Research Center
Finance & Information Management

Fraunhofer
FIT

Project Group
Business & Information
Systems Engineering

Discussion Paper

Towards a descriptive Framework of Demand Side Flexibility

by

Gilbert Fridgen, Benedict Drasch, Michael Schöpf, Rebecca Trick

April 2016

University of Augsburg, D-86135 Augsburg
Visitors: Universitätsstr. 12, 86159 Augsburg
Phone: +49 821 598-4801 (Fax: -4899)

University of Bayreuth, D-95440 Bayreuth
Visitors: Wittelsbacherring 10, 95444 Bayreuth
Phone: +49 921 55-4710 (Fax: -844710)

WI-559

www.fim-rc.de

Towards a descriptive Framework of Demand Side Flexibility

Abstract

The objective of this paper is to contribute to the understanding of Demand Side Management (DSM) in future energy markets. DSM is considered one of the most promising concepts to meet the challenge of balancing demand and supply in the future power grid. In contrast to traditional electricity systems, where manageable supply is used to ensure grid stability, DSM strives to influence demand in accordance with current electricity production. From a market perspective, this generates a new, turned-around supply chain: While electricity is traded from generation to consumption, demand side flexibility (DSF) is offered by consumers to grid operators. We address the requirement of a theoretical foundation for DSF by conducting the first step towards a descriptive theory to classify different dimensions of DSF. Further, we suggest an overarching, interdisciplinary unification for further research in the topic and enable various research disciplines to join forces on this challenge. The targeted descriptive theory shall be fundamental research on DSM (e.g. electric vehicle charging, flexible industry processes).

Motivation

Over the past decades, the energy system faced a profound transformation as social, environmental, and technical developments challenge existing structures (Coll-Mayor et al. 2007). In common energy systems, the supply chain is typically directed towards the energy customer and is oriented at delivering energy. However, in the past few years, an additional turned-around flow of transaction emerged beside the conventional flow. With an increasing share of automation in electricity distribution grids through Information and Communication Technology (ICT), novel measures to secure energy grid stability become accessible. While the decisive balance in electricity grids is usually secured on the production side (e.g. dispatching generators), the approach of Demand side management (DSM) strives to manage demand to follow current electricity production. DSM is a portfolio of measures, such as smart energy tariffs, sophisticated real-time control, which is directed at improving the energy system at the side of consumption (Palensky, Dietrich 2011). In order to utilize the advantages of DSM, the demanded energy load has to inherent flexibility from the consumer's perspective: This is described as Demand side flexibility (DSF), which is given when the consumer has the ability, the willingness, and the right to adapt the energy consumption. The efficient adaption of energy consumption to balance volatile energy production bears enormous technical and economic potential (e.g., Wissner 2011).

Adapting the demand side is a process that offers a wide variety of starting points (e.g. automated solutions, economic incentives), methods, and stakeholders that have to be considered. As such, many disciplines are currently developing and exploring DSM. Engineering disciplines focus on the structure and control mechanisms for the future energy grid (Tsikalakis, Hatziargyriou 2011). Computer Science focuses on requirements for devices and communication channels to participate in the grid of the future (Niyato et al. 2011). Management Sciences concentrate on valuation mechanisms of measures and pricing structures to manage demand side through incentive structures (Strbac 2008). Social Sciences and Management Science analyze the underlying preference structures in order to inform the development of adequately information systems (cf. e.g. Dütschke, Paetz 2013; Kirschen 2003). Economics focuses on the impacts of DSM on market prices and price volatility (Albadi, El-Saadany 2008; Zhou et al. 2011) as well as on social welfare (Su, Kirschen 2009).

With DSM being developed from several disciplines separately, only partial and narrow aspects of the greater research problem are addressed. Many researchers have focused on single-perspective evaluations of DSM (e.g., from either supply or demand side) and applied a wide range of methods (e.g., case-studies, simulations, empirical analysis). Disparate terminology and concepts, complicate knowledge exchange between disciplines and as such, the development of an integrated and comprehensive theory that spans from technical requirements to management strategies for a successful market integration. To date, interdisciplinary theoretical foundation and a uniform terminology for researchers' communication in the world of DSM is absent. Yet, comprehensive design principles, a uniform terminology, and an integrated theory are eminent for an interdisciplinary, beneficial research success in this area.

Methodology

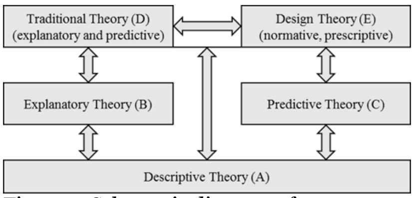

Figure 1: Schematic diagram of interrelationships among theory types (Gregor, 2002)

Research on DSM belongs in the realm of Engineering and IS disciplines. Therefore, we refer to the Design Science research (DSR) paradigm as a well-established standard for knowledge development in both disciplines (cf. e.g. Gregor, Hevner 2013; Hevner et al. 2004; Peffers et al. 2007; Kuechler, Vaishnavi 2008). In future research, we aim at developing a Design Theory that contains design principles for future DSM systems. To build a Design Theory of DSM, five types of theory have to be passed, as described in Gregor's taxonomy (2002) in Figure 1. These five types of theory represent our entire research agenda. The first step to tackle this challenge is developing a Descriptive Theory of DSM. Descriptive Theory aims at naming and classifying a phenomenon (Stevens 1984).

This paper provides the first step towards a comprehensive Descriptive Theory and thus the first step towards a Design Theory on DSM. The focus of this paper is developing a descriptive framework of different demand side flexibilities. The structural dimensions of the proposed framework are derived deductively by using the concept of "7Rs from logistics" (Shapiro and Heskett, 1985) as our kernel theory. We examine the validity of these structural dimensions in the given context by associating them with literature, own observations and by conducting expert interviews.

A descriptive Framework of Demand Side Flexibility

For structuring different dimensions of DSF, we use and adapt the "7R's" from the discipline of supply chain management. The "7R's" are a common concept that entails the success criteria: right customer, right time, right quantity, right quality, right product, right location, at the right price (Shapiro, Heskett 1985). The "7R's" is an applicable categorization framework as energy is a commodity to be delivered to the consumer. We adapt the concept as we make a generalization by using these criteria as degrees of freedom. Consequently, the knowledge contribution of this article comprises the extension of known solutions to new problems, which can be classified as an exaptation in the DSR Knowledge Contribution Framework (Gregor and Hevner 2013).

The concept of "7R's" shapes the core (5) of our descriptive framework which is shown in figure 1. The traditional energy supply chain (1) points from energy production (3) over markets (4) to consumption (6) where it generates output (7), e.g. physical products in the manufacturing industry. DSM adds an additional, turned-around supply chain (2): Flexibility in output (7) generates flexible energy consumption (6) along certain flexibility dimensions (5) that is offered on energy markets (4) to cope with varying energy production (3). The success factors "right customer" and "right price" are captured by the two components "energy markets" and "energy consumption". According to the direction of the considered supply chain, one of the two components represents the customer, while the price is determined by the other component. Due to the high complexity of these component's composition and interrelations, we focus this article on the five factors which represent the actual flexibility dimensions: Time (temporal flexibility), quantity (quantitative flexibility), quality (qualitative flexibility), product (product flexibility) and location (flexibility of location).

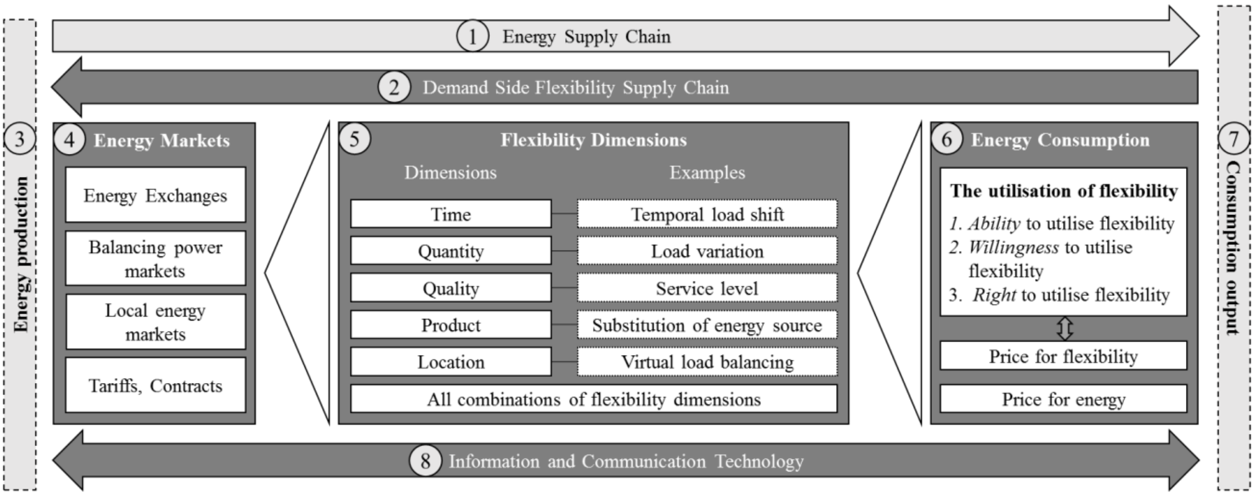

Figure 2: The five dimensions of Demand Side Flexibility in the center of the energy supply chain

We interpret *temporal flexibility* as the flexibility to shift a scheduled load to a later or earlier point in time. For many technical applications, the load can be shifted in time depending on current and expected electricity prices. From a demand perspective, the utilization of temporal flexibility can be offered as balancing power, used to bridge high electricity prices (decrease), or to exploit negative prices (increase). A simple example of providing such temporal flexibility is the use of plug-in electric vehicles. Instead of charging them as soon as they are plugged in, there is the possibility to charge them when prices are low or defer loading when prices are high (He et al. 2012; Kang et al. 2013; Fridgen et al. 2014; Fridgen et al. 2016). In order to clearly distinguish temporal flexibility from the other dimensions, we appoint that temporal flexibility only changes the temporal consumption pattern, while the overall amount of consumed energy remains steady.

We interpret *quantitative flexibility* as the flexibility to increase or decrease the overall amount of consumed electricity. In contrast to temporal flexibility, an increase (decrease) of consumed energy at one point in time does not imply a decrease (increase) of the same amount at another point in time. Quantitative flexibility is utilizable in balancing and spot markets and therefore, comprises an immense impact on the electricity grid. Quantitative flexibility can be utilized for instance by an overall reduction (increase) of production output in case of undersupply (oversupply). Nevertheless, this setting can be difficult in situations where employees (e.g. working hours) or contract fulfillment are affected. Increasing overall consumption can be e.g. offered as an emergency measure that "burns" electricity in times of oversupply (e.g. immersion heaters). This direction of quantitative flexibility is established on balancing power markets but not very desirable from the perspective of total energy use, as it often comes with an inefficient use of electricity or energy in general. A special setting of quantitative flexibility has been examined for instance in the case of "energy disposal when prices are negative (Huntowski et al. 2012; Zhou et al. 2016).

The dimension of *qualitative flexibility* can be interpreted in various ways: From a technical perspective, the quality of energy can be associated with certain attributes of the energy carrier, like the maximum available currency or voltage and frequency deviations in the case of electricity. A different perspective on quality refers to the energy service-level, which describes the percentage of time in which the availability of energy supply is guaranteed. We focus our research on the latter perspective, as it offers an interesting approach to incentive consumers to invest in their own energy storage facilities and is thus an appealing economic decision. Within this perspective, qualitative flexibility means to differentiate among the service level for different consumers, which allows spontaneous electricity cut-offs. Measures of Direct Load Control (DLC) are examples of qualitative flexibility. By such measures, an energy consumer grants the permission of controlling certain appliances to an intermediary. One use-case for DLC is the centralized dispatching of air conditioners by the grid operator in order to increase grid stability which has been examined for instance by Wei and Chen (1995). In delimitation towards quantitative flexibility, the dimension of qualitative flexibility refers to the unpredictability of electricity cutoffs and does not make a statement about the overall energy amount which is consumed.

We interpret *product flexibility* as the flexibility to dynamically decide on the energy carrier used (e.g. between electricity and gas). Hence, product flexibility depicts the satisfaction of energy demand using more than one energy carrier. As a result, product flexibility makes a monetarization of price differences for dissimilar energy carriers possible. To utilize this potential, a dynamic decision about the employed energy carrier is required. This decision is mainly influenced by energy prices and their expected developments, as well as energy carrier shortages and efficiencies. In this dimension, technical infrastructure is necessary to enable the interchangeability of energy carriers during the application. This infrastructure encompasses the functional components which have to be redundant for an interchangeability (e.g. one electric and one gas heater). The value of using the flexibility to switch between two different energy carriers has been examined first for the energy carriers of oil a gas by Kulatilaka 1993. Over the last years, the usage of electricity as an alternative energy carrier for heating purposes (Power-to-Heat) has gained attraction in research, since price fluctuations increased and negative prices appeared more frequently (Böttger et al. (2014); Böttger et al. (2015); Ehrlich et al. (2015)).We interpret *flexibility of location* as the flexibility to shift the electricity demand between locations, i.e. to spatially shift load. Independently considered, the overall energy demand for a certain task remains constant, but the load becomes spread over more than one consumption site. By shifting load over grid delimitations or even across national borders, it is possible to arbitrage different energy markets. In contrast to temporal load shifting (e.g. right time), flexibility is restricted to industries in which the electricity demand is not assigned to a certain location. Therefore, this dimension of flexibility is very rare, as it requires very complex coordination and necessary infrastructure. Presumably, only information goods and services perfectly fulfill that requirement. For example, in the area of service provision through cloud computing, an operation of two geographically distributed data centers enables the opportunity to dispatching incoming workload to the data center with lower energy prices (Chiu et al. 2012; Rao et al. 2012; Wang et al. 2014; Fridgen et al. 2015). For the consumer, it is necessary to install the required dispatching capacity at various locations. From a research perspective, flexibility of location enables new paths of shifting loads across regions, and therefore, an alternative to importing and exporting electricity or the construction of power lines. Thus, there is a need for the development of methods to assess the value of that flexibility dimension, which is very complex due to the high variety of different market structures in different locations. Generally, flexibility of location is becoming increasingly important, as tasks are becoming geographically more independent and as physical goods can increasingly be encompassed by information.

The five dimensions of DSF can occur alone or in combination with other flexibility dimensions. For five dimensions, we already get 31 different compositions of DSF. In addition, considering the ability to provide a single dimension of DSF with several different measures, shapes a nearly infinite number of possible outcomes that have to be valuated and rated against each other in future research.

Conclusion, Limitations and Further Research

Our energy system will be subject to major changes in the upcoming years. To date, research disciplines have not addressed the core of this challenge and lack interdisciplinary structures as well as understanding. In this work, we described the emergence of a turned-around value chain and the necessity to allocate and market DSM in future energy systems. As the exchange of information and associated ICT gain a key role, the IS discipline can significantly contribute to solve the challenges of the future. In order to reach the overarching goal of a design theory for DSM, our framework of DSF provides the first step towards the understanding of the field. Following papers shall further emphasize on the consolidation of existing research that can serve as a specification of DSM approaches (Descriptive Theory). Applying this knowledge, the mechanisms of DSM in a sociotechnical system need to be explained, the most successful approaches of DSM need to be identified, and DSF and its constraints need to be described (Explanatory and Predictive Theory). Subsequently, the coherent body of knowledge needs to be formalized (Design Theory) and evaluated.

In addition to the contribution and the impact provided by this paper, next steps need to address the following topics: First, although the framework has already been evaluated through few expert interviews, it needs an additional foundation in literature and a broader set of interviewees. Second, the suggested framework depicts only a brief – but initial – approach to unify research in this field, to harmonize existing concepts and different terminologies. This endeavor needs to be expanded across disciplines. Third, new market instruments, products, and incentive schemes that foster DSM need to be evaluated to help and shape the energy market of the future. And fourth, especially for IS disciplines, the application and-utilization of information systems to enable reliable, secure, efficient, and transparent solutions for the energy system of the future need to be addressed.

Existing research on DSM mostly considers purely technical or purely economic aspects of DSM. Our approach shall be interdisciplinary by design. It shall offer a comprehensive overview, clarification and classification of different concepts on DSM that currently exist. So far, there are a wide variety of different starting points and methods that evolved in various disciplines in parallel. Existing research on DSM is mostly focused on single dimensions of DSF or single electricity markets. Our Design

Theory shall consider all dimensions of DSF and all markets. Therefore, it needs to cope with the enormous complexity which is inherent to the combination of the different flexibility dimensions, the various markets and the high variety of consumers. It shall help all disciplines to apply DSM in research. Derived design principles shall help catalyze future research on specific issues and thus help the energy transition become a success.

Publication bibliography

Albadi, M. H.; El-Saadany, E. F. (2008): A Summary of Demand Response in Electricity Markets. In *Electric Power Systems Research* 78 (11), pp. 1989–1996. DOI: 10.1016/j.epsr.2008.04.002.

Böttger, Diana; Götz, Mario; Lehr, Nelly; Kondziella, Hendrik; Bruckner, Thomas (2014): Potential of the power-to-heat technology in district heating grids in Germany. In *Energy Procedia* 46, pp. 246–253.

Böttger, Diana; Götz, Mario; Theofilidi, Myrto; Bruckner, Thomas (2015): Control power provision with power-to-heat plants in systems with high shares of renewable energy sources–An illustrative analysis for Germany based on the use of electric boilers in district heating grids. In *Energy* 82, pp. 157–167.

Chiu, D., Stewart, C., & McManus, B. (2012). Electric grid balancing through lowcost workload migration. *ACM SIGMETRICS Performance Evaluation Review*, *40*(3), 48–52. doi:10.1145/2425248.2425259

Coll-Mayor, Debora; Paget, Mia; Lightner, Eric (2007): Future Intelligent Power Grids. Analysis of the vision in the European Union and the United States. In *Energy Policy* 35 (4), pp. 2453–2465. DOI: 10.1016/j.enpol.2006.09.001.

Dütschke, Elisabeth; Paetz, Alexandra-Gwyn (2013): Dynamic Electricity Pricing - Which Programs do Consumers Prefer? In *Energy Policy* 59, pp. 226–234. DOI: 10.1016/j.enpol.2013.03.025.

Ehrlich, Lars G.; Klamka, Jonas; Wolf, André (2015): The potential of decentralized power-to-heat as a flexibility option for the german electricity system: A microeconomic perspective. In *Energy Policy* 87, pp. 417–428.

Fridgen, Gilbert; Häfner, Lukas; König, Christian; Sachs, Thomas (2016): Providing Utility to Utilities: The Value of Information Systems Enabled Flexibility in Electricity Consumption. In *Forthcoming in Journal of the Association of Information Systems*.

Fridgen, Gilbert; Keller, Robert; Thimmel, Markus; Wederhake, Lars (2015): Virtualizing Balancing Power: An Energy-Aware Load Dispatcher for Cloud Computing. In *Presented at Energy Informatics & Management, Rotterdam, Netherlands*.

Fridgen, Gilbert; Mette, Philipp; Thimmel, Markus (2014): The Value of Information Exchange in Electric Vehicle Charging. In *In Proceedings of the 35th International Conference on Information System (ICIS), Auckland, New Zealand*. Available online at http://aisel.aisnet.org/icis2014/proceedings/ConferenceTheme/4.

Gregor, Shirley (2002): Design Theory in Information Systems. In *AJIS* 10 (1). DOI: 10.3127/ajis.v10i1.439.

Gregor, Shirley; Hevner, Alan R. (2013): Positioning and Presenting Design Science Research for Maximum Impact. In *Management Information Systems Quarterly* 37 (2), pp. 337–356.

He, Yingfeng; Venkatesh Bala; Guan, Ling (2012): Optimal Scheduling for Charging and Discharging of Electric Vehicles," in *IEEE Transactions on Smart Grid*, 3 (3), pp. 1095-1105, DOI: 10.1109/TSG.2011.2173507

Hevner, Alan R.; March, Salvatore T.; Park, Jinsoo; Ram, Sudha (2004): Design Science in Information Systems Research. In *Management Information Systems Quarterly* 28 (1), pp. 75–105.

Huntowski F, Patterson A, Schnitzer M (2012) Negative electricity prices and the production tax credit: Why wind producers can pay us to take their power and why that is a bad thing. Technical report, The NorthBridge Group, Concord, MA.

Kang, Joosung ; Duncan, Scott J; Mavris, Dimitri N (2013).: Real-time Scheduling Techniques for Electric Vehicle Charging in Support of Frequency Regulation. In: *Procedia Computer Science* 16, pp. 767-775, ISSN 1877-0509, http://dx.doi.org/10.1016/j.procs.2013.01.080.

Kirschen, D. S. (2003): Demand-Side View of Electricity Markets. In *IEEE Trans. Power Syst.* 18 (2), pp. 520–527. DOI: 10.1109/TPWRS.2003.810692.

Kuechler, W; Vaishnavi, V (2008): The Emergence of Design Science Research in Information Systems in North America. In *Journal of Design Research* 7 (1), pp. 1–16.

Niyato, Dusit; Lu Xiao; Ping Wang (2011): Machine-to-Machine Communications for Home Energy Management System in Smart Grid. In *IEEE Commun. Mag.* 49 (4), pp. 53–59. DOI: 10.1109/MCOM.2011.5741146.

Palensky, Peter; Dietrich, Dietmar (2011): Demand Side Management. Demand Response, Intelligent Energy Systems, and Smart Loads. In *IEEE Trans. Ind. Inf.* 7 (3), pp. 381–388. DOI: 10.1109/TII.2011.2158841.

Peffers, Ken; Tuunanen, Tuure; Rothenberger, Marcus A.; Chatterjee, Samir (2007): A Design Science Research Methodology for Information Systems Research. In *Journal of Management Information Systems* 24 (3), pp. 45–77. DOI: 10.2753/MIS0742-1222240302.

Rao, L., Liu, X., Xie, L., & Liu, W. (2012). Coordinated Energy Cost Management of Distributed Internet Data Centers in Smart Grid. *IEEE Transactions on Smart Grid*, *3*(1), 50–58. doi:10.1109/TSG.2011.2170100

Shapiro, Roy D.; Heskett, James L. (1985): Logistics strategy. Cases and concepts. St. Paul, MN: West Publishing Company.

Stevens, B.J. (1984): Nursing theory. Analysis, application, evaluation, (2nd ed.). Boston: Little, Brown.

Strbac, Goran (2008): Demand Side Management. Benefits and challenges. In *Energy Policy* 36 (12), pp. 4419–4426. DOI: 10.1016/j.enpol.2008.09.030.

Su, Chua-Liang; Kirschen, D. (2009): Quantifying the Effect of Demand Response on Electricity Markets. In *IEEE Trans. Power Syst.* 24 (3), pp. 1199–1207. DOI: 10.1109/TPWRS.2009.2023259.

Tsikalakis, Antonis G.; Hatziargyriou, Nikos D. (2011): Centralized Control for Optimizing Microgrids Operation. In *IEEE Power and Energy Society General Meeting*, pp. 1–8. DOI: 10.1109/PES.2011.6039737.

Wang, H., Huang, J., Lin, X., & Mohsenian-Rad, H. (2014). Exploring smart grid and data center interactions for electric power load balancing. *ACM SIGMETRICS Performance Evaluation Review*, *41*(3), 89–94. doi:10.1145/2567529.2567556

Wei, Deh-Chang; Chen, Nanming: Air conditioner direct load control by multi-pass dynamic programming. In *IEEE Transactions on Power Systems* 10 (1), pp. 307–313.

Wissner, Matthias (2011): The Smart Grid – A saucerful of secrets? In *Applied Energy* 88 (7), pp. 2509–2518. DOI: 10.1016/j.apenergy.2011.01.042.

Zhou, Zhi; Zhao, Fei; Wang, Jianhui (2011): Agent-Based Electricity Market Simulation With Demand Response From Commercial Buildings. In *IEEE Trans. Smart Grid* 2 (4), pp. 580–588. DOI: 10.1109/TSG.2011.2168244.

Zhou, Yangfang (Helen); Scheller-Wolf, Alan; Secomandi, Nicola; Smith, Stephen (2016) Electricity Trading and Negative Prices: Storage vs. Disposal. *Management Science* 62(3): pp. 880–898.