Besides the level of intrusiveness, there are other important elements that the authorities issuing the surveillance mandate have to keep in mind. These elements are incidental surveillance, accuracy of the data and retroactive surveillance. Each will be discussed in turn.

(a) Incidental surveillance

Incidental surveillance is the accidental collection of data from individuals that are not the target of the surveillance activity (Guiding document 2000) and therefore interferes with their private life. Thus far, there is no proper protection of the privacy of individuals that find themselves in situations of incidental surveillance in the European Union. The legislation does not regulate such situations while in the case law of the European Court of Human Rights this form of surveillance is considered as being compatible with the privacy rules, even though it is done without assessing the standards set in article 8 ECHR.[10]

Essentially two possibilities for an *ex post* remedy of the infringed right exist for an incidentally surveilled individual. The first possibility is to challenge the validity of the surveillance mandate as if it was directed to the incidentally surveilled individual, and the second consists in asking the deletion of the incidentally collected data.

The first possibility applies when the incidentally surveilled individual faces as a consequence a case before a court. A similar situation was discussed in *Lambert* where the European Court of Human Rights[11] gave the incidentally surveilled individual the possibility to challenge the validity of the surveillance mandate as if he was in person addressed by it.[12] The possibility for "effective remedy" is an *ex post* adjustment and improves only partially the situation of the incidentally surveilled person. In issuing the surveillance mandate the authorities have not been considering the need of such an interference in his situation and therefore it would be difficult to successfully challenge the surveillance mandate on its merits.

The second possibility is to delete the incidentally collected data once these do not have any more relevance for the investigation or, in alternative, to notify the concerned individual, as stated in Recommendation R(87)15 of the Council of Europe. Such an *ex post* notification has a specific importance for the protection of individuals in cases of incidental recording of data since it is an essential safeguard against abuse of monitoring powers and it is an important part of the right to an effective remedy. However, Recommendation R(87)15 does not have binding effect and has not been incorporated so far in most of the national legislation of the Member States (De Hert and Boehm 2012). The European Court of Human Rights has applied the 'notification' principle in a number of cases.[13] The most significant decision is *Ekimdzhiev* were the Court clearly established that omission of notification of surveillance measures, once it does not risk to jeopardize the inquiry, amounts to violation of article 8 ECHR.[14]

From the above elaboration it is clear that the right to privacy of individuals that find themselves in situations of incidental surveillance is not properly protected. This important conclusion has to be taken into account when deciding on the use for surveillance of smart meter data that per definition effect all the members (and temporary guests) of a household.

---

[10] Kruslin v. France, ECHR application no. 11801/85, 24 April 1990, para. 28.

[11] Lambert v. France, ECHR application no. 23618/94, 24 August 1998, para. 40.

[12] Ibidem para. 38.

[13] Klass v. Germany, ECHR application no. 5029/71, 6 September 1978, para. 50; Weber and Saravia v. Germany, ECHR application no. 54934/00, 29 June 2006, para. 114.

[14] Association for European Integration and Human Rights and Ekimdzhiev v. Bulgaria, ECHR application no. 62540/00, 28 June 2007, para. 91.

(b) Accuracy of the data

Closely linked with the possibility for incidental surveillance is the element of the accuracy of the data. As already seen, smart meters refer the energy consumption and activities of a household and not of targeted individuals. Processing of data and linking them with other sources gives the possibility to single out and distinguish the activities of different individuals, but there is always a possibility for errors and for creating false profiles which cannot be ignored (Beckel et al. 2014). This can be for example in those cases in which one member of the household engages in an activity that is always attributed to another member (e.g. daughter watches football match while the father is not at home). The accuracy of the data should be taken into account when deciding on the employment of smart meter data for surveillance.

(c) Retroactive surveillance

As seen above, smart meter data might be retained by service providers for different periods of time, for reasons required by national laws or for their own purposes. Data retention gives the possibility to law enforcement authorities to access data belonging to past activities and behaviours of targeted individuals. The data create the possibility to scrutinize past activities, belonging to a time that the individual was not under suspicion and no mandate for his surveillance was issued. Surveillance into the past might be easy due to the technology but, apart problems to the right to privacy it creates problems also for the right to presumption of innocence of the individual (Milaj and Mifsud Bonnici 2014). The problems created for the rights of the individuals must be taken into account by the national authorities issuing a surveillance mandate.

3.1.2 Mass Surveillance

Mass surveillance is a measure of preventive nature that, as the name states, is not directed to targeted individuals but at entire categories of them. There is evidence that mass surveillance programmes are used extensively in some Member States of the EU (Bigo et al. 2013; Explanatory memorandum 2015, paras. 26–29) and they enable intelligence services and law enforcement authorities to access, without an individual warrant, personal data on a large scale. Mass surveillance targets the use of certain technologies or the presence at certain locations. Smart meter data can be a source of mass surveillance.

The European Court of Human Rights extended the application of article 8 ECHR and of the test it has established for cases of individual surveillance also to cases of mass surveillance. For the Court there are no grounds to apply different principles concerning the accessibility and clarity of the rules governing the interception of individual communications, on the one hand, and more general programs of surveillance, on the other.[15] The effective remedy that individuals have in such situations is the possibility to challenge the mass surveillance programs as such, without the need to prove that they have been individually suffering from these programs.[16]

Apart special mass surveillance programmes that are operational in different Member States, this form of surveillance was introduced also in the EU with the (now invalidated) Data Retention Directive (2006/24/EC). The Directive essentially introduced a form of mass surveillance (Roberts and Palfrey 2010) via the retention of metadata from electronic communications for periods of time between 6 months and 2 years (art. 6). This was based on the ability of service providers to collect and retain a number of personal data for different purposes (as for example billing details) and then use these data for other purposes, in our case for mass surveillance of the users of electronic communications. Advancement in technology makes it easier in the future to use the same scheme as under the Data Retention Directive for the massive accessing of personal data collected for other purposes.

Even if there is not yet any evidence of the employment of smart meter data for mass surveillance purposes, this might be a possibility. In the invalidation of the Data Retention Directive the Court of Justice of the EU did not close the door to this form of surveillance and found data retention to be an appropriate method for attaining the objective of fighting serious crime. It was already seen that smart meters have a possibility to detect illegal activities that might take place within a household as for example the cultivation of illegal plants or broadcasting of copyright protected materials, etc. A routine control by the law enforcement authorities for detecting special crimes is therefore not to be excluded.

A routine control of retained smart meter data is, however, tantamount to a routine control inside a house and this goes against the right to inviolability of the home. That is why we argue and advice, in line also with the EDPS (2012) recommendation, against such uses of smart meters. The proportionality of the level of intrusiveness into the private life of the citizens of this method of surveillance is to be taken into account when deciding on mass surveillance of smart meter data.

4 European Legal Framework and Existing Safeguards

Surveillance activities by law enforcement authorities are mainly regulated at Member State level in the absence of a European legal framework regulating the field. The absence of harmonised rules on surveillance at EU level is related with the limited competence of the European institutions in the area of the former third pillar (Judicial and Police Cooperation in Criminal Matters). The existing EU

---

[15] Liberty and Others v. The United Kingdom, ECHR application no. 58243/00, 1 July 2008, para. 63.

[16] Weber and Saravia (n 13) para. 78.

legislation focuses exclusively on data exchange, as well as coordination and cooperation between law enforcement agencies of the Member States. Framework Decision 2008/977/JHA on police and judicial cooperation in criminal matters, even if introduces the data protection principles in the field, does not harmonise these sector-specific provisions and applies only in cases of exchange of data between the Member States. The legislation does not deal with the way data are obtained.

Apart the EU legislation, for activities within the area of police and judicial cooperation all Member States are part of the Council of Europe Recommendation R(87)15, which sets out the principles of Convention 108 for the police sector and has become the effective standard on these issues (Korff 2014, 113). This is not, however, a legally binding instrument and shows the lack of European legislation in the field.

While the surveillance laws and rules are regulated at national level, privacy and data protection are protected as fundamental rights at European level. The safeguards necessary for the protection of these rights and for avoiding potential abuse by State authorities come therefore from the laws, case law and the elaborations of the doctrine at European level. Below we will present the existing safeguards that need to be taken into account by service providers on one side and the authorities issuing surveillance mandates on the other.

(a) Safeguards for service providers

National rules must regulate the period for which the data are retained, which must follow objective requirements,[17] and ensure the irreversible destruction of the data at the end of the data retention period.[18] For as long as there are no specific rules on retention of smart meter data, the providers must keep only the data required for specific purposes (as for example taxation). There is no need to keep the detailed data on the basis of which it is possible to retrieve activities taking place within a household but only the final consumption of energy [Directive 95/46/EC, art. 6(1)(b)–(c)]. Data retained by service providers for their forecasting strategies must follow the principles of consent and anonymisation.[19] Substantive and procedural rules must be drafted on the access and the processing of the data.[20] It is also important to keep the data saved within the territory of the EU for avoiding that they could become subject to rules of other jurisdictions.[21] A data protection impact assessment must take place for identifying the risks to the right of the individuals when processing the data (Commission Recommendation 2012/148/EU, para. 4–9; Commission Recommendation 2014/724/EU).

---

[17] Digital Rights Ireland (n 8) para. 64.

[18] Ibidem para. 67.

[19] So far studies have shown, however, that de-anonymisation of data is possible (Buchman et al. 2013).

[20] Digital Rights Ireland (n 8) para. 60.

[21] Ibidem para. 68.

(b) Safeguards for authorities that issue surveillance mandates

In this chapter it was argued that surveillance via smart meter data creates problems for the right to privacy of European citizens. Any mandate for surveillance via these data must therefore be in conformity with the European rules and standards on the matter. As regulated by article 8(2) ECHR and clarified further by the case law of the European Court of Human Rights (Taylor 2001),[22] every interference with the right must be provided by the law. Keeping in mind the level of intrusion into the private sphere of the individuals that can be attained via the use of these data, the recommendation of the EDPS to issue personal surveillance warrants as in the case of a home search should be taken into account. In addition any interference must comply with the necessity and proportionality criteria.

The European courts so far have not been exhaustive in clarifying the concept of ‘necessity’ but stay with the broad understanding of a ‘pressing social need’ (which is also not defined!) (Harris 2009). This is related also to the fact that the European Court of Human Rights uses the margin of discretion (Arai-Takahashi 2002) left to the national courts and holds that the exclusivity to interpret and apply national law to domestic situations should remain within the domain of national authorities.[23] This approach becomes even stronger in cases of measures introduced with the scope of protecting national interests. The attention of the Court in such cases is focused on the analyses of the legal safeguards and guaranties offered to the individuals.[24]

Proportionality on the other side is seen as a general principle of law to be tested when limiting a fundamental right both at Council of Europe and at EU level. Similarly with the German administrative law, the test for establishing the proportionality of a measure is composed of three steps: (i) appropriateness; (ii) necessity; and (iii) proportionality *stricto sensu* (Troncoso Reigada 2012). The measure must be first of all appropriate or suitable to protect the interests that require protection. It must be necessary, meaning that no measure less restrictive must be available to attain the objective pursued. And it must be proportionate *stricto sensu*, meaning that the restriction that it causes must not be disproportionate to the intended objective or result to be achieved (Jans et al. 2007, 149). The criteria that the measure must be the less restrictive alternative is important when deciding on the surveillance mandate since one has to keep in mind the level of intrusion, the possibility of the incidental involvement in the surveillance of other untargeted members of the household, or even guests, as well as the possibility of errors made during data processing.

Finally, the surveillance mandates must be reviewed by a judicial or independent administrative body whose decisions would seek to limit access to the data to what

---

[22] Kopp v. Switzerland, ECHR application no. 23224/94, 25 March 1998, para. 55; Perry v. The United Kingdom, ECHR application no. 63737/00, 17 July 2003, para. 55.

[23] Kruslin (n 10) para. 29; M.K. v. France, ECHR application 19522/09, 18 April 2013, para. 43.

[24] Weber and Saravia (n 13) para. 106; Klass (n 13) para. 50.

is strictly necessary.[25] The proper use of the legal requirements when deciding upon a surveillance measure would limit the discretion of the authorities and minimize the possibilities for abuse.

5 Conclusion

The economic benefits that have inspired the introduction of electricity smart meters in Europe should not turn into a burden for the protection of the fundamental rights of the individuals. Law enforcement authorities must, therefore, properly assess the necessity and proportionality of any interference with these rights before deciding to use smart meter data for surveillance purposes.

This chapter has shown the challenges that the introduction of smart meters in the European Union creates for the protection of the right to privacy of individuals in cases in which the transferred data are used by law enforcement authorities for surveillance purposes. It was argued that the challenges created are not adequately addressed in the European legislation and the existing case law. This lacuna in the legislation and jurisprudence must be taken into account by law enforcement authorities when conducting their assessments on the surveillance methods to be used and interpreted in favour of the protection of the fundamental rights of the individuals.

Law enforcement authorities might be tempted to use smart meter data because they constitute inexpensive and easy means for direct surveillance or dataveillance in individual as well as mass surveillance situations. The analysis of smart meter data is to be regarded as being highly intrusive because it enables the law enforcement authorities to surveil activities taking place within the walls of a private residence in the same way as having a 24 h physical presence of an investigator in the home. Moreover, it enables the law enforcement authorities to benefit from a *de facto* retroactive effect of their investigatory mandate in the sense that smart meter data is stored for prolonged periods of time (in some cases for several years) and is thus available for analysis.

While mass surveillance of smart meter data is advised not to be used due to the level of interference with the individual's private life, for cases of individual surveillance a number of challenges not properly addressed in the current legal framework (e.g. the risk for incidental surveillance, non-accuracy of the data, violation of the principle of presumption of innocence) are identified. The legal safeguards established thus far by the laws, case law and discussed by the doctrine for both service providers and law enforcement authorities do not directly address these challenges.

---

[25] Digital Rights Ireland (n 5) para. 62.

Points for Discussion

- The present debate about privacy versus collective security is much wider than the discussion about deviances in European legislation about smart meters (think of the NSA scandal revealed in June 2013 by whistle blower Edward Snowden). How does this affect the stance on privacy risks of smart grids? How can we navigate between the stance ‘as long as we can’t solve the wider problematic, the development of smart grids should not be hampered by these legal concerns’ or the position that ‘since smart grids are still in a developmental phase, strict legal protection of user rights should be an integrated part of the new energy system, even if this causes delays in implementation’?
- Can new technology and/or cyber security measures, provide means to speed up the process?

References

Anderson, R., Fuloria, S.: On the security economics of electricity metering. In: Proceedings of the Ninth Workshop on the Economics of Information Security (WEIS 2010), vol. 18 (2010)

Arai-Takahashi, Y.: The margin of appreciation doctrine and the principle of proportionality in the jurisprudence of the ECHR. Intersentia, Antwerp (2002)

Article 29 Data Protection Working Party (2011) Opinion 12/2011 on Smart Metering, 4.4.2011

Beckel, C., et al.: Revealing household characteristics from smart meter data. Energy **78**, 397–410 (2014)

Bigo, D. et al.: National programmes for mass surveillance of personal data in EU Member States and their compatibility with EU law. Study submitted to the European Parliament’s Committee on Civil Liberties, Justice and Home Affairs, http://www.europarl.europa.eu/RegData/etudes/etudes/join/2013/493032/IPOL-LIBE_ET(2013)493032_EN.pdf. Accessed 1 Nov 2013 (2013)

Bohli, J., Sorge, C., Ugus, O.: On the security economics of the electricity metering. In: Proceedings of 2010 IEEE International Conference on Communications Workshops, vol. 10 (2010)

Borton, D.A., et al.: An implantable wireless neural interface for recording cortical circuit dynamics in moving primates. J. Neural Eng. **10**(2), 16 (2013)

Buchman, E., Boehm, K., Burghardt, T., Kessler, S.: Re-identification of smart meter data. Pers. Ubiquit. Comput. **17**, 653–662 (2013)

Cavoukian, A., Polonetsky, J., Wolf, C.: Smart privacy for the smart grid: embedding privacy into the design of electricity conservation. https://www.privacybydesign.ca/index.php/paper/smartprivacy-for-the-smart-grid-embedding-privacy-into-the-design-of-electricity-conservation/. Accessed 15 Apr 2015 (2010)

Chalmers, D., Davies, G., Monti, G.: European Union Law, 3rd edn. University Press, Cambridge (2014)

Clarke, R.: Introduction to Dataveillance and Information Privacy, and Definitions of Terms. http://www.rogerclarke.com/DV/Intro.html. Accessed 22 May 2014 (1997)

Commission Recommendation 2012/148/EU of 9 March 2012 on preparations for the roll-out of smart metering systems, OJ L 73, 13.3.2012

Commission Recommendation 2014/724/EU of 10 October 2014 on the Data Protection Impact Assessment Template for Smart Grid and Smart Metering Systems, OJ L 300, 18.10.2014

Convention 108 for the protection of individuals with regard to automatic processing of personal data, 28 January 1981

Council Framework Decision 2008/977/JHA of 27 November 2008 on the protection of personal data processed in the framework of police and judicial cooperation in criminal matters, OJ L 350, 30.12.2008

Covrig, C.F. et al.: Smart Grids Projects Outlook, ftp://ftp.cencenelec.eu/EN/European-Standardization/HotTopics/SmartGrids/SGCG_SGIS_Report.pdf. Accessed 29 Apr 2015 (2014)

Cuijpers, C., Koops, B.-J.: Smart metering and privacy in Europe: Lessons from the Dutch case. In: Gutwirth, S., Leenes, R., de Hert, P., Poullet, Y. (eds.) European data protection: coming of age, pp. 269–293. Springer, Dordrecht (2012)

Datenschutzgesetz 2000, Bundesgesetz über den Schutz personenbezongener Daten

De Hert, P., Boehm, F.: The rights of notification after surveillance is over: Ready for recognition? In: Bus et al. (eds.), Digital enlightment year book 2012, vol. 19. IOS Press, Amsterdam (2012)

Directive 2004/22/EC of the European Parliament and of the Council of 31 March 2004 on Measuring Instruments, OJ L 135, 30.4.2004

Directive 2006/24/EC of the European Parliament and of the Council of 15 March 2006 on the retention of data generated or processed in connection with the provision of publicly available electronic communications services or of public communications networks and amending Directive 2002/58/EC, OJ L 105, 13.4.2006

Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC, OJ L 114, 27.4.2006

Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC, OJ L 211, 14.8.2009

Directive 95/46/EC of the European Parliament and of the Council of 24 October 1995 on the protection of individuals with regard to the processing of personal data and on the free movement of such data, OJ L 281, 23.11.1995

EDPS (2012) Opinion of the European Data Protection Supervisor on the Commission Recommendation on preparations for the roll-out of smart metering systems

Enev, M., Gupta, S., Kohno, T., Patel, S.: Televisions, video privacy, and powerline electromagnetic interference. In: Proceedings of the 18th ACM Conference on Computers and Communications Security, pp. 537–550 (2011)

Essential regulatory requirements and recommendations for data handeling, data safety, and consumer protection, Recommendation to the European Commission, 5 December 2011

Explanatory memorandum on the Parliamentary Assembly of the Council of Europe draft Resolution and draft Report on Mass Surveillance prepared by Mr. Pieter Omtzigt, rapporteur. http://assembly.coe.int/nw/xml/XRef/X2H-Xref-ViewPDF.asp?FileID=21583&lang=en. Accessed 28 Apr 2015

Faraqui, A., Harris, D., Hledik, R.: Unlocking the €53 billion savings from smart meters in the EU: How increasing the adoption of dynamic tariffs could make or break the EU's smart grid investment. Energy Policy **38**(10), 6222–6231 (2010)

Guiding document to the UK Regulation of Investigatory Powers Acts 2000 by the Leeds City Council Legal Services (2013), http://www.leeds.gov.uk/docs/RIPA%20Guidance%20and%20Procedure%20-%20May%202013.pdf. Accessed 30 Mar 2015

Gutwirth, S., De Hert, P.: Privacy, data protection and law enforcement. Opacity of the individual and transparency of power. In: Claes, E., Duff, A., Gutwirth, S. (eds.) Privacy and the criminal law, pp. 61–104. Intersentia, Antwerp (2006)

Hargreaves, T., Nye, M., Burgess, J.: Making energy visible: a quantitative field study of how households interact with energy from smart energy monitors. Energy Policy **38**, 6111–6119 (2010)

Harris, D., et al.: Law of the European Convention on Human Rights, 2nd edn. University Press, Oxford (2009)

Jans, J.H., et al.: Europeanisation of Public Law. Europa Law Publishing, Groningen (2007)

Kalogridis, G., Denic, S.: Data Mining and privacy of personal behavior types in smart grid. In: Proceedings of the 11th IEEE International Conference on Data Mining Workshops, pp. 636–642 (2011)

Kim, Y., Schmid, T., Srivastava, M., Wang, Y.: Challenges in resource monitoring for residential spaces. In: Proceedings of the First ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings, pp. 1–6 (2009)

King, N.J., Jessen, P.W.: Smart metering systems and data sharing: why getting a smart meter should also mean getting strong information privacy controls to manage data sharing. Int. J. Law Inf. Technol. 1–39 (2014)

Kleining, P., et al.: Security and Privacy: Global standards for ethical identity management in contemporary liberal democratic states. ANU E Press, Canberra (2011)

Knyrim, R., Trieb, G.: Smart metering under EU data protection law. Int. Data Privacy Law **1**(2), 121–128 (2011)

Korff, D.: The rule of law on the internet and in the wider world. Issue Paper published by the Council of Europe Commissioner for Human Rights (2014). https://wcd.coe.int/ViewDoc.jsp?id=2268589. Accessed 1 May 2015

Lerner, J.I., Mulligan, D.K.: Taking the long view on the fourth amendment: stored records and the sanctity of the home. Stanford Technol. Law Rev. **3**, 13 (2008)

Lisovich, M., Mulligan, D., Wicker, S.: Inferring personal information from demand-response systems. IEEE Security and Privacy, 11–20 (2010)

Lo Schiavo, L., Fumagalli, E., Olivieri, V.: Changing the regulation for regulating the change—innovation-driven regulatory developments in Italy: smart grids, smart metering and e-mobility. IEFE Working Paper Series **46**, 40 (2011)

Mayer-Schoenberger, V.: Generational development of data protection in Europe. In: Agre, P.E., Rotenberg, M. (eds.) Technology and privacy: the new landscape, pp. 219–238. MIT Press, Cambridge (1997)

McDaniel, P.: Security and privacy challenges in the smart grid. IEEE Secur. Priv. **7**, 75–77 (2009)

McKenna, E., Richardson, I., Thomson, M.: Smart meter data: balancing consumer privacy concerns with legitimate applications. Energy Policy **41**, 807–814 (2012)

Milaj, J., Mifsud Bonnici, J.P.: Unwitting subjects of surveillance and the presumption of innocence. Comput. Law Secur. Rev. **30**(4), 419–428 (2014)

Mills, E.: Researchers find smart meters could reveal favorite TV shows. CNet News (2012) http://news.cnet.com/8301-27080_3-57364883-245/researchers-find-smart-meters-could-reveal-favorite-tv-shows/. Accessed 27 Apr 2013

Pallas, F.: Beyond gut level—Some critical remarks on the German privacy approach to smart metering. In: Gutwirth, S., Leenes, R., de Hert, P., Poullet, Y. (eds.), *European Data Protection: Coming of Age*, Springer, Dordrecht, pp. 313–345 (2012)

Quinn, E.L.: Privacy and the new energy infrastructure, *CEES Working Paper no. 09-0001*, 41 (2008)

Recommendation no. R(87)15 of the Committee of Ministers regulating the use of personal data in the police sector

Roberts, H., Palfrey, J.: The EU Data Retention Directive in an era of internet surveillance. In: Deibert, R., et al. (eds.) Access Controlled: The Shaping of Power, Rights, and Rule in Cyberspace, pp. 35–53. MIT Press, Cambridge (2010)

Savirimuthu, J.: Smart meters and the information panopticon: beyond the rhetoric of compliance. Int. Rev. Law Comput. Technol. **27**(1-2), 161–186 (2013)

Smart Grid Coordination Group (2014) Document for the M/490 Mandate Smart Grid Information society. ftp://ftp.cencenelec.eu/EN/EuropeanStandardization/HotTopics/SmartGrids/SGCG_SGIS_Report.pdf. Accessed 29 Apr 2015

Subrahmanyan, P.A.: Network security architecture for demand response/sensor networks, Report for the California Energy Commission, Public Interest Energy Research Group (2005). http://www.law.berkeley.edu/files/demand_response_CEC.pdf. Accessed 15 Apr 2015

Taylor, N.: State surveillance and the right to privacy. Surveill. Soc. **1**(1), 66–85 (2001)

Troncoso Reigada, A.: The principle of proportionality and the fundamental right to personal data protection: the biometric data processing. Lex Electronica **17**(2), 1–44 (2012)

Weiss, M., Helfenstein, A., Mattern, F., Staake, T.: Leveraging smart meter data to recognize home appliances. In: Proceedings of IEEE Pervasive Computing and Communication PerCom, vol. 8 (2012)

Zeadalli, S., Pathan, A.-S., Alcaraz, C., Badra, M.: Towards privacy protection in smart grid. Wireless Pers. Commun. **73**, 23–50 (2013)

Conducting a Smarter Grid: Reflecting on the Power and Security Behind Smart Grids with Foucault

Johannes Kester

Abstract A smart grid is about the delivery *of* power, but there is power *in* and *behind* a smart grid as well. This chapter takes stock of the current debate and the power relations behind smart grids by analysing it through two insights from the French philosopher Michel Foucault, in particular on the relation between 'power/knowledge' and his understanding of indirect government through 'the conduct of conduct'. Based on these insights this chapter makes two arguments. First, that debates about smart grids are hardly about electricity at all but mainly about the infrastructure to gather, analyse and problematize consumption data. In other words, they are about knowledge and in line with a simplified power/knowledge nexus of Foucault this knowledge relates to power and vice versa. Second, while smart grids are favoured to increase consumer choice, they are actually geared towards a particular way of life by organizing the circulation of electricity towards an impeccably behaving consumer. The choices offered to consumers are hence indirectly governed as companies and governments are conducting the conduct of consumers. Based on such an interpretation, there is cause to question the current conduct of smart grids not only from a privacy standpoint, but from a wider understanding on power as well. While smart grids might decentralise and thus democratise electricity production, the centralisation of information inherently negates this decentralisation of production.

1 Introduction

> A smarter grid applies technologies, tools and techniques available now to bring knowledge to power – knowledge capable of making the grid work far more efficiently…
>
> The U.S. Department of Energy (2014, 3)

J. Kester (✉)
Department of International Relations, University of Groningen,
Groningen, The Netherlands
e-mail: j.kester@rug.nl

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_13

A smart grid is about the delivery *of* power, but there is power *in* and *behind* a smart grid as well. Perhaps less visible and more diffuse than in the old “dumb” electricity grid, but there nevertheless. This chapter takes stock of the current politics on smart grids through the insights on power from the French philosopher Foucault (2007, 2008). With the help of Foucault it becomes possible to question the notion that smart grids are a win-win option for all parties involved, and, in particular, the idea that a decentralisation of electricity production leads to a democratisation of the electricity grids. To make this argument, this chapter firstly shifts the focus from electricity towards an understanding of smart grids as an infrastructure that gathers, analyses and problematizes consumption data. Smart grids are about knowledge as much as they are about electricity, which opens them up to a Foucauldian reflection on the power/knowledge nexus. Secondly, while smart grids are favoured to increase consumer choice, they actually enable a political economy that is geared towards a particular way of life by organizing the circulation of electricity towards a particular pro-environmentally oriented consumer. These arguments for pro-environmental consumer behaviour and demand side management (DSM) will be questioned below with Foucault’s idea that power is exercised through the ‘conduct of conduct’ and the securing of freedom.

This chapter builds on the insights from a recent upsurge in critical sociological research on the position of consumers within smart grids, smart meters and smart homes (Darby 2010; Hargreaves et al. 2010; Darby and McKenna 2012; Balta-Ozkan et al. 2013; Geelen et al. 2013; Hargreaves et al. 2013; Schick and Winthereik 2013; Verbong et al. 2013; Batel and Devine-Wright 2014; Goulden et al. 2014; Naus et al. 2014). This literature itself builds on insights on consumption and sustainability (Miller and Rose 1997; Rutherford 2007; Spaargaren and Mol 2008; Thaler and Sunstein 2008; Shove 2010; Shove and Walker 2010). These literatures are critical, but not explicitly Foucauldian. More Foucauldian driven research in relation to electricity often focusses on infrastructure in general (e.g. Graham and Marvin 1996; Collier 2011). In relation to smart grids in particular, Foucault is used to reflect upon the eco-friendly nudging of consumers (Hargreaves 2010), the agency of and governing through smart meters (Marres 2011), and the governing behind the coding of smart grids (Klauser 2013; Klauser et al. 2014).

The chapter will first introduce smart grids by offering a brief sketch of the reasons that are offered for the construction and development of smart grids. The second section moves on to Foucault’s later work and briefly touches upon his understanding of power. The third section highlights the close connection between power/knowledge by discussing the exclusions behind the visualisations and discourses around smart grids. It also discusses issues of expertise and the creation of particular subjectivied consumers. The subsequent fourth section shifts to the actual apparatus that is installed to govern such a particular eco-friendly, monetary rationalized consumer with the help of Foucault’s concept of governing as the ‘conduct of conduct’. The fifth section discusses the role of risk and resilience in securing the organized freedom of smart grids. The sixth section then reflects upon the decentralisation behind smart grids in relation to democratisation and social effect. It argues for centralising tendencies of information within the decentralisation of production. The last section concludes by arguing for a shift from the current technical-economic debate on smart grids into a political debate that moves beyond privacy considerations alone.

2 Politics of Smart Grids

Smart grids roughly entail the utilization of ICT infrastructure to organize the production, distribution and consumption of electricity. Irrespective how one defines smart grids, a shared understanding is that the electricity grid and ICT infrastructure are linked through smart meters. High-voltage grids and their interconnections rely on smart metering—even in their current 'dump' state. Likewise, micro and low-voltage smart grids need smart meters to combine and organize local decentralised production, storage capacity and variable consumption based on price incentives. In addition, on a household level smart meters and their data enable the further integration and communication between consumer applications (Balta-Ozkan et al. 2013). All of these rely on smart meters for the nonstop measurement of, and two-way communication about, the actual production and consumption of electricity on all levels of the grid. Without smart meters to measure and communicate the constant flow of electricity it is not possible to use algorithms to automatically control, protect, record, and ultimately, to optimize the grids, whether at the supply, transmission or demand side (IEEE 2014). Based on the information from smart meters and a further fusion of information and communication technology with the electricity grid, it becomes possible to *act at a distance* based on real time information.

Smart grids are seen as the solution for a range of issues in high-energy consuming countries, including a necessary modernization of the existing grid (European Commission 2005, 13; Battaglini et al. 2009, 913; Darby and McKenna 2012, 761; IEA 2013, 9), climate change and security of supply concerns. Climate change in particular seems to drive a transformation of the grids based on three appeals: a reduction in demand, a reduction of CO_2 emissions, and increasing resilience against extreme weather. In terms of an overall reduction in energy demand, the discussion is often summarized with the *Trias Energetica* logic: to prevent climate change reduce overall demand, then increase Renewable Energy Sources (RES), and lastly, if you have to use fossil fuels, do so as efficiently as possible. Smart grids are seen as a particular good option to help manage all three aspects. They are expected to help integrate RES, increase efficiency and reduce overall demand by enabling the management of consumption through DSM.

With the introduction of more renewable energy sources and an increase in new disruptive loads (electric vehicles and heat pumps) comes the intermittent and distributed nature of these resources and appliances. This challenges the Western electricity grids on both an operational level, a planning level and financial level (Römer et al. 2012; IEA 2013, 7–9). Operationally, the variability of wind and solar energy needs to be incorporated in the grid, meaning that the grid needs to be able to deal with drastically shifting load curves. A challenge that is complicated by the geographically dispersed location of the production sites, which are either located far away from urban regions (connection) or produced through many small scale production units in local neighbourhoods (coordination). Financially, the marginal cost-free renewable energy production of wind and solar provides a downward pressure on wholesale electricity prices and hence provides a disincentive for investments in large scale base-load generation like gas, coal and nuclear. Without these investments the available back-up capacity is reduced, which, in particular on the short term, could endanger the electricity system's stability (IEA 2013, 8). Together with fears of more extreme weather events and patterns, this leads to the third appeal of smart grids: a call for a more resilient electricity grid (e.g. decentralised production) that is able to resist such extremes while simultaneously be able to minimize the adverse effects if the grid is compromised nonetheless.

To cope with these challenges of higher variability and geographically dispersed electricity supply while increasing the resilience of the grid as a whole, smart grids with decentralised production are the preferred but not the only option. An alternative could be to curtail the variability of supply during stress moments, to reduce the amount of RES, invest in copper-plating, or to create capacity markets that support back-up capacity. Each of these options has its downsides in terms social acceptability, financial costs and environmental impact. The smart grid offers a convincing solution to many of, if not all the issues that are currently related to electricity production and consumption—including to those that result from the smart grid—and are sold as a no-regrets option that is beneficial for all (Clastres 2011, 5401; Mah et al. 2012, 133; El-hawary 2014, 241). Specific reference is often made to consumers who are said to face less disruptions and have more insight in their usage and thus their costs; generators, who are better able to optimize their production in line with actual demand; utility (service) companies, who are able to target customers with individualized offers, have the option to create and sell new products, and can reduce fraud and theft; and transmission and distribution operators, who are better able to optimize their grids and reduce downtimes; even if that necessitates the shutdown of loads. One of the few strong arguments against smart meters and smart grids is privacy (Cavoukian et al. 2010; Cuijpers and Koops 2013; Brown 2014). While privacy concerns slow down the distribution of smart meters, as happened in the Netherlands, the support is strong. The EU, for example, required member states to encourage the spread of smart meters in 2006, a year before the 20/20/20 targets (The European Parliament and the Council of the European Union 2006). It has formalised this intention and now aims for an 80 % European distribution rate of smart meters by 2020 (The European Parliament and the Council of the European Union 2009, Annex 1 art 2).

3 Power, Knowledge and the Conducting of Choice

As an infrastructure under development, smart grids are highly interdisciplinary and build and planned on a trial and error basis. As such they are constructed and governed on historic experience and future problematizations. The later work of Foucault is especially suited to analyse the political dynamics behind such a process due to his radical reinterpretation of power. Power, for Foucault, is not something that one person has over another; it is not tangible or intentional. As Dillon argues:

> Foucault teaches that power is less a commodity that can be held than a force which comes into circulation when human beings - who he considers to be free beings - come into relation with one another. To be crude, power as a force that circulates is more like electricity than it is like a lever or a sword (2010, 63).

In other words, power is not the ability to control the light switch and turn something on or off, but everything that lies behind one's ability and desire to pull the switch in the first place. It is that what makes people act, not the act itself. It has no source and no end, but it circulates and transforms. It is not in the hands of a king but 'located and exercised at the level of life' and therefore also resembles life in its messiness and dynamics (Lobo-Guerrero 2007, 330). What's more, Foucault argues that power is not only restrictive but productive as well. It not only forbids but also opens up particular ways of life, mainly through the production of particular subjects: individuals or consumers behaving within and conform to a distinctive system of thought (Foucault 1982). Those who set the system of thought hence influence what kind of subjects or consumer exists. It is this interpretation of power/knowledge, together with Foucault's ideas on how power is exercised in modern life, by conducting the milieu of the consumer instead of the consumer itself, that make him relevant to reflect upon the politics behind smart grids.

The power/knowledge nexus is Foucault's way of describing the close linkages between the two. It describes how knowledge, its systematic gathering, categorisation and analysis, always also contains ways to structure and dominate (Foucault 1980). As Rouse argues 'A more extensive and finer-grained knowledge enables a more continuous and pervasive control of what people do, which in turn offers further possibilities for more intrusive inquiry and disclosure (2005, 4).' In particular, it describes the practice of governing a group of people (a population) by gaining knowledge over that group and by defining in the gathering of knowledge what is to be normal behaviour. In relation to smart grids this knowledge on groups is, of course, closely related to the data gathered over consumption practices. Important in this respect is Foucault's claim that such a definition of the norm is not something that is intentionally practiced by those in charge. The discussion on the visualisations behind smart grids below will show how such norms stem from imbedded assumptions about subjects. Assumptions which stem from other pre-formed assumptions and which are part of broader systems of knowledge called discourses. These discourses are self-reinforcing, delimit the extent of thought and speech while regulating these processes, create binary systems of inclusion or exclusion based on monitoring and classification, and put forward what is true and what is false (Sylwan 2011, 174). Regarding smart grids there are four discourses that are of importance and which will return throughout this chapter. These are: technical competence and optimization, neoliberal markets, resilience, and decentralisation.

In relation to the exercise of power, Foucault discusses how a population is redirected towards ‘acceptable’ behaviour through ‘the right disposition of things arranged so as to lead to a suitable end (2007, 96)’. In distinguishing individually focused pastoral power and disciplinary power from bio-power, which is focused on populations and their way of life, Foucault introduces how power is exercised in modern societies not on humans directly but on their milieu, which limits and promotes their ability to act and to think. Modern (biopolitical) power conducts the actual ways of individuals by ‘[s]tructuring the desires, proprieties and possibilities that shape the operation of life working on and through subjective freedoms (Dillon and Reid 2001, 48).’ In a way it is organized freedom: people are allowed to act, think and choose as they like, within the boundaries that are set and towards a particular preferred way of life. For Walters and Haahr this means that ‘[f]reedom has become a tool, a technology for the achievement of specific governmental objectives […] (2005, 45).’ It is this preferred way of life, the norm, within this space of freedom that needs to be secured against those who try to break with it. Either by disciplining them towards the norm or by excluding them from the population as a whole. To do so a security apparatus is constructed (Foucault 2007), based on a constant surveillance and monitoring of the circulation of goods and people. In doing so, the security apparatus installed to conduct the conduct of individuals returns us to knowledge and its close relation with power.

4 Knowing the Grid and Its Consumers

The quote at the beginning of this chapter that ICT is ‘bringing knowledge to power’ might capture the essence of a smart grid, but does not come close to a Foucauldian understanding of the intricate relationship between knowledge and power. In particular to an understanding that the way knowledge is gathered and presented is an exercise of power in itself. For example, an important aspect of the debate on smart grids is that it is yet unclear how they will materialise in a future large scale rollout. The visual representations that are modelling smart grids are an important technology to manage this uncertainty. As a form of knowledge they simplify the complexity of smart grids and thereby structure future pathways. On such a planning level the work of Schick and Winthereik (2013) shows how visual representations can influence the future direction of smart grids. After comparing two visual representations of the smart grid, Schick and Winthereik conclude that consumers are depicted as either active or passive participants. Selecting one of these visual representations as an image for the future grid hence shapes the actual grid based on an implicit answer to the question whether consumers can be trusted to adapt their consumption if necessary. Schick and Winthereik argue that such representations of basically incomplete systems struggle to gather support so that they become the guiding model of a ‘roadmap to the future’ (2013, 85; c.f. Amoore 2013, on the sovereignty of visuality). They do this, not by fixating a vision the way templates or blueprints do, but through a shared understanding over the assumptions behind these visualizations.

Such assumptions behind visualised data and models do not only play a role at an abstract planning level. On the contrary, on a household level the visualization of smart meters is specifically designed to activate consumers to modify their consumption patterns. Engineers, designers and software developers are working hard to visualize the electricity consumption in such a way that it nudges consumers to act. They do so by designing hardware and software as beautiful and easy to use as possible, while at the same time trying to visualize the information in such a way that it is alarming enough to act upon. This last part is done by showing price savings, CO_2 emissions, or a comparison with family or neighbours. With the increasingly detailed knowledge over households’ consumption levels, these visual cues become stronger as they are being tailored to each specific household in ever increasing detail. Behind these design decisions too there is an implicit understanding on the activity of consumers as either active ‘energy managers’ and passive ‘energy consumers’ (Goulden et al. 2014).

This double conception of subjects stems from the main discourse behind smart grids: one of technological competence and optimization. This technical theology presents smart grids as a viable and optimal technological solution that is cheap, environmental friendly and secure. It comes in two flavours. A weak form that utilizes ICT technology and automation to provide the best information to consumers, to inform them so that they can become their own ‘energy managers’. And a strong version, which instead portrays consumers as a complicating factor to the roll-out of smart grids and more efficient energy consumption, and should therefore be “managed”, preferably by designing a fully automated system that reduces total energy consumption without consumers taking notice, let alone adjust their consumption patterns and daily routines. For example, Eising et al. (2014, 450) show how electric vehicles and their batteries could be used to reduce the stress on the networks, but for now are only adding stress to the network because consumers plug-in their car during peak-hours: the moment they come home from work.

That said, such a strong version is not without critique. A fully automated smart grid contrasts for instance with other ways of reducing energy consumption, ways that actually include showing how much work it costs to change once consumption patterns (Marres 2011). What is more, Strengers (2013), Darby and Mckenna (2012, 762) and Royston (2014) question whether such a focus on automation and ease of use ‘could lead to an exacerbation of energy-intensive practices, within fully automated, climate-controlled, hi-tech lifestyles (Royston 2014, 1244).’ Similarly, in relation to visualization, research by for example Hargreaves et al. (2010, 2013), Verbong et al. (2013) and Naus et al. (2014) has shown that the near-real time visualization of electricity use has a number of unintended feedback loops as well as social consequences. Among which, as Hargreaves et al. show, the fact that visual clues in time lead to a new normalization: after an initial period of deciding on good versus bad consumption patterns and reducing the bad, "over the course of the trial interviewees had come to accept their normal consumption levels and patterns as exactly that, 'normal' and thus not in need of further chance or reduction (2013, 130)."

Another consequence of such a take on consumers is that the weak version perceives of consumers to become their own 'energy experts' while the strong version instead creates an elite of experts that decides based upon aggregated data and other mediated information (Strengers 2013; Royston 2014). In the visualization and judgement on *aspects* of the daily energy practices of consumers, a line is drawn between experts and non-experts, and the crossing of this distance becomes a problem in itself. To cross it, there is often a call for an 'increase[d] communication' with local stakeholders and communities to convince them to participate and to allow construction to take place (Cotton and Devine-Wright 2012, 20). However, more communication alone is often not enough. Batel and Devine-Wright (2014) show how the NIMBY metaphor is used by experts to square away the complaints of local communities. Likewise, experts put aside the reservations of consumers to smart grids and renewable energy projects as an inability of consumers to take in "the overall picture" and to act in the interest of the grid. This justifies the experts in their use of a 'decide-announce-defend' strategy that excludes non-experts from the decision-making process (Cotton and Devine-Wright 2012, 21, 33). Yet, when it comes to smart grids and renewable energy non-expert stakeholders voice a range of arguments which are often more profound then experts grant them. Verbong et al. (2013), for example, note how households not only question a loss of privacy and a lack of control but also foresee difficulty in changing their behaviour in line with the intention behind smart grids based upon the systems that are currently installed.

5 Conducting the Conduct of Consumers

In addition to the automation and enlightenment of consumers, smart grids and DSM are built around a notion of price incentives. The idea being that through instantaneous price setting it becomes possible at times of high variability, peak demand, congestion or disruptions to set higher prices that reflect the instability of the electricity grid (Alexander 2010; Faruqui et al. 2010). This incentivises producers and prosumers to increase their production while end-consumers can either shift their load in time or alter their consumption volumes. Alternatively, DSO's can even use DSM in emergencies to absorb shocks and protect essential public services (hospitals, etc.) by closing off non-essentials loads during 'orange regimes' (USEF 2014). First pilot projects show that DSM, pending the form it is organized, reduces overall consumption on average with 5 to 15 % and peak consumption up to 30 % (compare: Faruqui et al. 2010, 6224; Darby and McKenna 2012, 762–767; Verbong et al. 2013, 120). The results differ widely between pilot projects, leading to calls that a decent efficiency program could contribute as much to the results as the demand response based on dynamic pricing (Alexander 2010; Darby and McKenna 2012).

In line with this conclusion, Hargreaves et al. argue that the idea of smart grids principally rest on the earlier mentioned technocratic as well as a neoliberal discursive assumption that feedback mechanisms will push rational consumers to adjust their consumption based on an individual cost benefit analyses. When pushed to its extreme such an assumption implies that consumers who do not react to price incentives are irrational and unwilling. This, of course, is not the case (Hargreaves et al. 2010, 6112, 2013; Verbong et al. 2013, 119; Royston 2014). Quite the contrary, Hargreaves et al. (2013) show that most adjusted behaviour is based on other mechanisms then price, many of which have to do with in-house power struggles and decisions on the different levels of comfortable living. Even in comparable households energy consumption can differ: some people deem a large aquarium to be a life's necessity while others put on an extra sweater when it freezes (2010, 6112).

In Foucault's terms we are witness to technologies that try to create energy consumers who are free to respond to price incentives. In the current electricity market prices are more or less fixed, although large consumers (industry, etc.) often pay reduced tariffs and consumers are sometimes able to enter day-night tariff schemes. With floating prices that differ over time and per region, the market behind smart grids is said to be able to respond more rapidly to both fluctuating generation and possible congestion within the grid. In other words, to secure the stability of the grid individual consumers are given more freedom to decide to consume or produce, to choose utility and service companies, to decide upon the sources of production, etc. What a Foucauldian inspired approach shows, however, is that consumers simultaneously, through the price incentives behind DSM, are "trained" to behave in the interest of the system as a whole (to move towards the norm). In other words, consumers are seen to be empowered by smart grids through an increase in information about themselves and the options to choose from, but simultaneously are not trusted to behave "responsible" and "rational". They are trained to behave correctly and the grid is secured against any irrationality through automated control of appliances and other solutions to keep the consumer "out". One can debate the ethics of such a system (Faruqui 2010), but one way or another '[i]n most versions of a distributed energy future, customers will effectively be enlisted as co-managers of the system, even if they are not conscious of it (Darby and McKenna 2012, 767).'

6 Securing Free Electricity Markets

The shift from load following to generation following is a perfect example of Foucault's conducting the conduct of consumers. As an organized freedom it requires security through constant surveillance (smart meters) and intervention (network switches) as well. Above, we have identified a number of 'problematized' issues, ranging from intermittency of RES to the security and privacy consequences of smart grids. All of these ultimately are imagined threats against the stability of the electricity grid, more in particular the 50 or 60 Hz frequency of the grid and anything that endangers the continuous balancing towards these frequencies. What smart grids do differently is that they target supply imbalances *by accepting them* and consequentially forcing through an imbalance on the demand side by punishing excess demand. In other words, the security of smart grids is based on the protection of the system by accepting and integrating new levels of volatility and uncertainty on an individual level. A level of volatility that will only increase as the introduction of DSM, following the entry of intermittent RES and the quest to decrease redundancy in the system (on all levels), will lead to less back-up capacity and a more volatile system with more uncertainty and an even greater demand for just in time-management.

The question then becomes who manages such a smartly organized power system? The grid and its smart components still need to be maintained, decisions still need to be made in emergency situations, and “externalities” still need to be incorporated. The last two indicate that smart grids still need a form of classic centralised control with regulation and a regulatory body to manage and visualize those instances when the markets do not deliver. The instantaneousness of electricity implies rather that it is the “market” that is responsible for a functioning daily routine of these new power systems. Actual control in a smart grid is consequentially outsourced to its ‘managers of unease’ (Bigo 2002): grid operators, software developers, automatic control systems, but also insurance and broker companies. From a Foucauldian perspective, these latter companies in particular will take a central position within the governing of smart grids through the sale of risk portfolios. On the one hand, these portfolios pool groups of consumers, prosumers and producers, and will represent them on the market. On the other hand, these are the companies that will offer different packages of “security” by offering end-consumers different price portfolios. Those who want to insure themselves against price hikes, black-outs or drops in prices (for prosumers) will have to pay an insurance premium. More importantly, in order to be allowed to participate in such schemes, these companies will set up the terms of conditions for end-users to adhere to. These companies will govern the grid by deciding on what they deem acceptable or unacceptable risks. With such profiles these companies actively influence the behaviour and actions of end-consumers as well as structure the materiality of the electricity grid and the overall way people live and organize their lives (Lobo-Guerrero 2012).

In strengthening a neo-liberal market discourse, the traditional discourse of security that is based on reserves and spare capacity is slowly replaced by a security discourse that is built around the logic of resilience (Lovins and Lovins 1982). The logic behind resilience presupposes a constant vulnerability of individuals to (external) shocks, which need to be countered by a constant process of adaptation on the level of the individual (O’Malley 2010; Reid 2012; Joseph 2013). This logic is increasingly questioned within the security literature. For example, Joseph remarks how, in the focus on individuals, resilience acts as a way to de-socialize risk by attributing the responsibility of risk decisions no longer on the level of the state but onto individuals (2013, 262). Similarly, Bourbeau highlights that resilience could slow down social change when people who are resilient against shocks also adapt to *intended* social changes (2013, 8–10). This reinforces the argument above that visualization and automation can lead to increased energy consumption patterns. What these critics of resilience argue is that resilience requires and pre-supposes a kind of fatality; it forces individuals to take advantage of a given newish-like situation, instead of trying to change it for the better on a social level as security does (Evans and Reid 2013, 86; Joseph 2013, 262). In respect to smart grids security initially meant that all people should always have access to electricity, whereas the resilient approach opens-up this position by arguing that the stability of the grid sometimes demands that people and appliances should be cut off. While following seemingly automatically from the discourses and technology itself, this is still a political choice with social consequences. Foremost of which, that decentralised energy production favours those with the capital and capacity to produce electricity. With a just-in-time logic, a reduction in redundancy and back-up capacity, and an increasing organizational complexity, such a system hides responsibility and accountability while shifting from an insecure towards a vulnerable electricity grid.

7 Decentralisation of Electricity

Local production, local markets and resilient self-healing two-way communicating grids all point toward a shift in the structure of the electricity grid from a centrally organized system towards a decentralised system. For some such a decentralised energy production is more resilient to accidents and attacks (Lovins and Lovins 1982; Sweet 2009), for others however this organizational discourse of decentralisation equals to an increase in democratisation (Greenpeace 2005; Kunze and Becker 2014). Greenpeace for example argues that

> Decentralising energy would also democratise energy, providing real opportunities for local political leadership on climate change, and curbing the influence of the centralized industry's powerful vested interests. By enabling local action and empowering individuals and communities as producers, decentralisation has the potential to bring about a massive cultural change in our attitude to and use of energy (2005, 5).

Democratising energy thus entails a twofold argument. First, that decentralised energy production brings "power to the people" by breaking the oligopoly of energy companies currently controlling the electricity markets. And, second, decentralisation is seen as a positive empowering development as it increases the range of options for people who become more actively involved in local communities.

It is unclear what the effects of a decentralised grid will be on society and democracy. While the 'democratic energy' movement so far mainly comprises of

NGO's and other small social movements—although increasingly small communities, cities, regions, and companies follow along—it cannot be denied that there is a clear link between the way energy and society are organized (Lakoff and Collier 2010; Mitchell 2013; Miller et al. 2015). There is hence little doubt that a decentralised energy system will affect current societies, just as it will affect international relations, which presently are heavily influenced by global energy practices and resulting capital flows. However as Winner already argued in 1980:

> Thus, some proponents of energy from renewable resources now believe they have at last discovered a set of intrinsically democratic, egalitarian, communitarian technologies. In my best estimation, however, the social consequences of building renewable energy systems will surely depend on the specific configurations of both hardware and the social institutions created to bring that energy to us. It may be that we will find ways to turn this silk purse into a sow's ear (1980, 135).

In this respect there are two remarks that can be made. First, while it is possible to see the current 'old' system as undemocratic there is a clear link between the current centralised manner in which energy is organized and how societies are organized as democracies (Miltchell 2013). Mitchell beautifully analyses how the centralisation of energy also helped gain those working the supply lines in this system the political influence, through strikes, to play an important role in pushing for further democracy (an influence that now shifts to hackers?). This insight leads him to conclude, in line with Winner above, that not 'forms of energy determine modes of politics, but that energy is a field of technical uncertainty rather than determinism, and that the building of solutions to future energy needs is also the building of new forms of collective life (2013, 238).'

In a sense, decentralised electricity production has only become a real possibility when ICT enabled DSM. This is transforming a sector that has been characterised by centralised oligopolies and non-adjustable demand that followed logically from the physical characteristics of the electricity grids. However, secondly, what is not changing as much is the organization of the grid itself, which will remain strongly hierarchical as both the electricity and ICT infrastructure have centralising tendencies. The grids themselves still need to be built and coordinated as not all production or storage is localized at all times. The organization of markets and their imminent price-setting requires the centralisation of supply and demand data while still being run by the centralisation logic of capital. Similarly, the ICT infrastructure needs construction, maintenance and application. Here again, while ICT has strong decentralising characteristics (open source coding, block chain verification) there are centralising tendencies as well. This can, for example, be witnessed in the binary and hierarchical way that program code is organized, as well as IT departments in companies or governments. In addition, IT and ICT equipment have inclusionary characteristics as software works better with more people using it. This implies that most successful programmes and ICT infrastructure are owned by a limited number of companies, in line with Google buying Nest—an inherent tendency comparable to the capital intensive monopolies behind old electricity grids. Also inherent in the gathering of data, from smart meters, is the urge to link different databases for new and more effective/efficient insights across sectors. Lastly, the stability of the grid will always require some centralisation. Even when code orange decisions become fully automated, they are still initially set and executed by someone.

8 In Reflection

The decentralisation of smart grids does not automatically equate with more democracy, more autonomy or power to all. In line with the argument above and Foucault's insights on power/knowledge, conduct of conduct and security apparatus, there is cause to question the current conduct of smart grids and shift the current technical-economic debate into a political debate that moves beyond privacy considerations alone. The power/knowledge nexus around smart grids enables two extreme subjectivities of consumers as active or passive. When meeting in the middle what we have are consumers that are in equal parts informed over, trained on, and excluded from active decision-making on their own consumption. Likewise, the four discourses of technological optimisation, neoliberal markets, decentralisation and resilience together form a self-reinforcing logic that is hard to question at all. Each on their own, however, they offer a point of discussion. Not opposition per se, but a realisation that smart grids are not purely a win-win option. In this sense, Foucault's theoretical insights do not prescribe or predict and they cannot be used as a blueprint for the construction of a smarter and more socially acceptable grid. Instead, what a Foucauldian perspective adds to the smart grid debate is an understanding that by offering freedoms to consumers, by creating a free market, there is need for an apparatus that secures these freedoms as well. With an infrastructure system that is deemed "too big to fail" it is this security apparatus that is currently debated *and* constructed next to the actual construction of an ICT infrastructure and the modernization of the power grid.

Points for Discussion

- This chapter addressed the 'activating of customers'. What are the differences between ways in which this can take place (visualisations, feedback, price, etc) and what do these say about power?
- Kester gives the following quotation: 'The perception of end-users as barriers to change is representative for a technocratic view on users and user behavior.' (Wissner 2011, 2515). Do you agree with this characterization? Why does it matter how we frame end-users in energy systems?
- Do other chapters in this volume contain material to reflect on Kester's observation that "A smart grid is about the delivery of power, but there is power in and behind a smart grid"?

References

Alexander, B.R.: Dynamic pricing? Not so fast! A residential consumer perspective. Electr. J. **23**, 39–49 (2010). doi:10.1016/j.tej.2010.05.014

Amoore, L.: The Politics of Possibility: Risk and Security Beyond Probability. Duke University Press, Durham (2013)

Balta-Ozkan, N., Davidson, R., Bicket, M., Whitmarsh, L.: Social barriers to the adoption of smart homes. Energy Policy **63**, 363–374 (2013). doi:10.1016/j.enpol.2013.08.043

Batel, S., Devine-Wright, P.: Towards a better understanding of people's responses to renewable energy technologies: insights from Social Representations Theory. Publ. Underst. Sci. 0963662513514165 (2014). doi:10.1177/0963662513514165

Battaglini, A., Lilliestam, J., Haas, A., Patt, A.: Development of SuperSmart Grids for a more efficient utilisation of electricity from renewable sources. J. Clean. Prod. **17**, 911–918 (2009). doi:10.1016/j.jclepro.2009.02.006

Bigo, D.: Security and immigration: toward a critique of the governmentality of unease. Altern. Glob. Local Polit. **27**, 63–92 (2002). doi:10.1177/03043754020270S105

Bourbeau, P.: Resiliencism: premises and promises in securitisation research. Resilience **1**, 3–17 (2013). doi:10.1080/21693293.2013.765738

Brown, I.: Britain's smart meter programme: a case study in privacy by design. Int. Rev. Law, Comput. Technol. **28**, 172–184 (2014). doi:10.1080/13600869.2013.801580

Cavoukian, A., Polonetsky, J., Wolf, C.: Smartprivacy for the smart grid: embedding privacy into the design of electricity conservation. Identity Inf. Soc. **3**, 275–294 (2010)

Clastres, C.: Smart grids: another step towards competition, energy security and climate change objectives. Energy Policy **39**, 5399–5408 (2011). doi:10.1016/j.enpol.2011.05.024

Collier, S.J.: Post-Soviet Social: Neoliberalism, Social Modernity, Biopolitics. Princeton University Press, Princeton (2011)

Cotton, M., Devine-Wright, P.: Making electricity networks "visible": industry actor representations of "publics" and public engagement in infrastructure planning. Publ. Underst. Sci. **21**, 17–35 (2012). doi:10.1177/0963662510362658

Cuijpers, C., Koops, B.J.: Smart metering and privacy in Europe: lessons from the Dutch case. In: European Data Protection: Coming of Age, pp. 269–293. Springer, Berlin (2013)

Darby, S.J.: Smart metering: what potential for householder engagement? Build. Res. Inf. **38**, 442–457 (2010). doi:10.1080/09613218.2010.492660

Darby, S.J., McKenna, E.: Social implications of residential demand response in cool temperate climates. Energy Policy 49. Special Section: Fuel poverty comes of age: commemorating 21 Years of research and policy, 759–769 (2012). doi:10.1016/j.enpol.2012.07.026

Dillon, M.: Biopolitics of security. In: Peter Burgess, J. (ed.) The Routledge Handbook of New Security Studies, pp. 61–71. Routledge, London and New York (2010)

Dillon, M., Reid, J.: Global liberal governance: biopolitics, security and war. Millennium J. Int. Stud. **30**, 41–66 (2001). doi:10.1177/03058298010300010501

Eising, J.W., van Onna, T., Alkemade, F.: Towards smart grids: Identifying the risks that arise from the integration of energy and transport supply chains. Appl. Energy **123**, 448–455 (2014). doi:10.1016/j.apenergy.2013.12.017

El-hawary, M.E.: The smart grid—state-of-the-art and future trends. Electr. Power Compon. Syst. **42**, 239–250 (2014). doi:10.1080/15325008.2013.868558

European Commission: EU-TEN Energy Invest. TREN/04/ADM/S07.38533/ETU/B2-CESI. Centro Elettrotecnico Sperimentale Italiano; Instituto de Investigación Tecnológica; Mercados Energeticos; RAMBØLL A/S (2005)

Evans, B., Reid, J.: Dangerously exposed: the life and death of the resilient subject. Resilience **1**, 83–98 (2013). doi:10.1080/21693293.2013.770703

Faruqui, A.: The ethics of dynamic pricing. Electr. J. **23**, 13–27 (2010). doi:10.1016/j.tej.2010.05.013

Faruqui, Ahmad, Harris, Dan, Hledik, Ryan: Unlocking the €53 billion savings from smart meters in the EU: how increasing the adoption of dynamic tariffs could make or break the EU's smart grid investment. Energy Policy **38**, 6222–6231 (2010). doi:10.1016/j.enpol.2010.06.010

Foucault, M.: Power/Knowledge: Selected Interviews and Other Writings, 1972–1977. In: Gordon, C. (ed.), 1st American edn. Pantheon Books, New York (1980)

Foucault, M.: The subject and power. Crit. Inquiry **8**, 777–795 (1982)

Foucault, M.: Security, Territory, Population: Lectures at the College de France 1977–1978. In: Senellart, M. (ed.), Translated by Graham Burchell. Palgrave Macmillan, New York (2007)

Foucault, M.: The Birth of Biopolitics: Lectures at the Collège de France 1978–79. In: Senellart, M. (ed.), Translated by Graham Burchell. Palgrave Macmillan, New York (2008)

Geelen, D., Reinders, A., Keyson, D.: Empowering the end-user in smart grids: recommendations for the design of products and services. Energy Policy **61**, 151–161 (2013). doi:10.1016/j.enpol.2013.05.107

Goulden, M., Bedwell, B., Rennick-Egglestone, S., Rodden, T., Spence, A.: Smart grids, smart users? The role of the user in demand side management. Energy Res. Soc. Sci. **2**, 21–29 (2014). doi:10.1016/j.erss.2014.04.008

Graham, S., Marvin, S.: Telecommunications and the City: Electronic Spaces, Urban Places. Routledge, London (1996)

Greenpeace: Decentralising Power: An Energy Revolution for the 21st Century. London (2005)

Hargreaves, T.: Putting Foucault to work on the environment: exploring pro-environmental behaviour change as a form of discipline. CSERGE working paper EDM (2010)

Hargreaves, T., Nye, M., Burgess, J.: Making energy visible: a qualitative field study of how householders interact with feedback from smart energy monitors. Energy Policy **38**, 6111–6119 (2010). doi:10.1016/j.enpol.2010.05.068

Hargreaves, T., Nye, M., Burgess, J.: Keeping energy visible? Exploring how householders interact with feedback from smart energy monitors in the longer term. Energy Policy **52**, 126–134 (2013). doi:10.1016/j.enpol.2012.03.027

IEA: Secure and Efficient Electricity Supply: During the Transition to Low Carbon Power Systems. OECD/International Energy Agency, Paris (2013)

IEEE.: Smart Grid Conceptual Framework Diagram—IEEE Smart Grid. Institute of Electrical and Electronics Engineers (2014). http://smartgrid.ieee.org/ieee-smart-grid/smart-grid-conceptual-model. Accessed 8 July 2014

Joseph, J.: Resilience in UK and French security strategy: an Anglo-Saxon Bias? Politics **33**, 253–264 (2013). doi:10.1111/1467-9256.12010

Klauser, F.: Through Foucault to a political geography of mediation in the information age. Geogr. Helv. **68**, 95–104 (2013). doi:10.5194/gh-68-95-2013

Klauser, F., Paasche, T., Söderström, O.: Michel Foucault and the smart city: power dynamics inherent in contemporary governing through code. Environ. Plann. D Soc. Space **32**, 869–885 (2014). doi:10.1068/d13041p

Kunze, C., Becker, S.: Energy Democracy in Europe: A Survey and Outlook. Rosa Luxemburg Stiftung (2014)

Lakoff, A., Collier, S.J.: Infrastructure and event: the political technology of preparedness. In: Braun, B., Whatmore, S.J. (eds.) Political Matter: Technoscience, Democracy, and Public Life, pp. 243–266. University of Minnesota Press, Minneapolis (2010)

Lobo-Guerrero, L.: Biopolitics of specialized risk: an analysis of kidnap and ransom insurance. Secur. Dialogue **38**, 315–334 (2007). doi:10.1177/0967010607081513

Lobo-Guerrero, L.: Insuring War: Sovereignty, Security and Risk. Routledge, London (2012)

Lovins, A.B., Hunter Lovins, L.: Brittle Power. Brick House Publishing Company (1982)

Marres, N.: The costs of public involvement: everyday devices of carbon accounting and the materialization of participation. Econ. Soc. **40**, 510–533 (2011). doi:10.1080/03085147.2011.602294

Miller, C.A., Richter, J., O'Leary, J.: Socio-energy systems design: a policy framework for energy transitions. Energy Res. Soc. Sci. **6**, 29–40 (2015). doi:10.1016/j.erss.2014.11.004

Miller, P., Rose, N.: Mobilizing the consumer assembling the subject of consumption. Theory Cult. Soc. **14**, 1–36 (1997). doi:10.1177/026327697014001001

Mitchell, T.: Carbon Democracy: Political Power in the Age of Oil. Paperback, Verso, London (2013)

Naus, J., Spaargaren, G., van Vliet, B.J.M., van der Horst, H.M.: Smart grids, information flows and emerging domestic energy practices. Energy Policy **68**, 436–446 (2014). doi:10.1016/j.enpol.2014.01.038

Mah, D.N., van der Vleuten, J.M., Ip, J.C., Hills, P.R.: Governing the transition of socio-technical systems: a case study of the development of smart grids in Korea. Energy Policy **45**, 133–141 (2012). doi:10.1016/j.enpol.2012.02.005

O'Malley, P.: Resilient subjects: uncertainty, warfare and liberalism. Econ. Soc. **39**, 488–509 (2010). doi:10.1080/03085147.2010.510681

Reid, J.: The disastrous and politically debased subject of resilience. Dev. Dialogue **58**, 67–79 (2012)

Römer, B., Reichhart, P., Kranz, J., Picot, A.: The role of smart metering and decentralized electricity storage for smart grids: the importance of positive externalities. Energy Policy **50**, 486–495 (2012). doi:10.1016/j.enpol.2012.07.047

Rouse, J.: 4 power/knowledge. Camb. Companion Foucault 95 (2005)

Royston, S.: Smart energy technologies in everyday life: smart Utopia? Technol. Anal. Strateg. Manag. **26**, 1242–1247 (2014). doi:10.1080/09537325.2014.975789

Rutherford, S.: Green governmentality: insights and opportunities in the study of nature's rule. Prog. Hum. Geogr. **31**, 291–307 (2007). doi:10.1177/0309132507077080

Schick, L., Ross Winthereik, B.: Innovating relations-or why smart grid is not too complex for the public. Sci. Technol. Stud. **26** (2013)

Shove, E.: Beyond the ABC: climate change policy and theories of social change. Environ. Plann. A **42**, 1273–1285 (2010). doi:10.1068/a42282

Shove, E., Walker, G.: Governing transitions in the sustainability of everyday life. Res. Policy **39**, 471–476 (2010). doi:10.1016/j.respol.2010.01.019

Spaargaren, G., Mol, A.P.J.: Greening global consumption: redefining politics and authority. Glob. Environ. Change **18**, 350–359 (2008). doi:10.1016/j.gloenvcha.2008.04.010

Strengers, Y.: Smart Energy Technologies in Everyday Life: Smart Utopia? Palgrave Macmillan, New York (2013)

Sweet, D.M.: The decentralized energy paradigm. In Luft, G., Korin, A. (eds.) Energy Security Challenges in the 21st Century: A Reference Handbook, pp. 308–317. ABC-CLIO, Santa Barbara (2009)

Sylwan, M.: The construction of paternity leave in Swedish television. In: Sjölander, A.E., Payne, J.G. (eds.) Tracking Discourses: Politics, Identity and Social Change, pp. 169–96. Nordic Academic Press, Lund (2011)

Thaler, R.H., Sunstein, C.R.: Nudge: Improving Decisions About health, Wealth, and Happiness. Yale University Press, New Haven & London (2008)

The European Parliament and the Council of the European Union: Directive 2006/32/EC of the European parliament and of the council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC (Text with EEA relevance). Off. J. Eur. Union (2006)

The European Parliament and the Council of the European Union: Directive 2009/72/EC of the european parliament and of the council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC (Text with EEA relevance). Off. J. Eur. Union (2009)

The U.S. Department of Energy: The Smart Grid: An Introduction. Washington, D.C. http://energy.gov/oe/downloads/smart-grid-introduction-0 (2014). Accessed 17 Sept 2014

USEF: An Introduction to the universal smart energy framework. The Universal Smart Energy Framework (2014)

Verbong, G.P.J., Beemsterboer, S., Sengers, F.: Smart grids or smart users? Involving users in developing a low carbon electricity economy. Energy Policy **52**, 117–125 (2013). doi:10.1016/j.enpol.2012.05.003

Walters, W., Haahr, J.H.: Governing Europe: Discourse, Governmentality and European Integration. Routledge, London and New York (2005)

Winner, L.: Do artifacts have politics? Daedalus **109**, 121–136 (1980). doi:10.2307/20024652

Part III

Implementing Smart Grids: What Have We Learned?

Emerging e-Practices, Information Flows and the Home: A Sociological Research Agenda on Smart Energy Systems

Bas J.M. Van Vliet, Joeri Naus, Robin Smale and Gert Spaargaren

Abstract This chapter examines the emergence and development of smart grids from a sociological perspective. In particular we draw on 'social practice theory' to understand the dynamics of domestic energy consumption and production in emerging smart energy configurations. There are two focal points in the analysis. First, we will concentrate on a specific type of social practices, so called 'e-practices'. This is a term that we coin to refer to all those practices in and around the home that involve the consumption, conservation, monitoring, generation and storage of energy. Second, we incorporate 'information flows' as a key element in our understanding of the emergence of new e-practices. Although the term "smart" has been defined in various ways, a common denominator is that the generation, handling and use of data, information and knowledge is part of what makes a system smart. After introducing both concepts, we outline a conceptual framework around e-practices and information flows that can guide social scientific research on smart energy systems. We also illustrate how this framework can be put to use empirically, based on data that have been gathered in the Netherlands. The chapter is concluded with a research agenda that outlines theoretical and methodological challenges for future smart grid research.

B.J.M. Van Vliet (✉) · J. Naus · R. Smale · G. Spaargaren
Environmental Policy Group, Wageningen University, Hollandseweg 1, 6706,
KN Wageningen, The Netherlands
e-mail: bas.vanvliet@wur.nl

J. Naus
e-mail: joeri.naus@wur.nl

R. Smale
e-mail: robin.smale@wur.nl

G. Spaargaren
e-mail: gert.spaargaren@wur.nl

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_14

1 Introduction

The remarkable and widespread diffusion of the adjective "smart" to energy technologies has led to confusion and debate among utility managers, academics and policy makers about technological development and behaviour change, about autonomy and privacy concerns, and about the objective of smartness (do systems, meters and devices become smart, or their users, managers or regulators?). This chapter aims to shed some light on smart energy systems from a sociological perspective. In doing so, it draws upon conceptual frameworks being developed in the social sciences and on ongoing empirical research in the Netherlands.

Our understanding of the uptake of "smart" systems is based on Social Practices Theory. On the one hand, this theory deviates from many engineering perspectives on smart grids in that it considers social and material worlds/systems as inextricably entwined. On the other hand, it also deviates from behavioural approaches in (social) psychology and economics that concentrate on the minds and/or (trans) actions of individuals. Instead, a social practice approach promotes an understanding of reality in which thoughts and actions are structured by the socio-material contexts in which they take place.

This chapter is built up as follows. In Sect. 2 we start with an elaboration of what Social Practice Theory has to offer for analysing the emergence and uptake of smart energy systems in and around the home. To this discussion we add insights of 'informational governance' to construct an analytical framework around emerging e-practices and information flows. Section 3 presents selected findings of ongoing research in this field to show how this conceptual framework can be set to work. To conclude, a research agenda on e-practices in smart grid configurations is presented in Sect. 4. The agenda reflects research in progress as well as research directions for the future.

2 Social Practice Theory and Smart Energy Systems

Since about a decade, Social Practice Theory (Giddens 1984; Schatzki 2002; Shove 2003; Spaargaren 2003) has become a prominent theoretical perspective in social scientific research of domestic energy consumption. It presents a valuable addition to our understanding of domestic consumption, an understanding that was so far dominated by social psychological theories of Attitudes and Behaviour (Fishbein and Ajzen 1975), Planned Behaviour (Organ et al. 2013), Normative Behaviour (Abrahamse and De Groot 2014) and Bounded Rationality (Simon 1955). Rather than focusing on individual attitudes, behaviour and choice as the main attributes of domestic consumption, Social Practice Theory directs attention to the shared, routinized and embedded nature of everyday consumption practices. Within this sociological view domestic routines and activities that involve energy use are pictured as much more complex than often suggested in the above mentioned literature or than often expected by policy makers and energy providers

(Gram-Hanssen 2010; Shove et al. 2012; Strengers 2012). In this section we will first elaborate on energy practices (or: e-practices), as a specific type of practices, and then touch upon some concepts that are relevant for analysing the dynamics of e-practices in and around the home.

2.1 Energy Practices

Social practices have been defined as "a routinized type of behaviour which consist of several elements, interconnected to one other: forms of bodily activities, forms of mental activities, things and their use, a background knowledge in the form of understanding, know-how, states of emotion and motivational knowledge" (Reckwitz 2002, p. 249). Practitioners draw upon their know-how, emotions, conjunctural (practice-specific) dispositions (Spaargaren and Oosterveer 2010) to perform mundane everyday activities. Besides, social practices produce and reproduce social rules and norms (Giddens 1984). For our analysis a specification of Reckwitz' definition of social practices is needed: connecting with "things and their use" should be understood as employing technology and information flows. People tap into information flows in their daily performances of practices, e.g. gardening is typically coordinated with weather forecasts, online shopping involves checking the bank account balance, while domestic energy management requires energy data from meters and displays. Social practices, including e-practices can thus be defined as routinized types of behaviour that result from conjunctural dispositions, and know-how of groups of individuals who draw upon specific objects, information flows, technologies and social rules and norms in order to (re) produce the practice.

With the help of Social Practice Theory it can be shown how every day behavioural routines of specified groups of energy-users emerge, stabilise, become reconfigured, and dissolve or fade away. Analysing the dynamics of social practices implies investigating the know-how of individuals that take part in a practice and the meanings they attribute to it, while taking into account the co-shaping roles of objects, technologies and infrastructures that are relevant for that practice. Individual norms, values and preferences are thus not considered in isolation, but as shaped in a context of practices that are shared with others and that co-produce new value-orientations of individuals. As such, a practice approach allows us to investigate in detail the dynamics of activities taking place in domestic and local settings, while not losing sight of the broader context of systems of energy provision (Spaargaren and van Vliet 2000; van Vliet 2012).

We propose to speak of "e-practices" when the routine behaviours refer to the production, distribution, storage, monitoring and use of domestic electricity in a domestic or decentralised setting. Studying the emergence of e-practices that comes along with the roll-out of smart energy systems in the Netherlands and Europe means that we are dealing with moving targets. We aim to investigate how this emergence takes shape. Will we indeed witness the emergence of an independent set of e-practices as a consequence of enrolling citizen-consumers into smart energy systems? Or rather, do we expect to see changes in various existing domestic practices that involve the use of energy? As this is also very much an empirical question, we see emerging e-practices, for the time being, both as the birth of new practices (i.e. the monitoring of domestic energy flows, the utilisation of new smart meters and smart appliances) and as adaptations of existing practices (i.e. adapting the timing of laundry practices to moments of abundant solar energy supply).

2.2 *Dynamics of the Home*

Studies of domestic (energy) practices should take account of the immediate context in which they take place: that of a home. The boundaries of the home, and the personal lives that it harbours, are blurry and flexible, but the dynamics of e-practices in the domestic sphere constitute unique theoretical and empirical challenges regarding intervention and transformation (May 2011). Here we discuss various aspects of the home that are relevant to understanding the emergence of e-practices.

First of all, from a social practice perspective the home is to be understood as a means of association between practices—e.g. doing the laundry, showering, cooking and eating, or communicating—that fulfil specific domestic tasks (Gregson et al. 2007; Shove et al. 2012). These practices are performed by human agents who communicate about and make use of technological objects, machines, energy and information flows that connect them to wider technological infrastructures delivering energy, water, data, etcetera (Cowan 1983; Otnes 1988). We consider households as "hybrids of objects and people, which are implied in the (routine) performance of a series of interconnected practices reproduced in the domestic arena with the help of energy as a key resource" (Naus et al. 2014). Figure 1 depicts a number of domestic energy practices (in the circles) that are of special relevance when considering smart energy systems.

Besides consisting of interconnected practices, each household has its own "socio-technical configuration" and "moral economy", which condition the

Fig. 1 Domestic energy practices (adapted from: Naus et al. 2014, p. 438)

performance of these practices. The socio-technical configuration points to the specific qualities of a household that emerge from several factors, most importantly the education level, age, gender, life phase and income level of its residents, as well as the technological infrastructures and devices present in the home (Gram-Hansen 2010). The concept of moral economy “recognises that different households, even if they are demographically and technically comparable, have different histories and social practices through which they have developed agreed norms and values, habits and routines which are normally unquestioned” (Hargreaves 2012). A moral economy is (implicitly) shared by the members of the household, naturalising and moralising a certain way of ‘doing things’ in the home. Hence, a moral economy ties together various e-practices on the basis of a ‘regime’ of norms, including norms regarding comfort, convenience, autonomy, control, privacy, sustainability.

Running a household also involves specific rhythms and sequences of events. Smart energy systems challenge existing rhythms of everyday life (Walker 2014). People organise their daily activities, balancing convenience and care, and spontaneity and stability, and end up creating “hotspots” (periods of mindful activity) and protected “coldspots” (when people relax) throughout the day and the week (Southerton 2003, 2006). As people go about their daily lives in and around the home, they continuously waver between routine and reflexive behaviour (Southerton 2012). Therefore, domestic energy consumption has always been more or less reflexively ‘monitored’ and ‘timed’. Yet, with the emergence of smart energy systems the monitoring and timing of use are given new precedence. Therefore concepts of hotspots and coldspots can be usefully applied to assess the temporal dynamics (flexibility in particular) of new and existing energy practices.

Finally, interventions in the home often involve a process of “habituation” in which householders learn to work with new technologies and, at the same time, shape the functions of these technologies durably. The roll-out of smart grid technology constitutes an intervention into established domestic practices, introducing new technologies, engagements, emotions, knowledge and know-how. Such interventions can spark a habituation process in which households alternately reflect on their routines (“cultivation”) and turn new conscious acts into new routines (“naturalisation”) (Wilk 2009). From an environmental perspective, a habituation process is successful, when households abandon old carbon-intensive practices and are durably enrolled in new, more sustainable energy practices that are endorsed by the smart grid.

3 Information Flows in Smart Grid Configurations

Thus far we addressed the enrolment of households in (smart) energy systems through their practices. This section zooms in on the role of information as a key flow next to energy flows in smart energy systems. It builds up to a conceptual framework that connects information flows to energy practices.

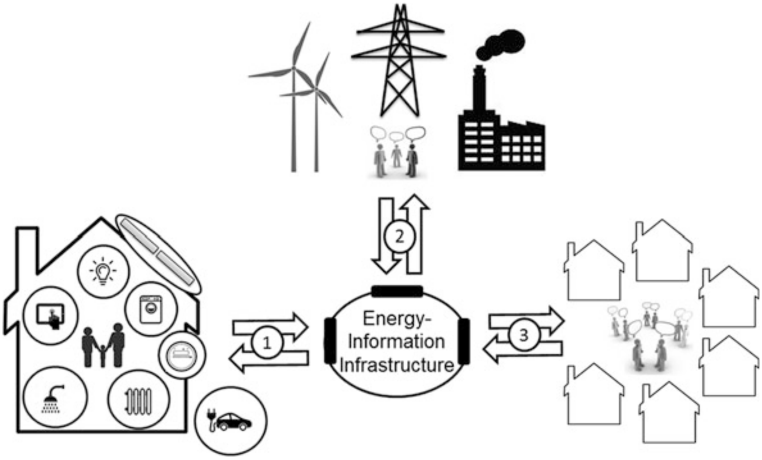


Fig. 2 Energy and information flows in the smart grid: *1* between household members, *2* between households and service providers, *3* between local and distant households (adapted from: Naus et al. 2014, p. 439)

Following Castells (1996) and scholars of informational governance (Mol 2008; Van den Burg 2006) we identify information flows as a key concept for analysing emerging e-practices in smart grids. The term ‘information flows’ is a sociological concept that refers to the exchange of diverse forms of data, information and knowledge (Mol 2008) between actors. Figure 2 discerns three flows of information that are relevant in a smart grid (Naus et al. 2014).

A first information flow is largely generated and used by residents within the context of the household. This is the information about energy use of devices, generated by generic meters or by specific meters that monitor energy demand in specific rooms or devices and at different times. The information is interpreted, shared and used in (daily) conversations among household members dealing with the timing and use of heating, cooling and lighting in domestic e-practices.

A second information flow pertains to the interactions between households and their energy service providers. Traditionally this is a one-way flow of information between utility companies and their clients, in the form of an annual energy bill that specifies energy consumption and payments. With the emergence of smart meters, and renewable electricity generation by consumers, these flows of information have become two-way, more frequent and more complex.

The third information flow relates to the interactions between households and other local and/or distant households. This is the case, for instance, when householders join a local energy cooperative, or when they become co-owner of a wind turbine or solar power plant. Also storage of locally generated electricity and the charging of electric vehicles may require information exchange between householders.

So, whereas the first category of information flows is largely contained within the private sphere of the home, the other two flows refer to information exchange with actors operating in the realm outside the household.

Our conceptual framework of a smart grid configuration now consists of three domains: (1) the household, as a set of interconnected (e-)practices; (2) energy service providers, including grid operators, electricity suppliers and regulators; and (3) groups of households, that can work together in various ways. In between these three categories there are energy and information flows that are operated and maintained in what is now called a smart infrastructure.

3.1 Information, Control and Privacy

All three information flows can have desirable as well as undesirable consequences. On the positive side, it has been suggested that smart meters put citizen-consumers in a better position to reduce the climate impact of their energy consumption (van Vliet 2002; Mol 2008; JRC 2011; Nyborg and Røpke 2011). Firstly, through real-time monitoring of domestic consumption, possibly down to the level of individual rooms and appliances, citizen-consumers acquire an increased understanding of possibilities to lower energy use. Secondly, based on the display of production information on smart meters (e.g. fluctuating tariffs, generation source, efficiency) citizen-consumers can make better informed choices between (sustainable) power options and energy suppliers (Darby 2010; Nye et al. 2008). So in this sense, smart meters enhance citizen-consumers' control over energy-related practices and facilitate the realisation of an 'ecological rationality' (cf. Mol et al. 2009).

However, on the negative side, the disclosure of detailed energy consumption data also implies a potentially undesirable opening-up of activities occurring inside the household; smart meters can reveal (intimate) rhythms of everyday life, like consumption behaviour, eating and sleeping routines and whereabouts (Cavoukian et al. 2010). In this way, daily practices and routines enacted in the private sphere 'behind the meter' are made 'visible' for energy suppliers as well as for other family members and neighbours (Van den Burg 2006; Mol 2008). These increased levels of transparency raise critical questions on the secondary use of information, and particularly on privacy (Cavoukian et al. 2010; Van Gerwen et al. 2010; JRC 2011). In this respect the large-scale 'roll out' of smart meters has been framed as introducing new forms of 'surveillance' (cf. Foucault 1995) and as the 'colonisation of the lifeworld' (cf. Habermas 1981) by energy systems, that citizen-consumers will tend to resist.

The deployment of smart grids and smart meters for environmental goals is therefore not self-evident; while new forms of information disclosure may facilitate the 'greening' of domestic energy consumption, this disclosure can also result in new forms of surveillance. As such, smart grids reconfigure existing power relations, and introduce new forms of control (Spaargaren 2003; Southerton et al. 2004).

4 Findings on Emerging e-Practices and Information Flows

Having presented the domains and concepts of sociological research on smart grid configurations, in this section we show how our framework can be utilised for empirical research. In doing this, we use findings from several studies that were conducted in the Netherlands. First, we present findings from a number of qualitative interviews with householders who participated in a one-year smart meter trial that was set up by a Dutch grid operator and a consumer organisation (Naus et al. 2014). Second, we present survey data on the involvement of householders in an energy cooperative (Naus et al. 2015; Sedee 2015).

The Netherlands provides a particularly interesting venue for research given the public and political debate on smart meter implementation as a result of concerns over consumer privacy (Hoenkamp et al. 2011), the widespread emergence of local energy cooperatives in recent years (Schwencke 2012), and the establishment of several ‘experimental gardens’ for the testing of smart grid technologies in real-life settings.

Rather than using all of the concepts that have been introduced in the previous section, we will limit the analysis to the interrelations between information flows and e-practices. In particular, it is shown how information flows interfere with and redefine social and power relations within the household, between households and energy providers, and between different households. This has consequences for whether and how e-practices emerge, develop and take shape.

4.1 Information Flows Within Households

During the first weeks after installation of energy displays, participants in the smart meter trial showed significant interest in energy monitoring. The new energy displays enabled them to make better informed decisions, since data on specific uses had become available. Interviewees reported a variety of changes in their consumption practices in terms of timing of use of appliances, the use of lights in the evening and replacement of inefficient appliances for more efficient ones. However, the practice of energy monitoring faded somewhat over time; after a few months it did not provide much new information and the monitoring practice became established as a more ‘modest’ routine in some cases, while in other cases it faded away all together. Yet, some of the measures that were taken during the time of more intensive monitoring lasted in the form of newly established routines. One of the interviewees developed a new routine of recharging electric devices:

> At this moment (2p.m.) all kinds of stuff is being charged. Until 3 pm, that’s when I have to switch them off (…) You become a bit of a slave of your solar panels, so I have to restrain myself a bit. But I like it so much! Because now it is clean, and it is my own energy!

This example clearly shows that new rules have been established regarding the timing of recharging practices. Afters some time it was no longer necessary to check the energy meter for information, but the timed recharging remained as part of everyday life. Furthermore, the example shows that both the technical configuration and the emotions that came along with that played an important role in the process of re-routinization. In fact, it seems reasonable to assume that the new practice became established only because it involved energy that was produced by the interviewee's own solar panels.

Furthermore, the trial showed that the emergence of new monitoring practices depends not only on the particular form in which energy data can be accessed (e.g. through a smart display or through a monthly email), but also on the creative selection and interpretation of the information by the householders. Some interviewees used smart meter information to engage family members in energy saving practices. In other cases monitoring rather introduced a new mode of surveillance. In the following example data on electricity demand are used by a parent to question an adolescent's behaviour:

> This [electricity peak] is, I think, my son, who returns home in the evening and turns on the microwave. (…) We have asked him: what are you doing here? But he is not interested and not very eager to think along.

Thus, rather than having an effect on energy use, energy monitoring (re)produced a power relation between parent and child. It shows that monitoring is not always geared towards energy saving, but can have multiple uses and sometimes unexpected outcomes (Naus et al. 2014).

4.2 Information Flows Between Households and Providers

In traditional relations between energy utilities and customers, information flows are generated from annual meter readings at home, resulting in an annual energy bill reflecting and justifying the kilowatt hours delivered and consumed. In settings where smart meters have been installed, or where renewable energy is generated on a local or household level, information flows can multiply and become multi-directional. Our interviews with householders and institutional actors revealed that smart meters and smart grids open up new opportunities for information exchange between households and energy service providers. Providers speak of business opportunities in providing their clients with energy saving or time-shifting advices based on more fine-grained monitoring data. In fact, one of the energy providers foresees a wholesale shift in the role of energy providers from energy supply to the provisioning of energy saving services:

> There is more money to be earned with giving pro-active advice and helping consumers in their efforts to save energy.

If the energy market indeed develops in this direction, then increasingly household practices would become connected to external advices and demands. While this may foster sustainable energy use and reduce household energy bills, there we also interviewed consumer organizations and householders who have serious reservations about the idea that energy companies can intervene in domestic practices. A representative of a consumer organisation argued that it would not be very sensible if energy providers would be able to steer cooking practices:

> People are certainly not going to wait until 11 (p.m.) to put a pizza in the oven or a ready-to-serve meal in the microwave.

While this statement may indicate a more general suspicion towards any kind of intervention by energy providers, it seems reasonable to state that some practices are more ‘open’ to external modes of steering than others. Indeed intervening in cooking practices seems more intrusive than intervening in, for instance, food conservation practices (e.g. optimising energy use by fridges or freezers).

Yet, control and surveillance could also work the other way around. A number of interviewees stressed the potential of smart energy technologies to disclose information about energy providers to consumers as a potential form of ‘counter-surveillance’. According to the consumer organisation, consumers could, for instance, benefit from smart meters that measure “*the spikes and dips and trends*” in power supply. Knowledge about energy distribution and supply could help consumers and consumer organisations to keep a check on energy providers and to “*unravel the world of energy*”. Again, this shows that smart energy technologies are not neutral technologies, not from a provider perspective, nor from a consumer perspective. Instead, they are engaged in a dynamic interplay of consumer-provider power relations, which has consequences for the ways in which domestic practices can be steered externally (Naus et al. 2014).

4.3 Information Sharing Between Householders

Over the last decade citizens are discovering and exploring new ways to cooperate at the local level, increasingly also in smart grid environments. By doing so they run into various social and technical issues where information plays an important role. Meanwhile, institutional players are worried about the new non-expert based forms of energy-governance and establish new intermediary institutional actors to establish functional linkages to the decentralised initiatives. In this process, the governance of information flows emerges as a central concern. Here we present data from two surveys, one (N = 75) among members of Duurzame Energie Haaren (DEH), an energy cooperative that is working closely together with the regional Grid Operator Enexis (Sedee 2015), and a survey (N = 212) among householders sampled from a list of subscribers of an online sustainability newsletter. A small group of respondents in this latter survey participated in a focus group session (held in April 2014) to discuss energy practices and privacy issues in the smart grid (Naus et al. 2015).

Together with the energy cooperative DEH, the regional grid operator Enexis has initiated a project entitled "Together Smart with Energy". The aim is to acquire a better understanding of the flexibility of people's energy use to reduce peaks in electricity demand. In this project, members are provided with a smart meter and an online platform that offers them real-time insight into their energy use. The online platform is also used to provide incentives and to experiment with the time-shifting of energy use.

In the survey, members of DEH were asked to express their opinions about interactions with other participants. In one of the questions the members were specifically asked whether they would participate in different forms of information and knowledge sharing. As can be seen from Fig. 3, answer categories ranged from "information sharing with friends at home" to "information sharing on an open internet platform".

Figure 3 reveals that there was clear preference for information sharing through scheduled theme-evenings that involve energy experts. This may indicate a couple of things. First, it suggests that expert knowledge is seen as a valuable contribution to interactions between members. Second, and perhaps more interestingly from a social perspective, this outcome also suggests that most people would rather exchange information and ideas in such a setting (an organised theme-evening) than on an internet platform which is more anonymous, or in small groups with relatives which is less anonymous. The social setting thus plays an important role when it comes to information sharing, and it is likely to affect the potential for learning about ways to save energy and to use it more sustainably (Sedee 2015).

The survey among subscribers of a sustainability newsletter revealed that information sharing is not a completely novel practice. Many of the respondents have shared information about energy use before, for instance by comparing energy consumption levels with family members (57 %) or with their neighbours (34 %). It may therefore not be surprising to find that new opportunities for information sharing were generally met with enthusiasm. For instance, the majority of

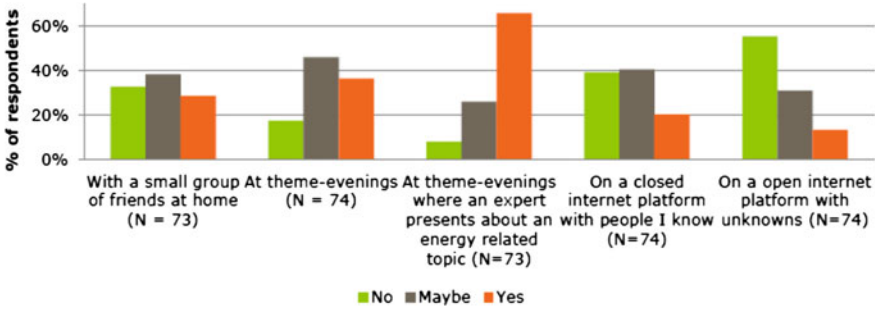


Fig. 3 Willingness to participate in information sharing practices amongst members of DEH (*Source* Sedee 2015, p. 77)

respondents would be willing to share their energy-performance through social media, with family and friends (60 %), while 69 % would be happy to enrol in a local energy-saving program. On the other hand, an energy saving competition (32 %) seemed less appealing, as this would imply competing with other households rather than helping each other out.

The survey also exposed that, for this group of respondents, information sharing between households serves as a welcome alternative to smart meter based energy advice by providers. Several respondents stated that they oppose the use of smart meter data "for commercial purposes", that they are afraid of being watched, or that they prefer interpreting smart meter data themselves. As opposed to expert advice, citizen-led initiatives were praised for the absence of a profit-orientation and for the possibility of "generating innovative ideas". The fact that such an initiative "originates from the users", rather than from an energy provider, is thought to take away the obligation to disclose information, as with the smart meter, and the possibility to use the information for commercial or administrative purposes.

The follow-up focus group sessions shed some more light on information sharing. Though participants initially expressed their enthusiasm about the unexplored opportunities of user-initiatives they also identified some undesirable consequences and limiting features. One of the focus group discussions clearly illustrated this:

Participant 1	"*The ideal situation, I think, is that everyone has a [carbon] footprint [that is visualised] near the front door of their house. Then everyone can see: this is how I did today*"
Researcher	"*Visible for others as well or…*"
Participant 2	"*Haha, A big cross! Misbehaving household, haha!*"
Participant 1	"*Haha, no, not on the outside! No, no, only when you enter your house. Only for yourself*"

This example shows that energy-related information is not only 'energy revealing' but also 'socially revealing'. The social judgement ("misbehaving") that may come along with information disclosure can form a limiting feature to information sharing practices So, similar to information flows between households and energy providers, care is also required regarding what energy-related information is shared among households (Naus et al. 2015).

5 Conclusion

The purpose of this chapter was to demonstrate the relevance of our conceptual framework through its application to recent and ongoing research on smart grids. A quantitative and qualitative assessment of smart meter trials and energy cooperatives in the Netherlands has allowed us to illustrate concepts of e-practices and information flows empirically. We would argue that the framework can sensitise smart grid researchers to study the ways in which new energy and information flows transform routines, rhythms, and practices of household members and their relationships with service providers and other households.

The findings presented here show that newly generated information flows in smart grid configurations may help householders to change their routines and practices. On the other hand, the same information flows can also redefine the relationships within households (as in the example of parents monitoring their children's activities through their energy use), between households (as in the case of information exchange for energy conservation), and between households and energy providers (e.g. when consumers obtain information about provider performances). Smart energy systems therefore do not produce new e-practices in linear ways. Instead, these systems co-evolve with existing domestic practices and norm sets in a dynamic socio-technical setting.

6 An Unfolding Research Agenda on Smart Energy Systems and e-Practices

Social scientific research on domestic practices and smart energy configurations is unfolding rapidly. The research presented in this chapter has given a taste of the themes, concepts and dynamics at play. In this section we spell out some of the work that is currently underway and some of the research challenges ahead.

First, there is a need for further theoretical development regarding the nature of energy practices and a need to connect practice-based research to other theories and concepts available in sociology. Theoretical development stretches from assessing the nature of energy practices (i.e. Strengers 2012), to whether and how they interconnect with other domestic practices (i.e. Powells et al. 2014) and with higher order concepts of 'energy citizens' (i.e. Goulden et al. 2014), 'lifestyles', and 'moral economies' (i.e. Hargreaves 2012) of the household and beyond. Equally promising is recent work on the intermediary processes, interfaces, and organisations (Grandclement et al. 2014) which organise consumer-utility interactions. Studies theorising the cultural, moral and political implications of smart energy configurations can further deepen our understanding of smart grid development. Such theoretical groundwork is required to sharpen the lenses through which social scientists can interpret and analyse the phenomena of co-evolving smart energy configurations and e-practices.

Second, there is a need for methodological innovation in practice-based research on energy systems. The methodological toolbox for traditional consumption studies (i.e. surveys, interviews) does not always match the scope and objectives of social practice research. Innovative methods are available and being developed for the study of domestic e-practices and the reconfiguration of energy infrastructures. With e-practices as the object of research, it does not suffice to focus on individuals and their intentions, attitudes or doings. Rather, we concentrate on the fate of practices, their histories, and the meanings, materials and know-how they contain. It means that practice research requires methodologies of participant observation including ‘shadowing’ (the researcher moves along with practitioners through their practices and poses questions in the meantime), and focus groups and stakeholder dialogues including methods of ‘co-creation’ (consumers and providers design new infrastructure services together). Furthermore, investigating the long term co-evolution of e-practices and energy infrastructures requires historical analysis (e.g. document studies or oral histories), longitudinal studies as well as future scenario and back-casting studies. Lastly, internationally comparative research will strengthen the understanding of practice dynamics in different socio-economic settings.

Third, there is a need to look across disciplinary boundaries and find more integrated ways of considering the potentials and pitfalls of smart grid development. This might be a significant challenge, as practice-based research is oftentimes positioned as fundamentally different from for instance psychological, economic and engineering perspectives. Yet, the development of a common ground is necessary to benefit from different insights and to better facilitate the role of households in this sustainability challenge. An integrated understanding of smart energy systems involves technology design, business model development, ethnographies of the home, behavioural modelling, policy assessments in equal measure. For example, only interdisciplinary work can produce a comprehensive understanding of how new domestic energy storage technologies shape—and are shaped by—behavioural patterns, power relations between consumers and utilities, and energy policy developments.

To conclude this research agenda, we would like to briefly mention two of our own research lines on smart energy systems. First, we are further examining the role of information flows in changing domestic e-practices. This is done, for instance, through a case study of ‘Smart grid Lochem’, a real-life smart grid pilot in the Netherlands. The pilot revolves around a local energy cooperative, LochemEnergie, which facilitates renewable energy generation and information exchange among its members. The study is inspired by the idea that the frequently articulated logic ‘to measure is to know is to save energy’ holds only limited explanatory power. Instead of being ‘out there’, waiting to be discovered, information may be better understood as something that is actively accomplished and put-to-work in and through practice. Accordingly, within this pilot setting we question when and how information is accomplished; when and how information is put-to-work; and how does the energy cooperative facilitate these processes?

Second, in the collaborative research project ‘Emerging e-practices in the smart grid’[1] we are following the emergence and evolution of several e-practices. The project consists of four research themes: (1) New forms of monitoring and feedback

---

[1] Project 2014–2018 coordinated by Environmental Policy Group Wageningen UR, partnering with: TU Eindhoven, MilieuCentraal, Enexis and Demand-Centre Lancaster.

for improving domestic energy performances; (2) Provider- and consumer-controlled timing of renewable energy provision, storage and use in the household; (3) The embedding of new e-practices in existing mobility routines, and (4) Consumer engagement in public-private collectives for the (co)production of renewable energy at community-level. The ultimate aim of this research project is to reduce uncertainty about consumer uptake of e-practices and consumer appreciation smart energy systems.

As is clear from this research agenda, energy provisioning and domestic consumption comprise very dynamic fields of research. This implies that there are many methodological and theoretical challenges on the road. Yet, we believe it is worth taking up these challenges as they will reveal how new, sustainable e-practices and smart energy configurations emerge. This is important knowledge that energy planners, utilities, consumer organisations and policy makers will need in working towards a sustainable energy future.

Points for Discussion

- The chapter shows that e-practices can change but seldom according to a prescribed manner. How can policy-makers and energy providers incorporate these uncertainties in their strategies and investments to implement smart grids successfully?
- To what extent is the development of smart grids structure-dependent or actor-dependent? The structural side involves: technological framework, legal framework, institutional framework, political framework, economic framework (markets); the actor side is about who implements, operates, (mis)uses, exploits the structure to reassure its implementation and continuity.

References

Abrahamse, W., De Groot, J.: The psychology of behaviour change: an overview of theoretical and practical contributions. In: Fudge, S., et al. (eds.) The Global Challenge of Encouraging Sustainable Living, pp. 3–17. Edward Elgar Publishing Limited, Cheltenham (2014)

Castells, M.: The Information Age: Economy, Society and Culture. Blackwell, Oxford (1996)

Cavoukian, A., Polonetsky, J., Wolf, C.: Smart Privacy for the Smart Grid: embedding privacy into the design of electricity conservation. Identity Inf. Soc. **3**, 275–294 (2010)

Cowan, R.S.: More Work for Mothers. Basic Books, New York (1983)

Darby, S.: Smart metering: what potential for householder engagement? Build. Res. Inf. **38**, 442–457 (2010)

Fishbein, M., Ajzen, I.: Belief, Attitude, Intention and Behaviour. Addision-Wesley Publishing Company Inc., Phillipines (1975)

Foucault, M.: Discipline & Punish: The Birth of the Prison. Vintage, New York (1995)

Giddens, A.: The Constitution of Society. California University Press (1984)

Goulden, M., Bedwell, B., Rennick-Egglestone, S., Rodden, T., Spence, A.: Smart grids, smart users? The role of the user in demand side management. Energy Res. Soc. Sci. **2**, 21–29 (2014)

Gram-Hanssen, K.: Standby consumption in households analyzed with a practice theory approach. J. Ind. Ecol. **14**, 150–165 (2010)

Grandclement, C., Karvonen, A., Guy, S.: Negotiating comfort in low energy housing: the politics of intermediation. Energy Policy **84**, 213–222 (2014)

Gregson, N., Metcalfe, A., Crewe, L.: Moving things along: the conduits and practices of divestment in consumption. Trans. Inst. Br. Geogr. **32**, 187–200 (2007)

Habermas, J.: A Theory of Communicative Action. Translated by Thomas McCarthy. Polity, Cambridge (1981)

Hargreaves, T.: Governing energy use at home: smart meters, governmentality and resistance. 3S working paper 2012-01. Norwich: Science, Society and Sustainability Research Group (2012)

Hoenkamp, R., Huitema, G.B., De Moor-Van Vugt, A.J.C.: The neglected consumer: the case of the smart meter rollout in the Netherlands. Renew. Energy Law Policy Rev. **2011**, 269–282 (2011)

JRC: Smart Grid Catalogue. Joint Research Centre of the European Commission, Institute for Energy and Transport (2011). Available at: http://ses.jrc.ec.europa.eu/smart-grid-catalogue. Accessed 12 May 2014

May, V. (ed.): Sociology of Personal Life. Palgrave Macmillan, Basingstoke (2011)

Mol, A.P.J.: Environmental Reform in the Information Age. The Contours of Informational Governance. Cambridge University Press, New York (2008)

Mol, A.P.J., Sonnenfeld, D.A., Spaargaren, G.: The Ecological Modernization Reader: Environmental Reform in Theory and Practice. Routledge, London (2009)

Naus, J., van Vliet, B.J.M., Hendriksen, A.: Households as change agents in a smart energy transition: on power, privacy and participation. Energy Res. Soc. Sci. (2015)

Naus, J., Spaargaren, G., van Vliet, B.J.M., Van der Horst, H.M.: Smart grids, information flows and emerging domestic energy practices. Energy Policy **68**, 436–446 (2014)

Nyborg, S., Røpke, I.: Energy impacts of the smart home—conflicting visions. Energy Efficiency First: the foundation of a low-carbon society, 1849–1860 (2011)

Nye, M., Burgess, J.: Promoting durable change in household waste and energy use behaviour. Report for the Department for Environment, Food & Rural Affairs, UK (2008)

Organ, S., Proverbs, D., Squires, G.: Motivations for energy efficiency refurbishment in owner-occupied housing. Struct. Surv. **31**(2), 101–120 (2013)

Otnes P.: The Sociology of Consumption. Humanities Press (1988)

Powells, G., Bulkeley, H., Bell, S., Judson, E.: Peak electricity demand and the flexibility of everyday life. Geoforum **55**, 43–52 (2014)

Reckwitz, A.: Toward a theory of social practices: a development in culturalist theorizing. Eur. J. Soc. Theor. **5**, 243–263 (2002)

Schatzki, T.R.: The Site of the Social: A Philosophical Account of the Constitution of Social Life and Change. Pennsylvania State Press (2002)

Schwencke, A.M.: De Energieke BottumUp in Lage Landen (in Dutch) (2012). Report. Available at: http://www.asisearch.nl/energieke-bottomup-in-lage-landen/

Sedee, C.: Lowering the peaks, Assessing the role of an energy cooperative on practices in the smart grid. MSc thesis. Wageningen University, Wageningen (2015)

Shove, E.: Converging conventions of comfort, cleanliness and convenience. J. Consum. Policy **26** (4), 395–418 (2003)

Shove, E., Pantzar, M., Watson, M.: The Dynamics of Social Practice: Everyday life and how it changes. Sage Publications Limited, London (2012)

Simon, H.: A behavioral model of rational choice. Q. J. Econ. **69**(1), 99–118 (1955)

Southerton, D.: 'Squeezing Time': allocating practices, coordinating networks and scheduling society. Time Soc. **12**(1), 5–25 (2003)

Southerton, D.: Analysing the temporal organization of daily life: social constraints, practices and their allocation. Sociology **40**, 435–454 (2006)

Southerton, D.: Habits, routines and temporalities of consumption: from individual behaviours to the reproduction of everyday practices. Time Soc. **22**(3), 335–355 (2012)

Southerton, D., Chappells, H., Van Vliet, B. (2004). Sustainable Consumption: The Implications of Changing Infrastructures of Provision. Edward Elgar Publishing

Spaargaren, G.: Sustainable consumption: a theoretical and environmental policy perspective. Soc. Nat. Resour. **16**, 687–701 (2003)

Spaargaren, G., Oosterveer, P.: Citizen-consumers as agents of change in globalizing modernity: the case of sustainable consumption. Sustainability **2**(7), 1887–1908 (2010)

Spaargaren, G., Van Vliet, B.: Lifestyles, consumption and the environment: the ecological modernisation of domestic consumption. Environ. Politics **9**(1), 50–76 (2000)

Strengers, Y.: Peak electricity demand and social practice theories: reframing the role of change agents in the energy sector. Energy Policy **44**, 226–234 (2012)

Van den Burg, S.: Governance through Information. Environmental monitoring from a citizen-consumer perspective. PhD thesis. Wageningen University (2006)

Van Gerwen, R., Koenis, F., Schrijner, M., Widdershoven, G.: Smart meters in The Netherlands: Revised financial analysis and Policy Advice. Report by KEMA Nederland B.V. for the Ministry of Economic Affairs, The Netherlands (2010)

Van Vliet, B.J.M.: Sustainable innovation in network-bound systems: implications for the consumption of water, waste water and electricity services. J. Environ. Plann. Policy Manage. **14**, 263–278 (2012)

Van Vliet, B.J.M.: Greening the Grid. The Ecological Modernisation of Network-bound systems. PhD thesis. Wageningen University (2002)

Walker, G.: The dynamics of energy demand: change, rhythm and synchronicity. Energy Res. Soc. Sci. **1**, 49–55 (2014)

Wilk, R.: The edge of agency: routines, habits, volition. In: Shove, E., Trentmann, F., Wilk, R. (eds.) Time, Consumption and Everyday Life: Practice, Materiality and Culture, pp. 143–153. Bloomsbury Academic, London (2009)

Smart Grid Pilot Projects and Implementation in the Field

Petra de Boer and Nynke Verhaegh

Abstract This chapter describes lessons learned from smart grid demonstration projects, which can provide common understanding for large-scale implementation of smart grids across borders. Although this paper is focusing on smart grid demonstration projects in The Netherlands, the analysis is executed from an international perspective. It turns out that each region requires tailor-made solutions depending on local conditions, such as local culture, electricity markets and regulations. Subsequently, this chapter focuses on smart grid projects in the Netherlands. The feasibility project PowerMatching City has demonstrated that it was possible to create smart grids with the associated market models using existing technologies. Small scale demonstration projects, such as PowerMatching City II and 'Smart Grid: Rendement voor Iedereen' (Smart Grid: Benefits for All) showed that smart grid services can balance the energy demand and supply in grids with renewable energy sources. Smart grids will only be successful when energy consumers embrace new technologies. Commercially attractive business models, timely standardization and secure IT solutions are required to realize a smart grid at affordable costs. Hence, a fair distribution of the benefits among all the stakeholders (consumers, energy providers and network operators) is essential. The next step is the large-scale demonstration of smart grids and standardization in order to lower the costs for implementation. Smart grid concepts should become available as a more common means of energy supply or even as value adding energy services. Hence, energy targets should be expressed in consumer benefits related with activities such as heating, cooking, washing and watching TV; and attractive incentives should seduce consumers to participate in services offering flexibility. New initiatives such as the Green Deal Smart Energy Cities and the Universal Smart Energy Framework have the objective to stimulate the application of repeatable solutions to increase the implementation of smart grids.

P. de Boer (✉) · N. Verhaegh
DNVGL, New Energy Technologies, Arnhem, The Netherlands
e-mail: Petra.deboer@dnvgl.com

N. Verhaegh
e-mail: Nynke.Verhaegh@dnvgl.com

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_15

1 Introduction

The rationale for the current energy transition is the need for sustainable energy amongst others, in order to reduce the environmental impact of energy use and that of e.g. electricity generation, and to be independent of fossil fuels. Therefore energy generation relies more and more on power supply from renewable energy sources, often at decentralised levels and with varying power output. Simultaneously the energy demand is changing: electricity use is predicted to increase due to the increasing demand by e-mobility and electric heating of buildings, while overall energy consumption per capita is predicted to decrease due to increased energy efficiency.[1]

The electricity infrastructure has to deal with this energy transition with the challenge to keep the system secure and reliable while introducing all these changes in power supply. This requires cost-intensive grid reinforcements to fulfil peak demand and peak load in extreme scenarios (for example no wind on winter days with high power demand), or—alternatively—smart grids which contribute to a reliable and affordable power supply by more intelligent balancing of energy generation and demand.

The growing interest in smart grids, as enabler for the energy transition, has resulted in the roll-out of a large number of demonstration projects worldwide. Most of these projects have been started to develop and demonstrate new smart grid technologies, tools, services and business models. The energy consumers involved were most often households, who can offer flexibility by shifting the demand of their appliances, like their heating system, their electric car, the washing machine or the dish washer. The challenge of most of these pilot projects is to bring all these technologies, services and stakeholders together in one system. Evaluations of smart grid demonstration projects both in Europe Fig. 1 and in the Netherlands[2] have shown that this is possible; however, there are still several steps to take. Important result of all these pilots is that they have shown that demand response strategies can reduce grid investments by 20–30 %.

This chapter focuses on the lessons learned from these demonstration projects, which can provide common understanding for large-scale implementation of smart grids.

The outline is as follows: Sect. 2 considers smart grid demonstration projects from an international perspective. Sects. 3 and 4 focus on The Netherlands and presents deep dives into one feasibility project (PowerMatching City) and two small scale demonstration projects (PowerMatching City II and Smart Grid: Rendement voor Iedereen). Chapter "What are Smart Grids? Epistemology, Interdisciplinarity and Getting Things Done" addresses next steps towards large-scale implementation of smart grids, and elucidates two Dutch initiatives which have the objective to

---

[1] Roadmap 2050, project by the European Climate Fund (a.o. DNV GL, 2013).

[2] Maatschappelijke kosten en baten van intelligente netten, CE Delft and KEMA, 2012.

scale up the implementation of smart grid solutions (Green Deal Smart Energy Cities and Universal Smart Energy Framework). The chapter ends with some conclusions.

2 Towards Regional Tailor-Made Solutions

The rationale for the energy transition is more or less the same in Europe, USA, and other "OECD" regions. The introduction of renewable energy sources such as wind turbines, photovoltaic (PV) panels and combined heat and power (CHP) systems can indeed be regarded as a global trend. The fast growing numbers of these distributed energy sources may cause local imbalance between generation and supply in the power grid, which may be solved by applying smart grid services.

Although this trend is global, the lessons learned from the smart grid demonstration projects have to be considered from a local perspective. Global inventories of smart grid demonstration projects have shown that due to the different specifications of the national grids and energy market or from national regulation, specific trends can be categorized per region. For example, the USA have higher (average) electricity consumption per customer and a lower reliability of the grid compared to Europe. Besides, the maximum load in the USA is much closer to the grid capacity than in Europe. Therefore, in the USA there is a stronger focus on peak load reduction technology and dynamic pricing tariff pilots, whilst in Europe more emphasis is placed on improving energy efficiency and reducing emissions by implementing more decentralised production.[3]

Likewise, local circumstances impact the imbalances in the electricity demand and generation. For example, the local climate determines the need for air conditioning systems, but the local culture determines whether remote control of this appliance is generally accepted, as it is in the USA but not in Australia out of fear for damage of the air conditioning systems.

Moreover, the nature of the local electricity market sets boundary conditions for the framework of smart grid services. For example, in unbundled electricity markets the value chain between generation and demand is 'interrupted'. Hence, it is not obvious which parties carry the responsibility for the implementation of smart grid services. There are several parties which will benefit from demand response actions reducing peak demand, but it is not evident which parties will pay for the investment costs of smart grid services. For example grid operators can defer or avoid grid reinforcements; balance responsible parties will need to purchase less electricity at peak demand; power generators can optimize their asset management since the load duration curve is less strained; and last but not least energy consumers will profit from reduced electricity bills due to behavioural changes. But what actions need to be taken to accomplish these scenarios?

---

[3] DNVGL knowledge.

Most likely third parties will enter the energy market which will manage to find positive business cases in offering local smart grid services to energy consumers, power generators, balance responsible parties and/or grid operators. The evolution of these new players will be defined by local culture and national regulation.

In summary, for large scale implementation of smart grids, each region requires tailor-made smart grid solutions depending on local conditions. That explains why it is useful to have all these demonstration pilots implemented at different locations. To understand the lessons learned it is necessary to perform a deep dive into the projects itself.

3 Lessons Learned from Dutch Demonstration Projects

The Netherlands are very active in the field of smart grids due to a suited infrastructure, a widespread knowledge on system integration and the on-going development of new services. Figure 1 shows the different stages within the development process for smart grids with examples from the Netherlands.

Initially there were several trial projects in the R&D phase. Subsequently there have been demonstration projects showing the feasibility of smart grids, e.g. PowerMatching City, see Sect. 3.1.

Next, small scale projects have been run in which smart grids services have been demonstrated, e.g. PowerMatching City II and Smart Grid: Rendement voor Iedereen, see Sects. 4.1 and 4.2.

The next step will be large scale demonstrations of smart grids. Smart grid concepts should become available as a more common means of energy supply or—even better—as value adding energy services. New infrastructures, technologies, service offerings and market models will be tested and demonstrated in a realistic environment instead of a confined project environment. Based upon outcomes from these large scale demonstration projects, future strategic choices will be made enabling large scale implementation of smart grids in the whole society.

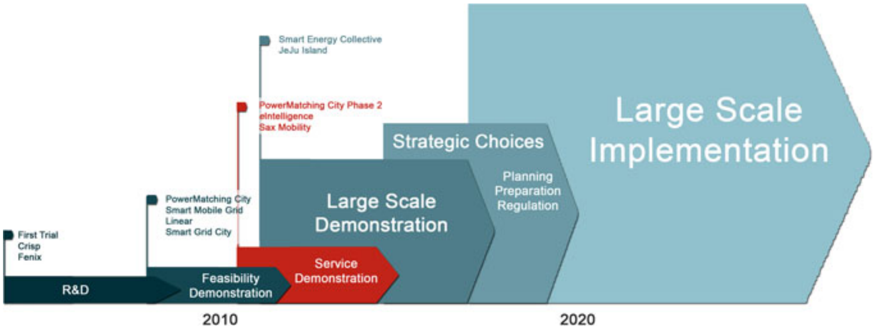


Fig. 1 Development process for smart grids with examples from the Netherlands (see Footnote 3)

3.1 Feasibility Projects: PowerMatching City

PowerMatching City is a demonstration project of a future power-infrastructure in the village of Hoogkerk, near Groningen, the Netherlands (Fig. 2). In 2010 the first phase of this project started including 25 interconnected households equipped with micro generation units, hybrid heat pumps, PV-solar panels, smart appliances and electric vehicles. Additional power was produced by a wind turbine. The aim of this first phase was to develop a technical feasible integrated solution for a smart grid under normal conditions. The connected households used the PowerMatcher control technology, a smart control mechanism to balance the local energy demand with the availability of renewable energy generation. For example, the washing machine was switched on when the sun was shining abundantly. In addition the PowerMatcher technology was used to optimize trading in a virtual power plant for balance responsible parties and to realize congestion management for grid operators. DNV GL/Gasunie collaborated in the first phase of PowerMatching City with knowledge institute TNO, software company ICT Automatisering and utility Essent. The role of DNV GL was in project management, in the integration of technologies and services and in contacts with energy consumers. The project was part of the EU FP6 funded INTEGRAL programme.

Fig. 2 PowerMatching City has been developed to integrate all elements of a future energy system in a total-concept smart grid. The main challenge was to develop an interactive, scalable solution integrating existing technologies and requiring active engagement of energy consumers (households) and partners (www.powermatchingcity.nl)

The first phase of PowerMatching City successfully demonstrated that it is possible to create smart grids with the associated market models using existing technologies. The system enabled energy consumers to exchange electricity freely while the level of comfort was maintained. This required efforts of all parties along the entire chain to fully exploit the opportunities inherent in smart grids. This PowerMatching City was pronounced one of the hundred most sustainable projects worldwide during the UN Conference for Sustainable Development in Brazil, Rio +20 (2012).

4 Small Scale Demonstration Projects

In 2014 more than 30 smart grid demonstration projects in the Netherlands have been evaluated.[4] These projects have shown the feasibility of smart grid products and services:

(a) It is possible to implement sustainable energy sources into the grid by smart balancing of demand and supply;
(b) It is possible to implement sustainable energy sources into the grid by combining power and gas grids;
(c) It is possible to implement sustainable energy sources into the grid by applying energy storage systems either in stationary systems such as batteries or in mobile systems such as electric vehicles;
(d) It is possible to implement energy management systems to provide insight in energy consumption to energy consumers;
(e) It is possible to develop demand response strategies to offer flexibility on the demand side.

In addition the feasibility demonstration projects yielded several lessons which should be considered in next steps towards successful implementation of smart grids on large scale.

1. The first lesson is that the awareness by energy consumers of their energy consumption was much lower than expected. It is of vital importance to invest in the involvement of energy consumers in smart grid concepts, since their commitment will ultimately determine the success of smart grids. Many demonstration projects have established that feedback on energy consumption increases awareness by energy consumers which often results in lower electricity demand.[5]
2. Another key factor influencing energy consumer behaviour is the type of demand response strategies used, for example dynamic price structures. So far

---

[4] Poster Intelligente Netten, Netbeheer Nederland, 2014.

[5] Home Energy Reports Evaluation, DNV GL, 2014.

the demonstration projects have not identified a most appropriate price structure. There is no 'one size fits all' due to a large variety in energy consumers.

3. Another lesson is that adequate system integration is an enabler of smart grids. Therefore there is a need for standardization which enables communication between cooperating technologies, which facilitates payment schedules and which effectuates cost reduction strategies. Clearly, IT technology plays a crucial role in the operation of smart grids, and of course there is still a huge concern among consumers regarding privacy and security of data handling.
4. Another important lesson is that successful deployment of smart grid services requires positive business cases. This is challenging, since in spite of the positive outcome of most societal cost-benefit analyses, there is no evident cost-benefit analysis available for existing key parties. Today grid operators play an important role to develop or implement new services in demonstration projects. However, to make the next step other parties may have to take that role or other collaboration structures are needed for developing services in conjunction. It is evident that close cooperation between all potential actors along the energy chain is required for the successful implementation of smart grids.

4.1 PowerMatching City II

In the project *PowerMatching City II*, which ended in the first half of 2015, DNV GL and its project partners focused on the added value of smart energy systems for the different stakeholders, using new market models. This requires an active guidance of stakeholders in the energy chain (energy provider, system operator and consumer), with different expertise and backgrounds which are not collaborating yet. In the project *Smart Grid: Rendement voor iedereen (Smart Grid: Benefits for All)* DNV GL and its project partners explored smart grid services from the energy consumer perspective.

In 2011 phase two of PowerMatching City started. In this phase DNV GL collaborated with the same consortium and Enexis as a distribution grid operator and several universities which study capacity management, industrial design and social behaviour (TU/e, TUD and Hanzehogeschool). Phase two extended the existing field trial to 40 households with thermal and electrical energy storage systems, home energy management systems and smart distribution transformers.

During the pilot, the consortium partners and the residents jointly established two energy services to facilitate flexibility: 'Smart cost savings'. Figure 1 enabled the residents to keep the costs of energy consumption and generation as low as possible, while 'Samen Aangenaam Duuzaam' energy service (Together Comfortably Sustainable). Figure 1 focussed on helping them to become a sustainable community. Both services use automated (heating) systems, semi-automated smart devices and flexibility provided by behavioural change based on additional insight. In order to realize these services, the back office wholesale and billing processes have been adapted. PowerMatcher, the smart software used in the study, played a key role by matching the energy supply and demand based on the information provided by the energy providers and the consumers. A striking result of PowerMatching City II was that the system was much more flexible than anticipated on the basis of previous studies and that the demand and supply were easier to balance than expected. In fact, the net gains from the consumer market could well reach €3.5 billion. These benefits are partly based on money saved by the grid operators by avoiding costs for investments and maintenance of grids. On the other hand, energy providers will be able to manage their customers' energy consumption more effectively so that they will be able to purchase energy for more competitive wholesale prices. Energy providers will also be able to use locally generated energy to match local supply and demand, which also saves costs.

At the end of PowerMatching City II the partners recommend the development of a new market model for the optimal distribution of the value of flexibility, in which the flexibility is put to the best possible use. Fair distribution of the benefits among all the stakeholders (end users—consumers, energy providers and network operators) is essential for a successful business case. This market model requires a single market party that can collect and redistribute the flexibility: the aggregator. Furthermore, standardisation can ensure the economic feasibility of large-scale implementation.

4.2 Smart Grid: Benefits for All

The project 'Smart Grid: Benefits for all' aimed to test and promote the possibilities of smart grids by developing and testing eight innovative services in two medium scale smart grids, localized in the cites Utrecht and Amersfoort, in The Netherlands. The project is executed by the Economic Board Utrecht together with LomboXnet, Icasus, Eemflow Energy, Stedin, Ecofys, DNV GL, CapGemini, Utrecht University, Hogeschool Utrecht and the University of Groningen. The project was sponsored by the Province of Utrecht, the City of Amersfoort and the City of Utrecht. The project is deployed in two existing neighbourhoods: Lombok in Utrecht and Nieuwland in Amersfoort.

In 200 houses the participants got a smart meter, smart plugs to measure the energy demand of specific appliances (dishwasher, washing machine, dryer, refrigerator and freezer) and equipment to measure the energy production of their solar panels. With apps and a web portal the participants got insight in their energy demand and production. Accordingly, the new services developed in this project were tested in these households. During the pilot, the impact of these services on the energy profile was measured, and in addition the customer acceptance and changes in their behaviour and experiences were evaluated with regular surveys.

Although both pilots make use of the same technology, the amount of interaction between the project organisers and the households differed: the pilot in Utrecht was based on a top-down approach where a local entrepreneur offered smart grid services in his neighbourhood; whereas in Amersfoort a bottom-up approach was established, in which new service concepts were developed in close cooperation with the energy consumers.

This active role of the participants in Amersfoort was realized by uniting them in a community of residents which frequently met to share information and to discuss results. About a dozen of residents were appointed as ambassadors of the smart grid project. These ambassadors fulfilled different roles, for example some of them were technical experts who tested new products as forerunners. Others were responsible for the communication within the pilot project. By using this bottom-up approach the participants in Amersfoort were strongly connected to the project. This resulted in a high energy saving of 15 %. Also the participation rate in demand response services was higher than in the Utrecht pilot. Thus, one of the outcomes of this project is that this bottom-up approach helps to get people connected to the project and its services. People share information and actively come up with new ideas and concepts. This helps to raise awareness in a neighbourhood and the increase the impact of smart grid services.

The pilot in Utrecht was characterized by a unique involvement of LomboXnet, a local optic fibre network entrepreneur, offering smart grid services like smart charging and vehicle to grid applications of electric vehicles to the neighbourhood. This pilot showed that one energetic entrepreneur can successfully bring new services to the market. One really needs these kinds of parties to develop this new market and to make to next steps after the demonstration phase.

The following statements summarize the major insights and results of the 'Smart Grid: Benefits for all' pilot[6]:

- It was possible to reach 15 % energy savings by giving insight to end users combined with a strong collective approach of all households;
- It was possible to increase the self-consumption of solar energy with 10 % by giving price incentives;
- It was possible to apply smart charging of electric vehicles using the solar energy produced locally;
- It was possible to realize a strong commitment of consumers by establishing a co-creation process with them;
- The most important driver for consumers to participate was the use of their own solar energy. This was more important than cost savings;
- The feasibility of a unique Vehicle2Grid charging system was successfully demonstrated;
- It turned out that demand response of domestic appliances like washing machines did not give enough flexibility for an attractive business case. However the pilot showed that with some simple price incentives the energy demand can already shift with 10 % just based on changes in behaviour.

---

[6] www.smartgridrendement.nl.

5 Towards Large-Scale Implementation

The next step will be large scale demonstrations of smart grids. Smart grid concepts should become available as a more common means of energy supply or—even better—as value adding energy services. Now it is time to test and demonstrate new infrastructures, technologies, service offerings and market models in a realistic environment instead of in a well-defined, confined project environment. Strategic choices will have to be made to enable large scale implementation of smart grids in the whole society.

The translation from small scale demonstration projects into 'business as usual' is not straightforward. First of all the need for smart grid services is not very strong yet, as long as the introduction of renewable energy sources is not causing problems in the energy system. However, this need will grow when more renewables get installed.

Secondly, smart grids services and technologies should become a commodity for ordinary people, for whom energy is not a real topic of interest, but rather a by-product of activities such as cooking, washing, watching TV, etc. For a successful implementation of smart grid services, it is important to translate energy targets in customer benefits related with these activities. New tools, e.g. apps that help people to understand their energy consumption facilitate this step.

If the public knowledge on their energy consumption is developed, the question arises whether energy consumers are willing to 'control' their demand. Dynamic pricing is a promising incentive, and indeed demand response by automatic control of washing machines seems to be at an early stage of market readiness. However, demand response by smart charging of electric vehicles is still input for public debate.

If energy consumers are willing to offer flexibility in demand (against beneficial counteractions), they probably prefer to outsource managing this flexibility to third parties, so called aggregators. Since they will often represent a number of consumers, they create a significant resource of energy demand and supply on the energy market. Today existing players are experimenting with the interpretation of this third parties-role. However, it is not evident whether they are the most suitable parties to develop such new business models. It is more likely that in, due time, new players will enter the energy market as an intermediary between energy consumers on the one hand and grid operators and energy suppliers on the other hand.

Based on this analysis it is clear that we are not yet ready for a large scale implementation of smart grids after these demonstration projects. Therefore new initiatives are needed to bridge the gap between the demonstration projects and the large scale implementation. These initiatives should answer questions such as:

- How should the industry control and use (distributed) energy?
- What should regulatory frameworks look like?
- What are the winning business models?
- What are the characteristics of a future-proof energy infrastructure?

In the next section two initiatives are presented which have the objective to scale up the implementation of smart grids: The Green Deal Smart Energy Cities (Sect. 5.1) and The Universal Smart Energy Framework (Sect. 5.2).

5.1 Green Deal Smart Energy Cities

In the near future there will be a shift in power from the national level to city level. That is because there is a strong tendency towards urbanization (in 2008 there were 3.5 billion people living in urban areas whereas in 2050 there will be 7 billion citizens, which is 70 % of total world population at that time[7]). This urbanization will have a strong impact on the energy transition: on the one hand it allows for efficient use of energy infrastructure and facilities; on the other hand it requires more effort to guarantee the 'liveability' and sustainability of the urban areas, for example by reduction of greenhouse gas emissions.

Smart (Green) Cities are facing several relevant trends related to energy and climate change in Fig. 1.

- The rise of self-supporting communities;
- The impact of climate change and resilience;
- Converging infrastructures (gas, electricity, heat and cold);
- New parties applying new business models and opening new market;
- Increasing role of IT leading to smarter grids;
- Big data management and cyber security threats.

These trends could be guided by initiatives such as the Green Deal Smart Energy Cities. Green Deals are agreements between companies, institutions and the Dutch government to accelerate the development towards a sustainable future in parallel with economic growth. One of the Green Deals handles the implementation of Smart Grid services. The Green Deal Smart Energy Cities' aim is that owners and users of 100,000 buildings in The Netherlands will apply smart energy concepts by the end of 2019. Thus, this Green Deal will contribute to local energy savings and to local sustainable energy supply in the built environment with electric mobility features, emphasizing the active involvement of energy consumers. The Green Deal Smart Energy Cities has been signed by the Ministry of Economic Affairs, the municipalities of Amsterdam, Arnhem, Eindhoven, Enschede and Groningen, the Dutch branch organization of grid operators Netbeheer Nederland and five Dutch Innovation Boards, both in the Energy Sector and in the Creative Industry.

Within the context of Green Deal Smart Energy Cities a kind of market place will be developed where supply and demand of (new) knowledge and innovation experiences will meet. A technical platform will be available to publish and store relevant data enabling companies to develop new services for energy consumers.

---

[7] www.UN.org.

Due to its significant size the Green Deal Smart Energy Cities is considered as a large-scale demonstration project. The economy of scale is aimed to attract attention of small and medium sized enterprises, which may offer an interesting potential for flexible demand in a wide range of buildings, which differs from focusing on households only. In this Green Deal innovative products and services are developed for all energy flows: electricity, heat, cold and (natural) gas.

5.2 Universal Smart Energy Framework

The Universal Smart Energy Framework (USEF) is an industry initiative driven by Alliander, ABB, DNV GL, IBM, ICT Automatisering, RWE-Essent and Stedin. The cooperation started in 2013 resulting in the establishment of a foundation in September 2014. This organisation is developing an open framework consisting of a set of rules, role descriptions, implementation guidelines and a market control mechanism for decentralized energy markets, in order to accelerate the large scale implementation of smart grids.[8]

Assuming that the 'classic' grid will not change fundamentally, USEF aims to transform the grid to be part of a modern and integrated energy system. This transformation impacts all parties involved, such as grid operators, balance responsible parties and retailers, but also new players like prosumers (i.e. energy consumers who produce energy for their own use and to sell to the grid), energy service companies and aggregators. Since the new players are confronted with the limitations of the current power grid, multi-disciplinary solutions have to be developed. Therefore USEF provides guidance via this open framework, taking into account the different perspectives. The open framework is an integrated market-based model, implying freedom of connection, transaction and dispatch, a level playing field and a warranty that costs are borne by those parties that are best equipped to do so.

All USEF-partners are developing commercially viable smart energy products and services allowing for large scale deployment. Since standardization is a pre-requisite to achieve interoperability, members of the USEF project team are actively participating in standardization committees. Moreover, USEF contains a Privacy and Security Guideline that addresses the privacy and security aspects associated with smart energy systems. It is designed to be compliant with the European Data Protection Regulation.

Ultimately, it is the goal of USEF to establish a fully functional smart energy system that is fit for a sustainable, reliable and affordable energy supply of the 21st century, by creating commercial conditions for large scale implementation.

---

[8] www.usef.info.

6 Conclusions

This chapter described lessons learned from smart grid demonstration projects, which can provide common understanding for large-scale implementation of smart grids.

First smart grid demonstration projects were put in an international perspective. Although the rational for the energy transition is global, each region requires tailor-made smart grid solutions depending on local conditions. The local culture, for example, determines the flexibility-in-demand potential; the local electricity markets and regulations determine the potential of new business models and new parties.

Subsequently, this chapter focused on smart grid projects in the Netherlands, which have a good infrastructure for smart grid services and a strong position in the field of system integration and development of new services. Smart Grid feasibility projects (such as PowerMatching City) demonstrated that it was possible to create smart grids with the associated market models using existing technologies. The system enabled energy consumers to exchange electricity freely while maintaining their level of comfort.

Small Scale demonstration projects (such as PowerMatching City II and 'Smart Grid: Benefits for all) showed that sustainable energy sources can be implemented into the grid by smart balancing of demand and supply, by combining power and gas grids and by applying energy storage systems. In addition these demonstration projects showed that direct involvement of energy consumers is a prerequisite for the success of smart grids. Insight into their energy consumption could be provided by energy management systems, thus improving the awareness by energy consumers. The bottom-up approach applied in Amersfoort within the 'Smart Grid: Benefits for all' pilot is a good example of successful consumer participation via co-creation.

The Small Scale demonstration projects also showed that demand response strategies could successfully contribute to offer flexibility on the demand side. Consequently, adequate system integration is an enabler of smart grids, requiring standardization to enable communication between cooperating technologies and secure ICT technology.

At the end of PowerMatching City II it has been recommended to develop new market models for the optimal deployment of flexibility. In order to obtain positive business cases it is essential to guarantee fair distribution of the benefits among all the stakeholders (end users—consumers, energy providers and network operators). This market model requires an emerging market party that can collect and redistribute the flexibility: the aggregator. New regulation and standardisation should ensure the economic feasibility of large-scale implementation.

The next step in the development process for smart grids is the large scale demonstration of smart grids. However, the translation from demonstration projects into 'business as usual' is not straightforward. That is because nowadays there is not yet an urgent need for smart grids, since the introduction of renewable energy sources is not yet causing grid problems. Secondly, energy targets should be expressed in consumer benefits related to activities such as heating, cooking, washing, watching TV and socializing (social media) in order to involve consumers. Thirdly, the deployment of flexibility requires the development of attractive incentives to seduce consumers to join in with new services provided by emerging third parties.

New initiatives such as the Green Deal Smart Energy Cities and the Universal Smart Energy Framework have the objective to scale up the implementation of smart grid solutions. They will explore answers to the following questions:

- How should the industry control and use (distributed) energy?
- What should regulatory frameworks look like?
- What are the winning business models?
- What are the characteristics of a future proof energy infrastructure?

It is time to test and demonstrate smart grid concepts in a real-life environment instead of in a well-defined, confined project environment. The outcomes will facilitate future strategic choices for implementation of smart grids in the whole society.

Points for Discussion

- Is the development of smart grids linear as the authors indicate? Which other terms could be used and what would be the effect?
- How does the roadmap in this chapter compare to that of others in the volume?
- The chapter describes the pros and cons of top-down and bottom-up approaches to achieve energy saving and optimal use of renewables. What are the societal consequences of both approaches in urban and rural settings you are familiar with?
- How do political, (multi) cultural and economic factors play a role in creating local projects? How will successful local projects affect (local) politics and societal stability?

Energy Efficiency in a Mobile World

Mikkel Baun Kjærgaard, Zheng Ma, Emil Holmegaard and Bo Nørregaard Jørgensen

Abstract The Danish path to a sustainable energy system focuses on increasing energy efficiency and flexible consumption via smart grid technologies. Information and communication technology is fundamental for achieving these goals by enabling among others new methods and systems for data collection and decision support. This book chapter covers new data collection options exemplified in the concrete case of a living lab for smart grid technologies. Furthermore, the chapter covers the use of visualisation to design decision support for such collected data. We formulate energy management based on energy data as a visualisation problem in the nested model for information visualisation. We prototype a visualisation tool chain to produce a rich set of visualisations based on energy data from five commercial and industrial buildings. Finally, we present qualitative study results for the value of visualisations as an analytical tool. Building on the results we identify important information needs for users of data analysis tools.

1 Introduction

The Danish path to a more sustainable energy system depends on new methods and technologies for increasing the energy efficiency and flexibility of consumption to handle the variable production from renewable energy sources. The Smart Grid Strategy published by The Danish Ministry of Climate and Energy from 2013

M.B. Kjærgaard (✉) · Z. Ma · E. Holmegaard · B.N. Jørgensen
SDU Center for Energy Informatics, University of Southern Denmark, Odense, Denmark
e-mail: mbkj@mmmi.sdu.dk

Z. Ma
e-mail: zma@mmmi.sdu.dk

E. Holmegaard
e-mail: em@mmmi.sdu.dk

B.N. Jørgensen
e-mail: bnj@mmmi.sdu.dk

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_16

(KEB 2013) details these needs and requested efforts whereby Denmark plans to have a 100 % renewable energy system in 2050. Denmark was one of the first nations to focus on a diversified energy mix, promoting renewables and energy efficiency. Consequently, in 2009 the Danish system already exhibited 18.5 % of intermittent renewable generation (mostly wind power) (Brandstatt et al. 2012). Denmark has a tradition of consumer involvement via municipal and consumer-owned network operators. With its history of bottom-up approaches, the targeted smart grid concept aims to decentralize responsibilities in the system and to equally incorporate demand side and generation resources (Brandstatt et al. 2012). Denmarks smart grid efforts focus on the integration of renewable energy sources, expansion of transmission and distribution networks, active customer participation, advances in information and communication technologies, markets and pioneering concepts of system control and operation in the Danish power system (Zhao et al. 2009). To realize the goal in 2050 the Danish strategies outline a focus on energy efficiency to decrease the total loads and flexibility through out the energy system.

Information and communication technology is a fundamental technology for these developments by enabling new methods and systems for data collection and decision support. Data collection is enabled among others by developments in pervasive and mobile computing providing new modalities and concepts for gathering sensor information about energy consumption and occupant behavior. For instance, energy consumption for individual equipment (Weiss et al. 2012) or temporal-spatial data about humans (Ruiz et al. 2014). For the development of new data processing methods and decision support options it is important to experiment with new options for data collection. One approach is the living lab approach collecting data in situ about buildings, occupant and devices.

Decision support can build on new methods for data mining of collected data or data visualisation to enable data analytics and feedback tools. Buildings account for approximately 40 % of the total energy consumption in Denmark (DEA 2015) and is therefore very important to consider in these efforts. To increase the energy efficiency and decrease consumption of buildings it is important to improve decision support tools with analytical capabilities. In this chapter we focus on electricity consumption which represents often more than fifty percent of the energy consumption in commercial and industry buildings. Surveys of existing energy information systems for buildings report that the systems are limited in their visualisation capabilities and focus on details rather than creating summarizing analytical visualisations of the data (Granderson et al. 2009). Recent studies also report that more advanced data processing tools are underutilized by building energy managers (Granderson et al. 2011). Furthermore, recent commercial efforts to introduce visualisation into commercial tools have so far not been evaluated in terms of their value to domain experts by the research community. The research community has for this domain so far mainly considered visualisation in terms of feedback displays in residential settings (Costanza et al. 2012; Froehlich et al. 2010), detached visualisations of processed data (Jung et al. 2013) or as cases in a design process (Goodwin et al. 2013). Therefore, studies of visualisation on sensing data for commercial and industry buildings are lacking. Both to understand the value of visualisations and the information needs of domain experts not matched by existing pervasive sensing systems.

This chapter provides the following two contributions:

- Present a living lab setting focusing on the collection of rich energy data sets covering renewable energy sources, commercial and industrial buildings and their occupants.
- We formulate energy management based on energy data as a visualisation problem in the nested model for information visualisation. We prototype a visualisation tool chain to produce a rich set of visualisations based on energy data from five commercial and industrial buildings. Finally, we present qualitative study results for the value of visualisations as an analytical tool. Building on the results we identify important information needs for users of data analysis tools.

2 Data Collection in a Smart Grid Living Lab

To stimulate data collection efforts for energy data one approach build on the construction of a living lab. The Green Tech Center Micro Grid Living Lab focuses on the collection of rich energy data sets covering renewable energy sources, commercial and industrial buildings and their occupants.

The Green Tech Center Micro Grid Living Lab is located in Vejle, Denmark, comprising three main buildings, a geothermal platform, a storage platform, a wind turbine and a solar platform with solar panels. The 3-storey building includes a 3500 m^2 area with a commercial Living Lab and various demonstration spaces equipped with different smart energy solutions. In addition an energy guild of nearby companies have been formed. The guild has been established with the goal to foster improvements in energy efficiency in commercial and industry buildings. Together with the guild members we installed a digital metering infrastructure to collect a rich data set of electricity consumption and environmental data. The denseness of submetering differ over the companies from whole building consumption of electricity up to 109 submetered points per building. The temporal granularity of the measurements is one measurement per minute and our repository contains readings for more than a year. The companies can access their data using a web portal. Two energy advisors from a local utility company and a private energy consultancy company, respectively, are associated with the energy guild to assist the companies with their energy efficiency efforts. The energy data from the living lab is also available for other partners via http://data.greentechcenter.dk.

3 Information Visualisation for Sensing Data

Information visualisation hold the potential to create new means for extracting knowledge from sensor data. Today model-based and machine-learning (Rollins and Banerjee 2014; Jung et al. 2013; Hasenfratz et al. 2014) driven approaches are often used in sensing data processing tools. In comparison, information visualisation applies to contexts where domain tasks can only be fuzzy defined (Sedlmair et al. 2012) which makes it hard to apply algorithmic tools. For the study of information visualisation in this context we follow the theoretical model for visualisation research proposed by Munzner (2009). They propose a nested model for visualisation research that nest the four levels of: domain characterisation, data types and operations, and visual encoding and algorithms. Domain characterisation is the description of the domain tasks of users in the target domain. The next level is a mapping of these into operations and data types. The third level is the design of visual encodings and interactions to support those operations, and the innermost fourth level is the algorithms to carry out that design automatically and efficiently (Munzner 2009). In this work we focus on the two outermost levels and the visual encoding which is the most relevant parts for establishing early visualisations for domain experts.

We propose for the visualisation-driven approach to follow a problem-driven visualisation research approach (Sedlmair et al. 2012) which apply relevant methods to inform and validate visualisation work. This includes for our case study literature review, semi-structured interviews, data-driving evaluation of visualisations and observation. The selection of methods provide relevant information to all the considered levels of the nested model (Munzner 2009). Literature review focuses on existing case studies and guidelines for energy management. Semi-structured interviews for understanding domain problems and tasks using open ended questions. Observation for understanding the particular building and places that the building energy managers work in and their options for energy management. Data-driven evaluation of visualisations to collect domain expert’s opinion on data types, operations and visual encodings. For a comprehensive discussion of the different types of visualisation methodology we refer the reader to Sedlmair et al. (2012).

4 Case Study on Energy Management

As a case study we consider the improvement of energy management tools with energy data for commercial and industry buildings. To involve domain experts we ran the case with members of an energy guild placed in the Danish city of Vejle (ENE 2015). Our study ran together with five companies and the two energy advisors. The study was conducted by contacting the companies through the person listed as the contact person for the energy guild. A meeting was arranged that included an interview part, visualisation evaluation and observations as part of a

Table 1 Listing of company and interviewee details

	Company A	Company B	Company C	Company D	Company E
Company domain	Office Hotel	Coldstore	Conservation	Conference Hotel	Public Institution
Largest consumption types	Ventilation and Lighting	Cooling	Ventilation and Climate Control	Kitchen and Lighting	Ventilation and Lighting
Interviewees (energy efficiency experience)	Building Administrator (high)	Chief Engineer (high)	Manager and Administrator (low)	Building Administrator (moderate)	Two Chief Engineers (high)
Recent energy efficiency initiatives	New energy efficient building	Optimization of equipment and replacement of inefficient equipment	Optimization of existing equipment and new energy efficient facilities	Optimization of existing equipment and replacement of inefficient equipment	Optimization of equipment and installation of more efficient equipment
Yearly consumption	MWh	GWh	MWh	MWh	MWh

facility tour. As we ran the study with members of the energy guild the companies are biased by having expressed interest in energy efficiency and the results should be judged in this light. The meetings with the two energy advisors included an interview focusing on the role of an advisor and visualisation evaluation with data from the companies. Table 1 lists the details for each of the companies which are selected to differ both in company domain, main consumption types, experience with energy efficiency and amount of yearly consumption. Interviews and evaluations were recorded and pictures were taken to document evaluations and observations at the facilities. The material was afterwards transcripted and coded to identify important topics which was the basis for the presented analysis results.

4.1 Domain Characterisation

Visualisation methodology prescribes a domain characterisation as the first element of developing visualisations and is a contribution in itself (Munzner 2009). As no domain characterisation has been published for energy management in the visualisation community, we will provide one with a focus on tasks relevant to pervasive sensing. To characterise the domain problems and tasks, we combine three sources of information. Firstly, the recent ISO 50001 standard for energy management (Eccleston et al. 2011), case studies of energy information systems and semi-structured interviews to validate the characterisation in the energy guild context. The recent ISO 50001 standard (Eccleston et al. 2011) outlines a number of tasks to be performed by energy managers. We analysed the standard and identified five domain tasks (listed in Fig. 1) prescribed by the standard that focus on analysis

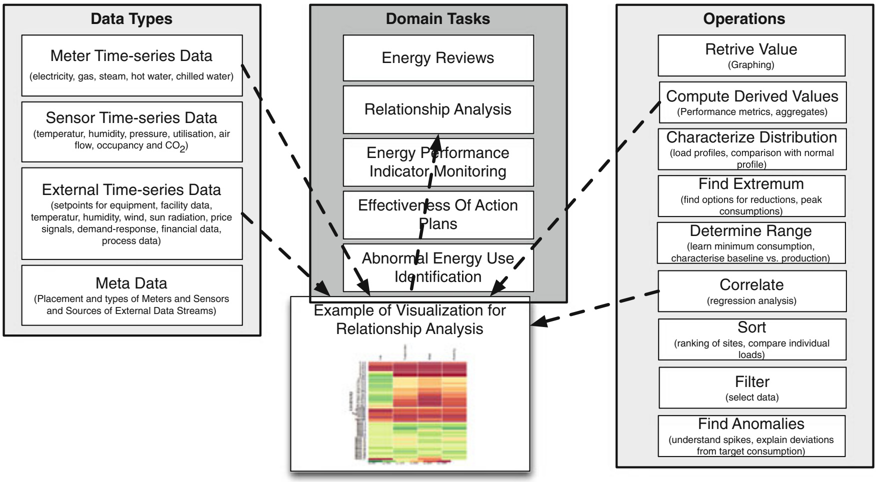


Fig. 1 Domain characterisation, data types and operations

of energy data and therefore possibly supported by visualisation: Firstly, *energy reviews* to identify significant energy use and options for optimization. Secondly, *relationship analysis* to characterize factors that affect energy use, e.g., environmental conditions or production volume. Thirdly, *energy performance indicator monitoring* to track company defined indicators, e.g., reduction targets defined in comparison to a baseline or normalized indicators compared among different buildings or company sites. Fourthly, *abnormal energy use identification* due to faulty equipment or overuse. Fifthly, monitoring the *effectiveness of action plans* including plans for reductions by increased awareness of energy use among staff and installation of more energy efficient equipment.

Granderson et al. (2011) present case studies of energy information systems covering the four large organisations: UC Merced, Sysco, Wal-Mart and UC Berkeley. In the following we analyse if the above five tasks cover the presented case studies. In the case studies, *energy reviews* were mentioned in three out of four cases with UC Merced as the exception due to newly build facilities. *Relationship analysis* is mentioned by all cases except again UC Merced. However, in several of the cases the reported analysis activities are based on intuition from graph plots rather than based on extensive statistical analysis. *Energy performance indicator monitoring* was reported in all cases, for some only comparing the performance over time and for others extensive ranking over the whole building portfolio. *Abnormal energy use identification* was also performed in all cases but the temporal span differ mainly due to staffing restrictions from daily to monthly tracking. Monitoring the *effectiveness of action plans* were also mentioned in all cases but it varied if the activity is described as a short term task on a per action basis or more systematically organized. The cases did not report other significant activities not covered by the tasks described above.

In our study we asked interviewees what the main tasks are for performing energy management. As an underlying issue most companies mentioned that energy management tasks compared to business tasks are running as secondary tasks on an ad hoc basis. For *energy reviews* all company interviewees mentioned concrete activities including: (i) using digitally metered data to understand the breakdown of their consumption. Some had added additional submetering to help break down the consumption into individual loads. Others had tried to manually turn on and off equipment to understand each equipment's impact on the overall consumption; (ii) making detailed analysis of equipment to understand the consumption impact of setpoints; (iii) producing reports from the web portal to provide data to other people in the organisation. For *energy performance indicator monitoring* only company B had made efforts to track key performance indicators more regularly where they had normalized the consumption in regards to production data and environmental data. For *relationship analysis* again only company B had put in effort to understand the relationship between setpoints, outside temperature and energy consumption using scatter plots and linear regression. For *abnormal energy use identification* the participants mentioned that they had used the web portal with live access to their consumption data to follow the consumption on an ad hoc basis to notice deviations. For monitoring the *effectiveness of action plans* most of the companies had compared existing equipment to new equipment on the market to evaluate options for increasing efficiency by replacing equipment. Company B and C had also performed analysis of small experiments with setpoints and after the installation of new equipment quantified the returns. The interviews with the energy advisors generally confirmed that the above domain characterisation captured the main tasks of energy management. Therefore the different sources of information support that the five tasks (listed in Fig. 1) is a fair description of the main tasks of energy management in regards to data analysis.

4.2 Data and Operations

The next level of the nested model is data and operations. Our efforts are informed by existing literature including the case study of Granderson et al. (2011) and their earlier report (Granderson et al. 2009) analysing the data types and operations of energy information systems and information from the interviews. Generally data relevant to energy management are time series of different kinds of physical information. We analysed both the data types mentioned in the case studies of Granderson et al. (2011) and the ones mentioned by our interviewees. Figure 1 lists the identified of types of data relevant to consider when analysing energy data.

Taxonomies have been proposed that describe the low-level operations of analytical activities. We follow the taxonomy proposed by Amar et al. (2005), which define the following low-level operations: retrieve value, filter, compute derived value, find extremum, sort, determine range, characterize distribution, find anomalies, cluster and correlate. However, many domain tasks are compound tasks mapping to several of such low-level operations, e.g., it is very common that domain tasks include retrieve values or computing a derived value. We have listed these operations including examples in Fig. 1. Given that we have analysed domain tasks, data types and operations designing an information visualisation for a specific domain tasks should consists of a mapping to relevant data and operations as illustrated by the example in Fig. 1.

5 Visualisations for Domain Experts

Given the list of identified domain tasks, data types and operations, there are many different options for applying information visualisation. Here we study a subset of these combinations. In this work we focus on the visual encoding and leave interaction design for future work.

We choose to focus on the tasks of *energy reviews*, *relationship analysis* and *abnormal energy use*. Firstly, these are central analytical activities and, secondly, the two remaining tasks can not be implemented in visualisations based on company data without previous interaction with the companies to establish performance indicators and running actions plans. Therefore the remaining two tasks are left for follow-up work. Figure 2 gives an overview of the tasks, data types and visualisation forms designed for the study. The shown visualisations are generated using electricity data from *Company A*. In the following we will refer to the individual visualisations by (X) where X refers to the alphabetic labels in Fig. 2. In regards to the data types listed in Fig. 1 when designing the visual encodings the work was restricted by the available data sources from the companies.

Existing Tool: As the basis of our investigations we took the current web portal available to the members of the energy guild. The portal uses bar charts as the basic visualisation form marked (K) in Fig. 2. Selection mechanisms allow the filtering of data for metering points, periods of time and aggregation levels, e.g., hourly, daily, weekly or monthly. Furthermore, the web portal also provides the ability to extract reports that include measurements as totals listed in tables and pie charts marked as (L) in Fig. 2.

Data Processing Chain: For preparing the visualisations we implemented a data processing chain as shown in Fig. 3. As the first step electricity consumption readings for all submetered loads in the five companies are imported as JSON data (1). The visualisations shown to the interviewees were based on data from January to May 2014. External data is imported in our case weather readings of temperature, humidity and wind speed as JSON data from the REST API of openweathermap.org for the city of Vejle (2). Data is then processed to handle missing data by interpolation and calculate additional model-based time-series in our case a gross estimate of the sun radiation as the hours of sun calculated using a sunset model (Sun 2015) (3). Afterwards, we apply the multichannel weekly model of Braga et al. (2013) who propose to aggregate electricity consumption into a multichannel structure where each hour of the week is represented as a separate channel (4).

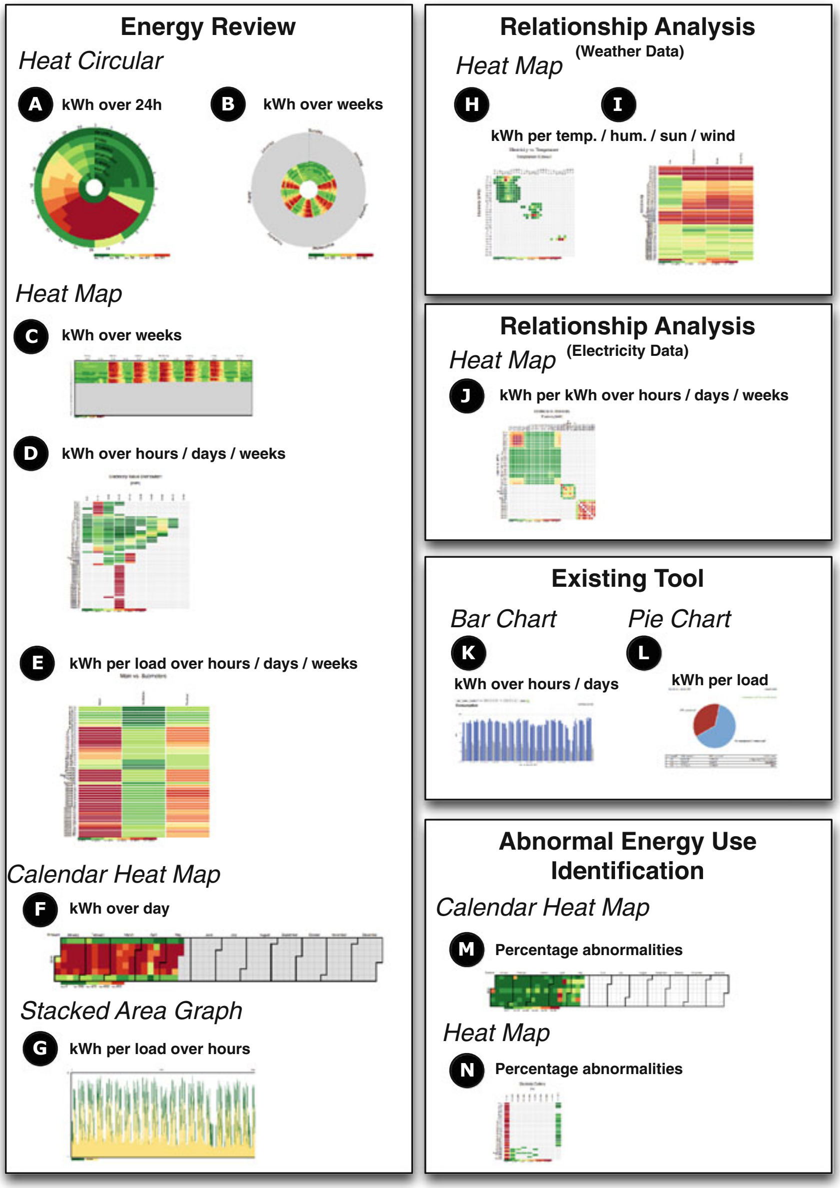


Fig. 2 Summarizing visualisations for domain experts

The readings of each channel is then readings of different weeks for the same hour of the week. Different operators can then be applied to the readings of a channel, e.g., aggregate them by summary statistical operators to compute the mean, minimum, maximum, distribution or standard deviation. For the relationship analysis

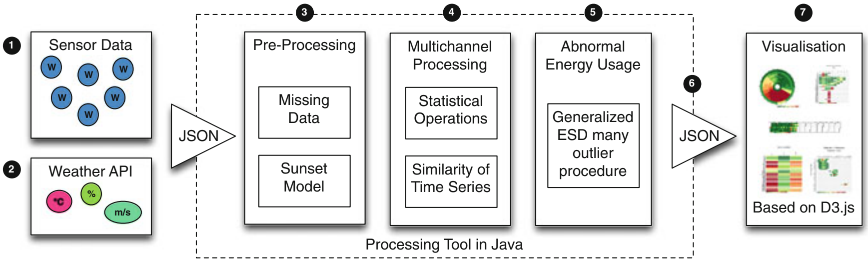


Fig. 3 Processing chain for visualisations

visualisations we compute the similarity of two time-series by, firstly, applying a mean standard deviation normalisation. Finally, we compute the similarity of the normalized time-series using dynamic time warping which can compute a similarity metric for time-series as the cost of the minimum-distance of an optimal alignment.

To provide identification of abnormal energy use we implemented the algorithm proposed by Seem (2007) for detecting abnormal energy use and applied it per channel for the multichannel weekly model (5). The algorithm uses the generalized ESD many-outlier procedure. The algorithm depends on a parameter that specify the likelihood of abnormal energy usage which we set to five percentage to detect only rare cases. The processing chain outputs JSON data for visualisations produced using the D3.js framework. Many of the visualisations were developed taking as outset general templates from the D3.js repository. These were then adapted to the types of data and improved to provide rounded scales, good color schemes and legends to increase usability. The color scheme goes from green over orange to red where green represents low values and red represents high values. The processing chain produces the visualisations with good runtime performance where the only bottleneck for large data sets is the similarity metric based on dynamic time warping which runs in $O(n^2)$.

Energy Reviews: The goal of energy review visualisations is to help domain experts perform energy reviews of commercial and industry buildings. We focus on providing summarizing visualisations to supplement the existing tool focusing on detailed measurements. The *heat circular* visual encoding displays data using a circular clock as a metaphor. This visual encoding allows the folding of time-series data for different time spans across multiple rings to align the same hour of the day or the same day of the week across rings. We developed two visualisations using this visual encoding. Visualisation (A) uses data averaged with the multichannel weekly model and each ring represents a day of the week and the scale of the ring is the 24 h of a day. Visualisation (B) uses hourly readings and each ring represents a week of a year and the scale of the ring covers the hours of the week with markings for each day. The *heat map* visual encoding displays data using a matrix representation as a metaphor. The row and columns represent different dimensions and each entry is color coded to represent the values of the matrix. Visualisation (C) uses hourly readings and folds the time series so each row represents a week. Visualisation (D) uses data averaged with the multichannel weekly model where the first 24 rows represent the hours of a day, the next seven the days of a week and the remaining rows the covered weeks. The columns represent different electrical consumption ranges and each cell represents the percentage of measurements within that hour, day or week and range of consumption. The visualisation thereby shows data in the same visualisation with different aggregation levels. Visualisation (E) uses data averaged with the multichannel weekly model where the first 24 rows represent the hours of a day, the next seven the days of the week and the remaining rows the covered weeks. The first column shows the main load and the following columns the breakdown of the main load into subloads. Each entry is color coded based on the average consumption. The *calendar heat map* visual encoding displays data using a calendar as a metaphor. Each month is represented by a black polygon and each day as a square. The squares are laid out so each row represents a specific day of the week. Visualisation (F) uses this encoding to show the average electricity consumption for each day. The *stacked area graph* visually encodes data as a graph where the measurements from different time series are stacked. Visualisation (G) uses hourly readings of all submeters.

Relationship Analysis: The relationship analysis visualisations are designed to help understand causal relationships between either different data sources or between temporal shifts of the same data. *Heat maps* are used in the following two visualisations. Visualisation (H) uses data for electricity consumption linked with either temperature, humidity, wind or sun radiation. The row dimension represents electricity consumption and contains a scale from the minimum consumption to the maximum consumption repeated three times to represent hourly, daily and weekly data, respectively. The column dimension represents the scale of an external data source again repeated from minimum to maximum three times to represent hourly, daily and weekly data, respectively. Each cell is color coded based on how many hours, days or weeks had an average consumption of this level and an average external data value within the value range of the column. Visualisation (I) uses both electricity consumption data and external data. The row dimension represents temporal information where the first 24 rows represent the hours of a day, the next seven the days of a week and the remaining rows the covered weeks. The columns represent different types of external data. Each cell represents the similarity between the external time series and the electricity consumption computed by dynamic time warping. Visualisation (J) uses only electricity data and a *heat map* visual encoding. The row and column dimensions represent temporal information where the first 24 rows represent the hours of a day, the next seven the days of a week and the remaining rows the covered weeks. Each cell represents the similarity of the electricity consumption for a pair of hours, days or weeks computed by dynamic time warping for time series processed with the multichannel weekly model.

Abnormal Energy Use Identification: The following visualisations are designed to help identify abnormal energy use. Visualisation (M) uses the abnormal use classifications of the Seem (2007) algorithm and a *calendar heat map* visual encoding. Each cell of the calendar heat map represents the percentage of hours of a day classified as abnormal by the algorithm. Visualisation (N) uses the same data but with a *heap map* visual encoding aggregating data using the multichannel weekly model. The row dimension represents temporal information where the first 24 rows represent the hours of a days, the next seven the days of a week and the remaining rows the covered weeks. The column dimension represents the percentage of abnormal classified hours.

6 Evaluating Visualisations

In the following we present study results for the value of the visualisations for domain experts in energy management.

As an example of the visualisations shown to interviewees we discuss the visualisations for Company A shown in Fig. 2. Company A runs an office hotel in a 5500 m^2 large building from 2009 shown in Fig. 4a. To give an impression of the electricity consumption of the building we have included visualisation (A) showing the total consumption of the building in Fig. 4b and the ventilation in particular in Fig. 4c. Analysing the visualisations one can quickly notice the night and day, and week and weekends patterns for the building. Thereby the visualisations provide an easy comprehensible description of the building. For the ventilation one can observe that the maximum consumption stretches into the evening on weekdays and runs shortly at maximum Saturday before noon. If one compares the main consumption and the ventilation consumption it looks like the occupancy related peak

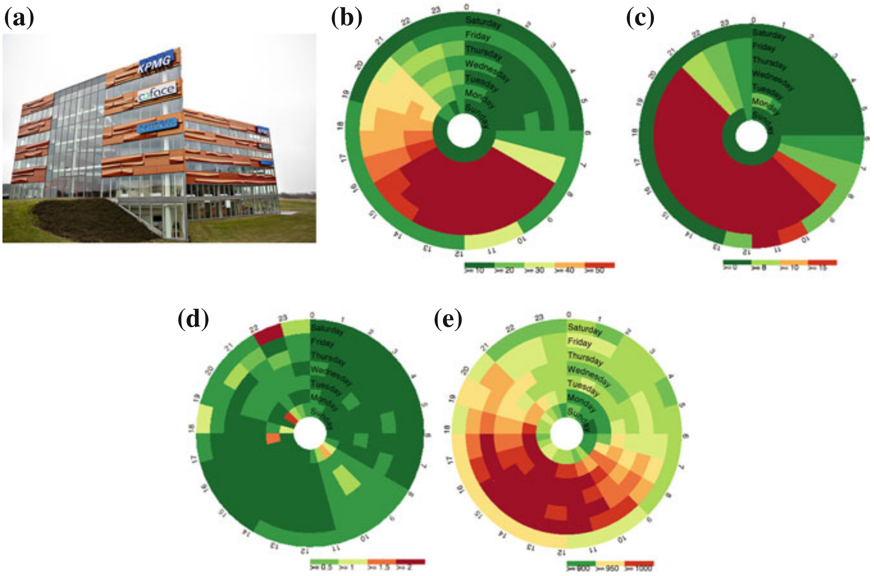


Fig. 4 Visualisation examples for visualisation A. **a** Building of Company A. **b** Total Consumption Company A. **c** Ventilation Company A. **d** UMass Smart* Home. **e** Sutardja Dai Hall at UC Berkeley

load in the building stops much earlier than the ventilation which might represent an option for optimizing the ventilation. The quick overview also makes it easy to recognize different building types, e.g., an office building versus a residential home as shown in Fig. 4d based on data from one of the UMass Smart* Homes. Another aspect is international differences, such as, the midday peak in data shown in Fig. 4e for the Sutardja Dai Hall at UC Berkeley due to air conditioning which is uncommon in Denmark and not present in the Company A building.

For the study we use qualitative methods to gather feedback as this facilitates the gathering of rich feedback from the interviewees based on open-ended questions. The evaluation was conducted by showing the visualisations in a random order on a laptop to interviewees and then at the same time give them a print out of the shown visualisation. The interviewees were then asked to provide comments for each visualisation which were added as post-its and categorise each visualisation into three categories of highly relevant, relevant or irrelevant. The print outs were used to emphasize that the visualisations were not final and thereby encourage the interviewee to provide comments, and to enable them to reorder visualisations if they changed their mind during the session. Figure 5 gives a qualitative overview of how the interviewees placed the visualisations into the different categories. Table 2 lists the analysis results covering both the established practices using the existing tool and the value of summarizing visualisations.

Energy Reviews. During the evaluation several themes emerged in regards to the value of summarizing visualisations in comparison with the established practice at the companies using the existing tool.

Learn consumption: All company interviewees mentioned that using the existing tool they had learned the energy consumption of their building based on the detailed views (K, L). However, the interviewees commented that they had found this process time consuming using the existing tool. When presented with the different visualisations for energy reviews we observed that people generally favoured the summarizing visualisations (A), (C) and (D). The reaction to the visualiations was that the interviewees were able to recognise the information they had gained using the existing tool. For instance, using the visualisations they were able to tell in great

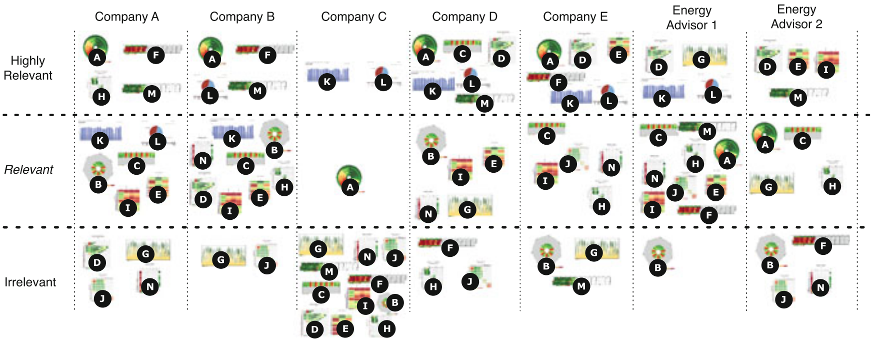


Fig. 5 Categorisation results from the evaluation of prototypes

Table 2 Established practice with comments and the value of summarizing visualisations including the best rated visualisations and comments

	Established practice [Comments]	Value of visualisations (Best Rated) [Comments]
Reviewing energy consumption		
Learn consumption	Numbers + DV [Time demanding]	Positive (A, C, D) [Good overview]
Understand interactions	DV [Time demanding]	*Not considered*
Understand breakdown	DV [Complex process] + Pie Charts [Limited information]	Balanced (E) [Good support for data navigation but easily complex to interpret]
Understand equipment	DV [Time demanding]	Positive (A, C, D) [Good overview]
Stakeholder communication	Numbers and Pie Charts [Too limited]	Positive (A, C, D) [Overview and informative]
Analysing relationships		
Learn dependencies	DV [Intuition rather than facts]	Balanced (H, I) [Multiple factors and missing data]
Handle multiple factors	DV [Intuition] + Linear Regression [Complex]	*Not considered*
Abnormal energy use		
Identification	DV [Ad hoc and complex] and threshold-based alarms [Require tuning]	Balanced (M) [Resolve abnormal usage or abnormal use as events]
Normalization	DV [Intuition]	*Not considered*
Feedback	DV [Not normalized]	*Not considered*

Detailed views (DV) are bar charts of the existing tool

detail what they had learned, e.g., about the variability of consumption, the effect of reconfiguring ventilation and start and end times of production processes. A few observed new things, e.g., Company D was surprised that the consumption varied so much in the evening. Thereby the visualisations enabled the interviewees to recall and communicate the knowledge they had built up. Most interviewees attributed this as a positive aspect of the visualisations and rated them as highly relevant. The two energy analysts generally liked visualisation (D) as they both attributed gave them a better overview and stated that "*The visualisation enabled me to quickly get an overview instead of having to browse through data of 24 weeks.*". Some of the interviewees told that they had personal preferences for preferring a heat circular view compared to a heat map view of the same data.

Understand interactions: Some of the companies had experimented with changing setpoints to learn the impact on the consumption and the consequences for the indoor climate and cooling of goods. However, they commented that these processes had been quite time consuming. As we did not have access to setpoint data, we did not design visualisations for this aspect.

Understand Breakdown: As part of reviewing the electricity consumption, many of the interviewees mentioned the importance of understanding the consumption of individual equipment. Some of the companies mentioned that they would like to get further loads submonitored, e.g., Company B who had installed the most extensive submetering.

Visualisation (E) and (G) were designed to give an overview of the different submonitored equipment. The existing tool uses a pie chart (L) to report the percentage of consumption for different submonitored loads. Several of the interviewees had used the pie charts to get an idea of the overall percentage breakdown. However, for the temporal patterns of consumption they had found this complex to study using the individual detailed views. In connection with visualisation (E) the interviewee from Company B said that it quickly gave him an overview but for (G) he noted that it was too complicated to see anything. Energy advisor 2 viewed displaying submetered data as important and liked (E) but for (G) also noted that it was too complicated but that he would like a version with different zoom levels. Furthermore, it was important that to analyse the behavior of specific equipment to be able to access detailed submetered measurements.

Understand Equipment: All the companies had experimented with switching on and off equipment to learn the impact on the total consumption and life cycle of equipment. They attributed this step as a time consuming process. For some equipment submonitoring had been installed to provide individual measurements. When viewing data for individual equipment people generally favoured the summarizing visualisations (A), (C) and (D). The visualisations also allowed them to spot odd events, e.g., the interviewee of Company A did not understand why they ran ventilation on Saturdays when the building was empty. The advisors liked the overviews but also asked for detailed views as the behavior of some equipment is only observable from minute scale data.

Stakeholder Communication: Several interviewees mentioned that they had used the existing tool to communicate about consumption to other stakeholders, e.g., to management to justify investments in new equipment, to the financial department to document the amount of consumption that is by Danish rules deductible from valued added tax and to other stakeholders to try to influence behavior. For instance, company A had discussed the data with their office renters and also saw it as an important tool to share knowledge in the organisation among both management and technical stakeholders. For the later case the interviewee mentioned that the summarizing visualisations would be important as they show data in a form where also non-technical people can appreciate them.

Analysising Relationships. During the evaluations two themes emerged.

Learn Dependencies: Several of the interviewees commented that learning about dependencies were important because this information could give insights for how to select setpoints to avoid inefficient states of equipment, e.g., for ventilation or to understand the depencies between consumption and influential factors. The factors mentioned included weather data, occupancy and production processes. The companies had tried to learn about these dependencies based on their own intuition as also observed by Granderson et al. (2011).

The visualisations (H) and (I) designed for relationship analysis were only by Company A and Energy advisors 2 rated as highly relevant and else were rated as being relevant. The reason some of the interviewees had reservations for the visualisations were that in several cases the companies' consumption depended on multiple factors and therefore the visualisations designed for only one factor did not show a plausible relationship. Another problem was that other factors than weather drove the electricity consumption, e.g., in the case of company E where the number of hotel and conference guests drove the consumption. A challenge in this connection is that proper analysis might be impossible because data is not collected today or resides in different IT systems. Visualisation (I) had for several of the companies low value as it showed several coincidental relationships. Visualisation (J) designed to analyse the relationship among different times a day, week or year was generally ranked low.

Handle Multiple Factors: For several of the companies the electricity consumption depends on multiple factors. To analyse the factors only company B and the energy advisors had applied different forms of linear regression to the data. They considered such methods complex to apply. In our work we did not design any explicit visualisations for analysing the impact of multiple factors.

Abnormal Energy Use Identification. The visualisations for abnormal energy use identification were designed to provide overviews of abnormal consumption events. Many of the interviewees mentioned that abnormal energy use is an important topic to consider and mentioned examples of cases where they had experienced abnormal consumption and first found out later. Examples mentioned include broken wires, failing thermostats for freezers and failing ventilation that ran at maximum speed.

Identification: Visualisation (M) and (N) were designed to visualize abnormal energy use events. The interviewees generally favored visualisation (M) over (N) as (M) gave them an overview of the different events. However, it was important for several of the interviewees that they would be able to go beyond the overview to see the details to understand what was the issue behind the abnormality. Furthermore, many of them stated that for this information to be really useful it was important to not only provide an overview but to get alarms in real-time so they could act on the information, e.g., for newly serviced equipment to know when it was time for a new service check. Furthermore, it was relevant if the visualisations supported helping to identify the fault as one might have to look into different types of sensor values and status messages for the equipment to find the fault. A situation where one of the advisors saw a special value for the overviews were for recording that an alarm had been appropriately resolved.

Normalization: An issue mentioned when detecting abnormal use was normalization as for some equipment increasing company production would increase consumption but not be a fault. An interviewee also added that it was important to detect abnormal consumption of both low and high consuming equipment because it might be important to handle faulty equipment for other reasons than the impact on total consumption. These aspects were not considered by our visualisations.

Feedback: The visualisations that we evaluated were designed to provide analysis capabilities to stakeholders rather than feedback (Froehlich et al. 2010). However, several of the stakeholders mentioned that in their daily work it was also important to have visualisations that confirmed that daily operations were going as planned. For instance, the interviewee from company B mentioned and showed us during the observations that some of his cooling compressors showed him a smiley when they were operating correctly. Therefore, he would like a similar interface for the rest of his equipment for normal versus abnormal electricity use.

7 From Needs to Better Decision Support

The evaluation results provide both positive and some more balanced results in regards to the value of the developed visualisations. Additionally, the results provide input to themes for improvements of the visualisations in their own right. Table 3 lists evaluations results, visualisation improvement themes and identified

Table 3 Visualisation results and future work coupled with relevant themes

	Visualisation	Themes
Reviewing energy consumption		
Learn consumption	Positive experiences	Learn about temporal patterns of consumptions
Understand interactions	*Open problem*	Learn about causal relationships [Residential: (Rollins and Banerjee 2014)]
Understand equipment	Positive experiences	Learn about equipment temporal patterns
Understand breakdown	Link overview with details	Similarity and ranking of loads, and NILM
Stakeholder communication	Positive experiences	*Not relevant*
Analysing relationships		
Learn dependencies	Multiple factors and missing data	Model dependency using sensing of occupancy behavior (Yang et al. 2014), business activities and environmental conditions
Handle multiple factors	*Open problem*	Disaggregation of multiple factors
Abnormal energy use		
Identification	Resolve abnormal use and events	Detection and modeling of abnormal use (Commercial: Jung et al. 2013)
Normalization	Missing data	Normalize using sensing of occupancy behavior (Yang et al. 2014), business activities and environmental conditions
Feedback	Abnormality feedback	Learn and classify performance

research and development themes for new systems to provide relevant types of information to domain experts. In the following we discuss an example from the list.

For *abnormal energy use* and *identification*, our visualisations were challenged by the domain experts as the most relevant mean. They pointed us to a need for systems to detectabnormal energy use with a low latency in real-time. This is not yet addressed by existing work (Jung et al. 2013). However, our evaluation results also point to an element of fuzziness in the task due to normalisation issues with regards to occupancy behavior and business tasks potentially invalidating solutions without a human in the loop. Additionally, we identified several tasks that could be improved by better system support for fault diagnosis and recording of actions taken to correct issues. These observations highlight the need for better decision support tools and the complexity involved in developing such tools.

8 Conclusions

In this chapter we use a living lab context to argue that using visualisations as a decision-making tool will help improve energy efficiency in commercial and industrial buildings. We presented a case in the domain of energy management for commercial and industry buildings where we applied a visualisation approach in a living lab context. We applied visualisation methodology to develop a domain characterisation, identified relevant data and operations and designed visual encodings for the visualisations. We prototyped a visualisation tool chain to produce these visualisations on a data set and involved domain experts to evaluate the utility of the visualisations. This enabled us to pinpoint working visualisations based on the needs of domain experts, and to identify themes for developing new visualisation tools. We aim to further improve energy management tools for commercial and industrial buildings as these tools can contribute to achieving the Danish sustainability targets.

Points for Discussion

- How does this chapter link new methods to produce new tools to achieve efficiency?
- How can visualisations link what you see and what you can conclude? Can the full complexity of the underlying mechanisms and data be visualized? Should it all be visualized?
- How can we determine what information is useful for an energy manager? Can this change over time or in different settings?

Acknowledgments The authors would like to thank European Regional Development Fund (The Region of Southern Denmark) and Regional Commercial Development Fond for funding the Micro Grid Living Lab project.

References

Amar, R.A., Eagan, J., Stasko, J.T.: Low-level components of analytic activity in information visualization. In: InfoVis, IEEE Computer Society, p. 15 (2005)

Braga, L., Braga, A., Braga, C.: On the characterization and monitoring of building energy demand using statistical process control methodologies. Energy Build. **65**, 205–219 (2013)

Brandstatt, C., Friedrichsen, N., Meyer, R., Palovic, M.: Roles and responsibilities in smart grids: a country comparison. In: Proceedings of the 9th International Conference on European Energy Market (EEM) (2012)

Costanza, E., Ramchurn, S.D., Jennings, N.R.: Understanding domestic energy consumption through interactive visualisation: a field study. In: UbiComp, ACM, pp. 216–225 (2012)

DEA: Energy consumption of buildings—http://www.ens.dk/byggeri/byggeriets-energiforbrug (2015)

Eccleston, C., March, F., Cohen, T.: Inside Energy: Developing and Managing an ISO 50001 Energy Management System. CRC Press, Boca Raton, FL (2011)

ENE: http://www.greentechcenter.dk/uk/ (2015)

Froehlich, J., Findlater, L., Landay, J.A.: The design of eco-feedback technology. In: CHI, ACM, pp. 1999–2008 (2010)

Goodwin, S., Dykes, J., Jones, S., Dillingham, I., Dove, G., Duffy, A., Kachkaev, A., Slingsby, A., Wood, J.: Creative user-centered visualization design for energy analysts and modelers. IEEE Trans. Vis. Comput. Graph. **19**(12), 2516–2525 (2013)

Granderson, J., Piette, M., Ghatikar, G., Price, P. Building energy information systems: state of the technology and user case studies (2009)

Granderson, J., Piette, M., Ghatikar, G.: Building energy information systems: user case studies. Energ. Effi. **4**(1), 17–30 (2011)

Hasenfratz, D., Saukh, O., Walser, C., Hueglin, C., Fierz, M., Thiele, L.: Pushing the spatio-temporal resolution limit of urban air pollution maps. In: IEEE PerCom, pp. 69–77 (2014)

Jung, D., Krishna, V.B., Khiem, N.Q.M., Nguyen, H.H., Yau, D.K.Y.: Energytrack: Sensor-driven energy use analysis system. In: BuildSys, ACM, pp. 6:1–6:8 (2013)

KEB: Smart grid strategy—the intelligent energy system of the future (2013)

Munzner, T.: A nested process model for visualization design and validation. IEEE Trans. Vis. Comput. Graph. **15**(6), 921–928 (2009)

Rollins, S., Banerjee, N.: Using rule mining to understand appliance energy consumption patterns. In: IEEE Percom, pp. 29–37 (2014)

Ruiz, A.J.R., Blunck, H., Prentow, T.S., Stisen, A., Kjærgaard, M.B.: Analysis methods for extracting knowledge from large-scale wifi monitoring to inform building facility planning. In: IEEE PerCom, pp. 130–138 (2014)

Sedlmair, M., Meyer, M.D., Munzner, T.: Design study methodology: reflections from the trenches and the stacks. IEEE Trans. Vis. Comput. Graph. **18**(12), 2431–2440 (2012)

Seem, J.E.: Using intelligent data analysis to detect abnormal energy consumption in buildings. Energy Build. **39**(1), 52–58 (2007)

Sun: Sunsetlib—java. https://github.com/mikereedell/sunrisesunsetlib-java (2015)

Weiss, M., Helfenstein, A., Mattern, F., Staake, T.: Leveraging smart meter data to recognize home appliances. In: IEEE Pervasive, pp. 190–197 (2012)
Yang, L., Ting, K., Srivastava, M.B.: Inferring occupancy from opportunistically available sensor data. In: IEEE PerCom (2014)
Zhao, X., Gordon, M., Lind, M., Østergaard, J.: Towards a danish power system with 50 (2009)

End User Research in PowerMatching City II

Carina J. Wiekens

Abstract In PowerMatching City, the leading Dutch smart grid project, 40 households participated in a field laboratory designed for sustainable living. The participating households were equipped with various decentralized energy sources (PV and micro combined heat-power units), hybrid heat pumps, smart appliances, smart meters, and an in-home display. Stabilization and optimization of the network was realized by trading energy on the market. To reduce peak loads on the smart grid and to be able to make optimal use of the decentralized energy sources, two energy services were developed jointly with the end users: Smart Cost Savings enabled users to keep the costs of energy consumption as low as possible, and Sustainable Together enabled them to become a sustainable community. Furthermore, devices could be controlled automatically, smartly, or manually to optimize the energy use of the households. Quantitative and qualitative studies were conducted to provide insight into the experiences and behaviours of end users. In this chapter, these experiences and behaviours are described. The chapter argues that end users: (1) prefer to consume self-produced energy, even when it is not the most efficient strategy to follow, (2) prefer feedback on costs over feedback on sustainability, and (3) prefer automatic and smart control, even though manual control of appliances felt most rewarding. Furthermore, we found that experiences and behaviours were fully dependent on trust between community members, and on trust in both technology (ICT infrastructure and connected appliances) and the participating parties.

The 'energy transition' is characterized by increased amounts of distributed generation, often from renewable energy sources with variable output. The increase of distributed generation in combination with an increase in power demand calls for solutions that enable optimization of the energy value chain (e.g., Wisner 2011). Optimization is needed to prevent exceeding the limits of our current energy

---

C.J. Wiekens (✉)
Research Centre Energy, Hanze University of Applied Sciences, Groningen, The Netherlands
e-mail: c.j.wiekens@pl.hanze.nl

A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*,
Power Systems, DOI 10.1007/978-3-319-28077-6_17

infrastructure, to reduce dependence on fossil fuel, and to reduce greenhouse gas emissions. Smart grids may be part of the solution by offering technology for integration and intelligent control of multiple generators and consumers. With smart grids, a better alignment of demand and supply can be achieved.

In smart grids, end users are expected to play a prominent role (e.g., Goulden et al. 2014; Siano 2014). As Wolsink (2012) points out, the development of smart grids “suffers from a focus on mere ‘technology’”. Since problems with the introduction of sustainable energy technology have shown that public acceptance is key to successful implementation (e.g., Huijts et al. 2012), researchers should focus on how smart grids are perceived and experienced by end users. In this chapter, smart grids are studied from an end user perspective. Specifically, end user research is described that was conducted within the smart grid project PowerMatching City. The main objective of this research was to understand the experiences and behaviour of end users in a smart grid. The central questions were whether smart grids can be attractive for end users, which kinds of demand-side management may lead to active engagement, and how different types of control in the smart grid (automatically, smartly, or manually) are experienced.

1 PowerMatching City

PowerMatching City is a smart grid project in the northern part of the Netherlands. In PowerMatching City, 40 households were equipped with decentralized energy sources (PV and microCHP), hybrid heat pumps, smart appliances, and smart meters. The first phase of the project ran between 2007 and 2011. The purpose of the first phase of the project was to study technical feasibility. The second phase of the project ran between 2012 and 2014. During this phase, an in-home display, referred to as the Energy Monitor, and two energy services were introduced. In this phase, end user experiences and behaviour became one of the central objectives of the research. In this chapter, an overview of the research conducted during the second phase of the project is presented.

1.1 Two Energy Services: Sustainable Together and Smart Cost Savings

During the second phase of the project (hence, PowerMatching City II), two energy services were jointly created with the end users: Sustainable Together was developed to make optimal use of the energy that was locally generated (within the community). End users were incentivized to consume energy when there was locally generated renewable energy available and postpone consumption when sufficient local energy was expected in the near future. This energy service takes into account the forecast of the individual household photovoltaics and the forecast for the production of solar energy by the community. Smart Cost Savings was developed to enable end users to consume energy when prices were low, and, if possible, sell self-generated and temporarily stored energy when prices were high. This service was based on a dynamic tariff based on the trade portfolio position on the day-ahead market (for more detailed information, see Wijbenga et al. 2014).

For research purposes, end users were randomly assigned to one of the two energy services. This did create some discomfort with some of the residents, especially amongst residents who had joined the project with sustainability motives and received the Smart Cost Savings energy service. However, random assignment in the current setting was the only way to establish the effects of both services. Self-selection would have pushed end users with sustainable motives towards Sustainable Together and end users with economic motives towards Smart Cost Savings. If we had established differences in reactions to the two energy services, we would not have known whether these were the result of the different energy service, or the result of the different motives.

The in-home display end users received, referred to as the ‘Energy Monitor’, displayed one active profile, which depended on the service they received. The active profile showed either the energy performance in euros, or the performance in percentage of the consumed energy that was generated locally. Participants could also access the other, non-active profile, which was in grey shades and offered insight into the other energy service. End users also received a forecast on which they could base their decision to consume energy immediately or delay consumption to a future moment (for an impression of the interface of the monitor, see Fig. 1).

Fig. 1 An impression of the energy monitor (courtesy of PowerMatching City Consortium)

1.2 Three Ways to Control Energy Use

In PowerMatching City, three types of ‘control’ were studied: appliances of the households were controlled either fully automatically (hybrid heat pump or microCHP), smartly (washing machine), or manually (general appliances). With these three ways to control energy use, energy use could be aligned to the energy services. A ‘PowerMatcher’ energy controller was designed to monitor demand and supply of electricity in the smart grid. The PowerMatcher could send signals to which automatic and smart devices responded. Based on present-day tariffs and information on the availability of locally produced sustainable energy, end users were enabled to make decisions on cost efficient and/or sustainable use of energy, for example by programming their smart dishwasher or time shift the use of regular appliances. For an impression of the infrastructure, see Fig. 2.

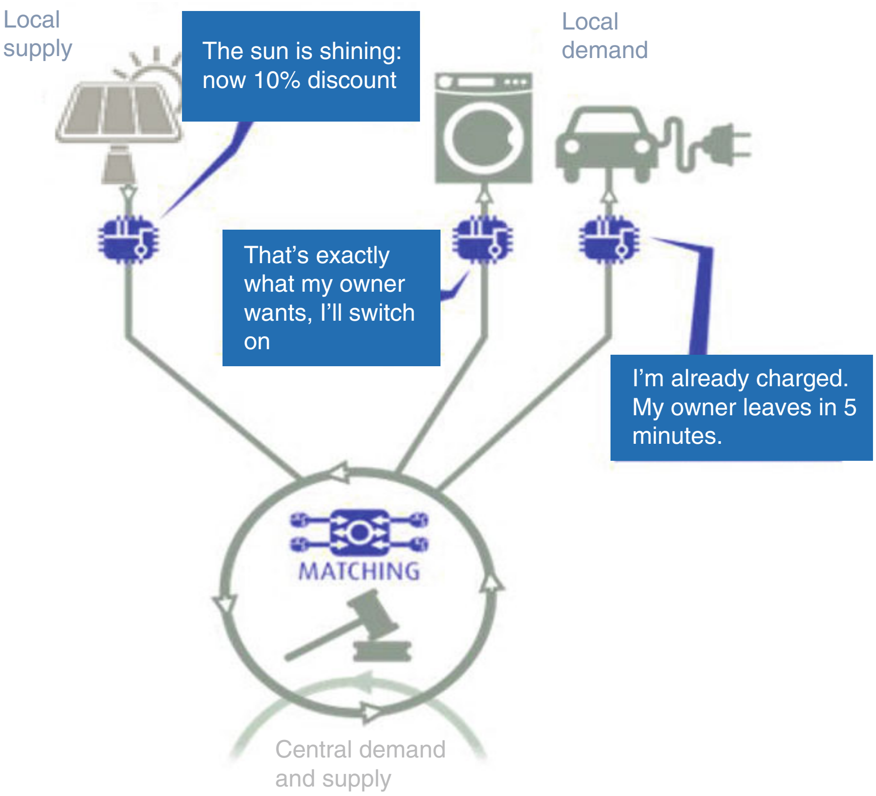


Fig. 2 The PowerMatcher in the ICT infrastructure of PowerMatching City (courtesy of PowerMatching City Consortium)

2 End User Research in PowerMatching City II

The end user research in PowerMatching City was designed to determine whether smart grids can be attractive for end users. More specifically, we were interested in:

(1) The experiences of end users with and reactions to the three types of control;
(2) The experiences of end users with and reactions to the two energy services;
(3) The experiences of end users with the Energy Monitor.

Our main theoretical model was based on a growing body of evidence that points out that values, attitudes and behavioural intentions are important determinants of behaviour (e.g., Ajzen 1991; Schwartz 1994; Stern et al. 1999). Values are abstract ideals, such as solidarity and sustainability. They serve as important guiding principles for life (Maio 2010). Values are only indirectly related to behaviour, for example through specific attitudes and intentions (Stern 2000; Darnton 2008).

In line with the research of de Groot and Steg (2008, 2009), we were interested in pro-environmental values (e.g., ‘saving the planet’), egoistic values (in this research, valuing money or technology), and pro-social values (e.g., ‘doing it together’ and ‘giving a good example to others’). Additionally, we asked end users to indicate the value they attached to autarky (the desire to be self-sufficient as a household or as a community). We expected these values to influence the attitudes end users had of the smart grid project as a whole, of the three types of control, and of the energy services we provided. Furthermore, we expected attitudes to influence end users’ intentions to actively engage with the energy services. We expected these intentions, in turn, to influence behaviour (e.g., time shifting energy demand). See Fig. 3 for an overview of the theoretical model.

2.1 *Timeline of the Research*

End users participated in a series of tests. See Fig. 4 for a timeline of the research. In case of a two-person (or more) household, both partners were invited to participate.

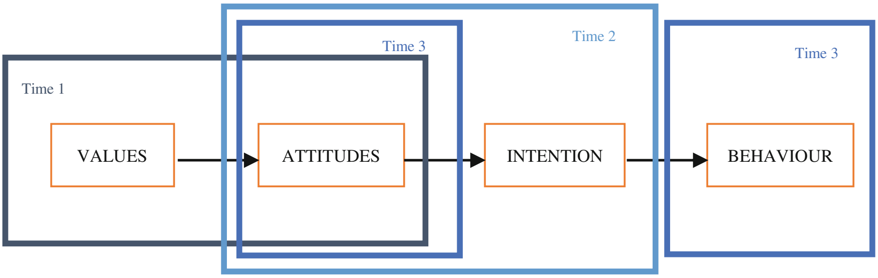


Fig. 3 Theoretical model and timing of the measurements

An initial test (Time 1) consisted of a digital questionnaire. This questionnaire was also filled out by a control group comprised of 255 randomly selected Dutch households from a customer database of Essent, the largest energy supplier in The Netherlands with about 2 million customers. This control group offered us the opportunity to investigate how representative end users of PowerMatching City were compared to a wider group of Dutch households.

The test phase started at the moment end users received one of the two energy services. During the test phase (Time 2), end users responded to a digital questionnaire. Approximately half of the end users attended a focus group session, which was organized to explore the results of the digital questionnaire in more depth. A final test (Time 3) consisted of a digital questionnaire, after which about half of the end users participated in a focus group.

2.2 Measures of Experiences and Behaviour

Values. Values were measured in an initial test, before end users received one of the two energy services. Values were also measured in the control group. We measured values in two ways: by means of a choice based conjoint analysis and by means of a direct, Likert scale measurement. Because both measurements rendered similar results, for the sake of space and clarity, the (simpler) Likert scales are reported here. End users were asked to indicate on six-point scales (1 = *not at all*, to 6 = *very much*) how much value they attached to sustainability (saving the planet), cost savings (economic gain), technology, autarky (independence and self-sufficiency of their household and of the community), and convenience.

Attitudes. Attitudes were measured three times: during the initial test, the test phase (Time 2 in Fig. 4), and the final test. Attitudes towards the two energy services and towards specific components of the energy services (e.g., control and feedback) were measured. Global attitudes were assessed with five statements,

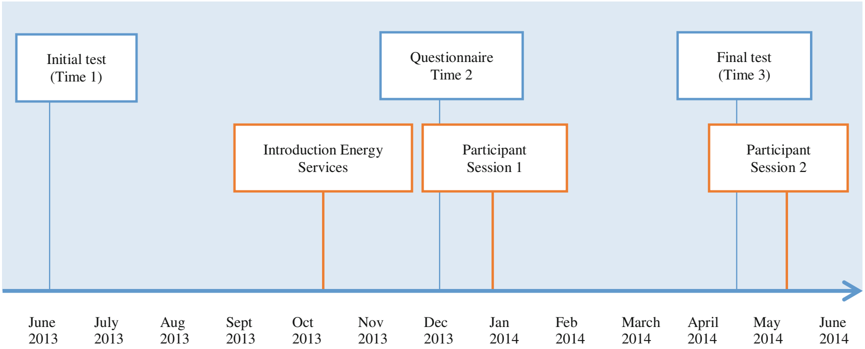


Fig. 4 Timeline of the research conducted in PowerMatching City II

for example: “I find my energy service attractive”, “This energy service appeals to me”, and “I like this energy service”. Specific attitudes were measured by five items. Examples of the items are: “I’m positive about my smart washing machine because it enables me to reduce costs”, “I find my smart washing machine attractive because it contributes to making my energy consumption more sustainable”, and “I find the smart washing machine attractive because it makes me more aware of my energy consumption”. Similarly, we measured attitudes towards (elements of) the Energy Monitor. End users were asked to indicate how much they agreed with the statements on six-point scales ranging from 1 “*totally disagree*” to 6 “*totally agree*”.

*Intention*s. Intentions were measured in the initial test. End users were asked whether they intended to make use of the energy services, for example to program their smart washing machine, or to manually time shift energy consumption. Intentions were also measured as statements. End users responded to the statements on six-point scales (1 = *totally disagree*, 6 = *totally disagree*).

Behaviour. Behaviour was assessed during the test phase and in the concluding test. Behaviour was measured by self-report, through the information we received from the smart appliances, and by measuring energy consumption patterns. The self-report measures consisted of questions about the use of smart appliances and about time shifting regular appliances. For example, we asked end users to indicate how often they time shifted their use of the dryer, dishwasher, oven, vacuum cleaner, et cetera. End users could indicate their responses on six-point scales ranging from 1 “*never*” to 6 “*always*”.

3 Key Results

A comparison between households in the two PowerMatching City groups and 255 randomly selected Dutch households, showed that end users in PowerMatching City valued sustainability significantly more, and costs and convenience significantly less than the control group. Also, the PowerMatching City group showed significantly more interest in technology compared to the Dutch Households (see Table 1 for an overview of the results). Differences between end users in pilot projects and the larger population are often found, because households that participate in these pilots are usually the ‘early adopters’. In a study on early adopters in the diffusion of sustainable (small-scale) energy solutions, Nygrén et al. (2015) found that early adopters were mostly driven by interest in technology, self-sufficiency, environmental concerns and/or cost savings. Except for the difference in attached value to economic gain, our results are consistent with these findings. An implication of these findings is that the results reported here should not be used to forecast results on a larger scale (e.g., in a broader population) without considering differences between the pilot group and the larger population.

Besides a difference between the PowerMatching City groups and the control group, we also found a difference between the two experimental groups: End users

Table 1 Values in the two PowerMatching City groups and in a control group

Values	Smart cost savings			Sustainable together			Control group		
	M	SD	N	M	SD	N	M	SD	N
Sustainability	4.0^a	1.64	31	4.6^b	1.82	25	3.6^c	1.75	255
Costs	3.8^a	1.67	31	3.9^a	1.34	25	4.7^b	1.07	255
Technology	3.8^a	0.89	31	3.8^a	0.96	25	3.3^b	1.11	255
Independence	3.2^a	1.01	31	3.3^a	1.12	25	3.3^a	1.07	255
Convenience	2.8^a	1.59	31	2.8^a	1.59	25	2.9^a	1.47	255

Note Means that do not share superscripts differ at $p < 0.001$. Values were measured on a six-point scale (1 = *not at all*, 6 = *very much*) (Dyadic data analysis (see Kenny et al. 2006) showed that the data of the partners within the household were not significantly more correlated than the data of the participants between households. Therefore, in the reported analyses we do not adjust for dependency of the data)

who received the Sustainable Together energy service significantly valued sustainability more than end users who received the Smart Cost Savings service (see Table 1). This difference is important to consider when interpreting the research results. For example, based on this finding (and the finding that both groups valued costs to a similar extent) it could be expected that end users with the Sustainable Together energy service are particularly pleased with the energy service, because their service was better aligned to their values.

3.1 *Evaluation of the Two Energy Services*

Results of the three digital questionnaires showed that expectations of the energy services were significantly higher than the experiences with the services. This may partly be due to inflated expectations, but the project team also found some issues with the control mechanism, which will be explained in the next section.

We also noticed that individual scores were highly correlated between the times the tests were taken: End users who had had relatively positive expectations of the service, also had more positive experiences with the service, and vice versa. For an overview of the results, see Table 2.

Table 2 Attitudes towards the energy services

Energy service	Initial test			Time 2			Final test		
	M	SD	N	M	SD	N	M	SD	N
Smart cost savings	4.8^a	0.60	19	3.9^b	1.00	16	4.2^b	0.79	19
Sustainable together	4.7^a	0.83	17	3.9^b	0.82	15	3.9^b	0.98	13

Note Means that do not share superscripts differ at $p < 0.001$. Attitudes were measured on a six-point scale (1 = *totally disagree*, 6 = *totally agree*). Because the six attitude items (3 global items and 3 specific items) were highly related (Cronbach's alpha = 0.92 in the initial test, Cronbach's alpha = 0.92 at Time 2, and Cronbach's alpha = 0.90 in the final test), we aggregated the scores of the six items

Table 3 Manually time shifting the onset of the dishwasher

Energy service	Dishwasher		
	M	SD	N
Smart Cost Savings	4.3[a]	1.59	33
Sustainable Together	3.2[b]	1.93	20

Note The dishwasher was shifted manually most often of all appliances. End users indicated the frequency at which they shifted their appliances on a six-point scale, ranging from 1 = *never* to 6 = *always*. Means differ at $p < 0.05$

Only one of the values could be reliably related to the attitudes towards the energy services: We found a positive correlation between autarky and the attitude towards the energy services ($r = 0.60$, $p < 0.001$).[1] Apparently, people who value self-sufficiency more, were also more positive about both energy services. Surprisingly, perhaps, is that we did not find a relation between both sustainability and economic gain, and the evaluation of the energy services. We expected to find that people who were strongly motivated by sustainability goals, would be more positive about Sustainable Together, but this relation was not established. Similarly, we did not find a correlation between value attached to economic gain and a more positive attitude towards Smart Cost Savings. Thus, even though some residents expressed their dissatisfaction with Smart Cost Savings before they received the energy services, and the energy service Sustainable Together was more attuned to the values of its users, both services were evaluated similarly. Moreover, in the final test we found a slight preference (just below the $p < 0.05$ threshold of significance) for the energy service Smart Cost Savings.

Interestingly, and consistent with the trend described in the previous paragraph, we noticed that end users who received the energy service Smart Cost Savings tended to manually time shift the onset of their regular appliances more often during the project than end users who received the energy service Sustainable Together. For an example, see Table 3. We also noticed that users of the Smart Cost Savings service looked, on average, one to two times per day at their energy monitor, whereas users of Sustainable Together looked less than one time per day at their energy monitor.

The results of the focus group sessions were consistent with the finding that Smart Cost Savings was evaluated more positively than Sustainable Together. One of the main reasons for the more positive attitude towards Smart Cost Savings was that feedback in euros had been perceived as more tangible than ‘feedback in leaves’, which represented sustainability scores. End users who received Smart Cost Savings also indicated that they felt more actively involved. During the last focus

---

[1] After analyzing the first results, we included some extra measures in the questionnaire to explore the value of autarky (see Kasl et al. 1964; Weinstein et al. 2012). Analysis revealed that autarky was related to the desire to be less dependent on larger energy suppliers and to the desire to be self-sufficient as a household (which was slightly more desirable than being self-sufficient as a community).

group session, two thirds of the participants stated that they would choose for the 'Smart Costs Savings' energy service in future. This, of course, is a surprising result in light of the findings that this group of end users highly valued sustainability, especially the users who received the energy service Sustainable Together.

3.2 Evaluation of Automatic, Smart, and Manual Control

Attitudes towards automatic, smart, and manual control did not differ between users of the two services. Because the smart washing machines had not been installed when the measurements at Time 2 took place, attitudes towards these smart appliances could be assessed only during the final measurement. Similarly to the responses to the energy services, expectations were significantly higher than experiences. For an overview of the results, see Table 4.

Even though end users had a slight preference for automatic control at the start of the project, based on experiences in this pilot they preferred smart control. From the focus groups we learned that end users find automatic and smart control most attractive because it requires the least personal effort. However, end users complained during the first focus group session that they did not always understand the logic behind when these appliances switched on. They expressed their doubts about the functioning of the PowerMatcher and the energy services. Indeed, the project team found some issues with the control mechanism (see Wijbenga et al. 2014), which were solved after the first focus group session. Nevertheless, end users indicated that their trust in the system was violated and they admitted that it was very hard to win it back. This was also the main reason participants preferred smart shifting above automatic shifting: with smart shifting they could always choose to take back control into their own hands and operate the washing machine manually. Consistent with these comments, we noticed that end users with a smart washing machine did not use the smart function most of the time: 88 % of the times the washing machine was used, participants operated it manually. Thus, even though end users preferred automatic and smart control, trust is elementary to acceptance and this was violated in this pilot.

Participants indicated that they would manually shift the timing of the washing machine, dryer, and dishwasher most often ($M = 4.4$, $SD = 1.24$ for the washing

Table 4 Attitudes towards automatic, smart, and manual control

Control	Initial test			Time 2			Final test		
	M	SD	N	M	SD	N	M	SD	N
Automatic	4.9	0.98	36	3.9	1.26	31	3.8^a	1.22	31
Smart	4.7	1.05	36	–	–	–	4.4^b	1.10	31
Manual	4.2	1.12	36	3.5	1.03	31	3.5^a	1.39	32

Note Means that do not share superscripts differ at $p < 0.01$. Again the six (global and specific) attitude items were highly related (Cronbach's alpha for all measures >0.86) and therefore aggregated to a single score machine; $M = 3.0$, $SD = 1.88$ for the dryer; $M = 3.9$, $SD = 1.80$ for the dishwasher, measured on a scale ranging from 1 = *never* to 6 = *always*). End users stated that they would shift rarely or never shift the timing of other appliances. Whereas time shifting appliances manually took relatively more effort than time shifting smart appliances, end users stressed that shifting their demand manually had been most rewarding.

3.3 Energy Monitor

To manually time shift their energy demand, end users had to consult their energy monitor initially. But as time passed, they discovered patterns in the forecasts and did not always have to look at their energy monitor before altering their energy consumption. These (self-)reports were corroborated by the data we retrieved with Google Analytics. The graph displayed in Fig. 5 clearly displays a decline in the number of the 'sessions'. Just after the introduction of the energy services, the forty household together looked at the energy monitor 730 times a week. Within the next month, the number of sessions decreased to 430, and after half a year, the forty households looked at their energy monitor on average 200 times a week.

There was a difference between the two energy services: end users who received Smart Cost Savings looked at their monitor an average of twice a day, whereas end users who received Sustainable Together looked a little less than once a day. Perhaps as a consequence, end users who received Smart Cost Savings indicated they were more aware of their energy consumption and experienced more control over their energy consumption than end users who received Sustainable Together.

3.4 Smart Grid Community

Most of the end users indicated that they had compared their energy usage with other end users, and more than 50 % compared their consumption patterns outside

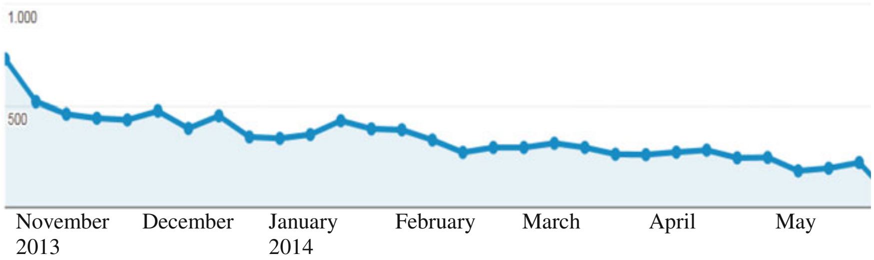


Fig. 5 Number of times the forty households consulted their energy monitor

of the organized sessions. To the question whether they were willing to share their energy data with their neighbours, 87 % indicated that they were willing to share their results. However, end users established three boundary conditions: (1) all data must be shared anonymously, (2) data may only be shared within the project and not with external parties (e.g. an energy supplier), and (3) data sharing is only meaningful when similar households participate in the smart grid.

Concerning their willingness to 'share energy', results of both quantitative and qualitative analysis showed that end users had a strong preference to use energy from their own production first and foremost. Only if they had a surplus of energy would participants agree to have the energy supplied to the community. During a focus group session they expressed their concerns regarding the supply of energy to their neighbours. As one end user put it: "What if my neighbour decides to use my sustainably generated energy for his Jacuzzi?" Trust in the people with whom energy is shared thus seems crucial for establishing an energy community.

4 Summary and Discussion

To summarize, the results of the current research on experiences and behaviours of end users in a smart grid show that end users preferred feedback on costs to feedback on sustainability. End users who received feedback on costs were more actively involved than end users who received feedback on sustainability. This is an interesting result in light of the findings that, compared with regular households, the group under study valued sustainability to a higher extent than economic gain. A possible explanation is that feedback in euros is more tangible than feedback in percentage of energy consumption that is produced locally.

Another interesting result is that end users in this pilot project preferred to use the energy they had produced themselves. This finding is interesting because it may not always be the most efficient strategy, either from a cost perspective or from a sustainability perspective. From a cost perspective, at times it may be better to deliver energy, for example when energy prices are relatively high. Similarly, it may not always be the most sustainable strategy to use your self-generated energy at all times, for example when delivering energy to the community can better balance demand and supply within the community.

The latter case, delivering energy to the community so that the community as a whole operates more sustainably, requires that people have sustainability motives that are not only applied to their own energy consumption, but to the energy consumption of the whole community. This may expose a complex problem, because end users expressed their doubts as to whether the other community members live in a sustainable way. This 'Sustainable Together' perspective requires an orientation that transcends the individual, egotistic perspective and, what is more, also seems to require trust between the community members. Whether these conditions are always present or can be incited within communities is questionable.

The results reported here show that automatic and smart demand side management are more popular, but that manually shifting energy demand is more rewarding. The main reason for the preference of automatic and smart control is that these kinds of control are relatively effortless. A prerequisite for end users concerning remotely controlled automatic appliances is that they have to trust the technology (ICT infrastructure and connected appliances) and the third parties involved. Once this trust has been violated, it is very hard to win it back. The current research involved a complex system in which demand and supply had to be matched in a smart grid with multiple actors involved (e.g., households, energy supplier, grid operator). In a system like this one, complex decisions are made that are not always in the direct interest of one specific end user. This end user, on seeing the results of the decisions on the display, has to trust that the system was well developed and will benefit the community as a whole. Similarly, end users have to trust all parties involved. Especially in the case of for-profit organizations, such as energy suppliers, this may be difficult. We experienced that people were on guard and were quick to ask questions such as "Why is this company involved?", and "How much profit do you make in this situation?".

One important limitation of the described research was its sample size: The small sample size reduced the power of the current quantitative analyses and may have obscured relations in the data. Because we chose a combination of quantitative and qualitative research, interesting findings nevertheless could be reported. In future research, larger sample sizes and a control condition are needed to determine whether the results reported herein can be replicated and consolidated.

We would also encourage further research on trust of end users in smart grids and in the other actors involved (companies, community members). We believe that active engagement of end users, and therefore the success of a smart grid, requires trust both in the system and between the parties involved. We encourage more research on community processes as well. We noticed in the current research that end users were focused primarily on themselves and not so much on the community. Nevertheless, they stated that they value the community and could see that a community may achieve more optimal results. Whether a pro-social/community feeling can be established, and under which conditions, may be addressed in future research.

In conclusion, the current research offers insight into the experiences and behaviours of end users in a smart grid project. Even though the sample size was relatively small, due to the use of different methods interesting findings have been observed. We hope that our research may inspire others to further investigate issues such as requirements of trust in the parties involved and in the community. In order to pave the path towards fully functioning smart grids, not only technical advances, but also behavioural and social changes are needed.

Points for Discussion

- How could smart grid technology be designed in order to help improve trust in the system for users?
- What is the role of expectations in developing trust? What are some of the ways in which expectations can be shaped?
- How can smart grids be implemented in ways that increase trust between actors? How would this differ from the way trust is implemented in the current grid?

Acknowledgments The author would like to thank all residents of PowerMatching City who participated in this research. Also, the author thankfully acknowledges Christian van Someren for his valuable comments and suggestions to improve the quality of this chapter, and Albert van den Noort for providing comments on an earlier version of this chapter. Finally, the author acknowledges the consortium partners DNV GL, Essent, Enexis, Gasunie, ICT Automatisering and TNO. The here reported research was supported by an IPIN subsidy program of the Dutch government.

References

Ajzen, I.: The theory of planned behavior. Organ. Behav. Hum. Decis. Process. **50**, 179–211 (1991)

Darnton, A.: Reference Report: An Overview of Behaviour Change Models and their Uses. GSR Behaviour Change Knowledge Review (2008)

de Groot, J.I.M., Steg, L.: Value orientations to explain beliefs related to environmental significant behavior: how to measure egoistic, altruistic, and biospheric value orientations. Environ. Behav. **40**, 330–354 (2008)

de Groot, J.I.M., Steg, L.: Mean or green: which values can promote stable pro-environmental behavior? Conserv. Lett. **2**, 61–66 (2009)

Goulden, M., Bedwell, B., Rennick-Egglestone, S., Rodden, T., Spence, A.: Smart grids, smart users? The role of the user in demand side management. Energy Res. Soc. Sci. **2**, 21–29 (2014)

Huijts, N.M.A., Molin, E.J.E., Steg, L.: Renew. Sustain. Energy Rev. **16**, 525–531 (2012)

Kasl, S.V., Sampson, E.E., French, J.R.P.: The development of a projective measure of the need for independence: a theoretical statement and some preliminary evidence. J. Pers. **32**, 566–586 (1964)

Kenny, D.A., Kashy, D.A., Cook, W.L.: Dyadic Data Analysis. The Guilford Press, New York (2006)

Maio, G.R.: Mental representations of social values. In: Zanna, M.P. (ed.) Advances in Experimental Social Psychology, vol. 42, pp. 1–43. Academic Press, Burlington (2010)

Nygrén, N.A., Kontio, P., Lyytimäki, J., Varho, V., Tapio, P.: Early adopters boosting the diffusion of sustainable small-scale energy solutions. Renew. Sustain. Energy Rev. **46**, 79–87 (2015)

Schwartz, S.H.: Are there universal aspects in the structure and contents of the human values? J. Soc. Issues **50**, 19–45 (1994)

Siano, P.: Demand response and smart grids: a survey. Renew. Sustain. Energy Rev. **30**, 461–479 (2014)

Stern, P.C.: New environmental theories: toward a coherent theory of environmentally significant behavior. J. Soc. Issues **56**, 407–424 (2000)

Stern, P.C., Dietz, T., Abel, T., Guagnano, G.A., Kalof, L.: A value-belief-norm theory for social movements: the case of environmentalism. Res. Hum. Ecol. **6**, 81–97 (1999)

Weinstein, N., Przybylski, A.K., Ryan, R.M.: The index of autonomous functioning: Development of a scale of human autonomy. J. Res. Pers. **46**, 397–413 (2012)

Wissner, M.: The smart grid: a saucerful of secrets? Appl. Energy **88**, 2509–2518 (2011)

Wijbenga, J.P., MacDougall, P., Kamphuis, R., Sanberg, T., van den Noort, A., Klaassen, E.: Multi-Goal Optimization in PowerMatching City: A Smart Living Lab. Retrieved from file:///C:/Users/Gebruiker/Downloads/wijbenga-2014-multi.pdf

Wolsink, M.: The research agenda on social acceptance of distributed generation in smart grids: renewable as common pool resources. Renew. Sustain. Energy Rev. **16**, 822–835 (2012)