Potentials of energy informatics to incentivize flexibility in the energy system in a short- and long-term perspective

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“Technological possibilities are irresistible to man. If man can go to the moon, he will. If he can control the climate, he will.”

John von Neumann

Abstract

To mitigate climate change, international agreements aim on decarbonization of energy supply. With electricity as pioneering energy sector, a promising option for the future decarbonized electricity system are renewable energy sources (RES), especially wind power and photovoltaics. Due to the weather-dependent, volatile feed-in of these energy sources, flexibility options are necessary to guarantee a stable electricity supply in the future, which includes flexible electricity supply, energy storage, flexible loads and electricity grid expansion. Insufficient and uncertain incentives for investments in liberalized electricity systems nevertheless impede the necessary expansion of these flexibility options. Thus, the aim of this doctoral thesis is to analyze different influencing factors on economic incentives for flexibility options and how information and communication technology, as well as information systems can improve these incentives. In six research articles, which provide deeper insights, an analysis is made which incentives are given by the regulatory framework and where information systems (IS) and information and communication technology (ICT) can act as a catalyst to improve market-based incentives for flexibility investments. The thesis illustrates various cases for IS and ICT enabled advantages by on different abstraction levels and highlights the importance of interdisciplinary cooperation in the domain of flexibility investment incentives.

Copyright Statement

The following sections are partly comprised of content taken from the research articles included in this thesis. To improve the readability of the text, I omit the standard labeling of these citations.

Oktober 2019 *Michael Schöpf*

TABLE OF CONTENTS

TABLE OF CONTENTS VI

LIST OF FIGURES VIII

I. Introduction 9

I.1 Motivation 9

I.2 Research aim 11

I.3 Structure of the thesis 13

II. Theoretical background and contribution 16

II.1 Terminology 16

II.2 A transaction cost approach to assess the structural impact of IS and ICT 17

II.3 The research discipline energy informatics 20

II.4 Contribution of this thesis 21

III. Long-term incentives for flexibility investments in the electricity system 24

III.1 European and national goals in the electricity sector 24

III.2 Electricity market design choices to enable a high share of RES 25

III.3 Incentives for flexibility investments in the long-term perspective 27

III.4 Potentials of energy informatics to improve long-term incentives for flexibility 28

IV. Short-term incentives for the flexibility commitment in the electricity system 31

IV.1 Remuneration mechanisms for flexibility commitment 31

IV.2 Improved incentives for flexibility by better matching of power market products 33

IV.3 Influencing factors on provided flexibility in the case of industrial demand response 34

IV.4 The potential of energy informatics to improve short term incentives for flexibility 35

V. Enhancing flexibility for the electricity system by a broader, cross-sectoral perspective on energy 37

VI. Conclusion 38

VI.1 Contribution, Limitations and Outlook 38

VI.2 Acknowledgement of previous work 41

VII. References 42

VIII. Appendix A: Extended abstracts of the research articles 56

VIII.1 Research article 1: From Energy Legislation to Investment Determination: Shaping Future Electricity Markets with Different Flexibility Options 56

VIII.2 Research article 2: Risk Mitigation Capability of Flexibility Performance Contracts for Demand Response in Electricity Systems 59

VIII.3 Research article 3: The search for the perfect match: Aligning power market products to the energy transition 62

VIII.4 Research article 4: The Impact of Substituting Production Technologies on the Economic Demand Response Potential in Industrial Processes 65

VIII.5 Research article 5: Don't lose sight of the big picture: A holistic view on sector coupling 68

LIST OF FIGURES

Figure 1: Exemplary interrelations between societal goals, political goals, technological potential and relevance of flexibility options. Source: own representation..........12

Figure 2: Structure of this thesis. Source: own representation 14

Figure 3: Scope of this thesis in a six-level model of the energy system. Source: own representation. 22

Figure 4: Flexibility remuneration potentials for the German case. Source: own representation 32

I. Introduction

I.1 Motivation

Climate change is seen as a fundamental threat to the continued existence of human civilization (Ehrlich and Ehrlich 2013). The increase in global temperature can trigger self-reinforcing feedbacks, which push the earth system towards a planetary threshold that shift the earth's climate to an unstable state with continued warming called as "Hothouse Earth". This would cause serious disruptions to ecosystems, society, and economies (Steffen et al. 2018). Therefore, increased efforts are necessary to keep global temperature below the critical level. Well-known are the decisions from the United Nations Climate Change Conference in Paris 2015, with the goal of keeping (Ehrlich and Ehrlich 2013) global temperature increase well below 2°C (above pre-industrial-level) and to pursue efforts to limit the increase even below 1.5°C (United Nations 2015). This decision was confirmed by the Climate Change Conference in Katowice three years later (United Nations 2018). To reach these goals, global decarbonization of energy supply is necessary. This requires a shift towards non-fossil technologies which implies a large scale implementation of renewable energy sources (RES), nuclear power, carbon capture and storage (CCS) (Zappa et al. 2019). The safety of nuclear energy and technological reliability, as well as the social acceptance of CCS, are queried (Akashi et al. 2014). As a result, many countries focus on RES to reach their decarbonization targets (Zappa et al. 2019).

The decarbonization of the electricity sector is seen as the first step towards a comprehensive transformation of the electricity sector (Rogelj et al. 2015). Therefore, a large share of electricity will be generated by the variable RES wind and photovoltaics (Ueckerdt et al. 2015). As the electricity generation of both technologies depends on weather conditions, electricity grid feed-in will increasingly decentral and underlie intermittency and uncertainty (Nazir et al. 2014). This induces two major transformations in the electricity system. The first transformation refers to the necessary balancing of electricity supply and demand, the second to organization and information exchange within the electricity grid.

The electricity system needs a balance between supply and demand at any time to function faultlessly. To ensure this balance in times of increasing and intermittent feed-in, the power system needs flexibility (Cruz et al. 2018; Papaefthymiou et al. 2018). Various definitions for flexibility in the context of the electricity system exist on different levels of abstraction: (CEN-CENELEC-ETSI Smart Grid Coordination Group 2012) define flexibility " [...] as a "general" concept of elasticity of resource deployment providing ancillary services for the grid stability and/or market optimization". (Zhao et al. 2015) provide a framework for defining and especially measuring flexibility by determining flexibility by the four dimensions time, actions, uncertainty and costs. Thereby, they describe flexibility as "the ability of a system to respond to a range of uncertain future states by taking an alternative course of action within acceptable cost threshold and time window" and by being a "[...] inherent property of a system [...]". A more technical and descriptive definition is given by (Mohandes et al. 2019) who describe the three characteristics of flexibility as ramping limit, power capacity and energy capacity. These definitions already illustrate the different dimensions and perspectives on power-system related flexibility. In the following, this thesis distinguishes between flexibility options, which describe different technical approaches to provide flexibility to the electricity grid and in flexibility assets, which are a specific instantiations of flexibility options. Flexibility options can be categorized into demand-side, supply-side, network-side and other sources of flexibility options, especially energy storage systems (Cruz et al. 2018). As (Lund et al. 2015) or (Papaefthymiou et al. 2018) use slightly different categories for arranging the different options (e.g. different role of electricity markets, definition of power-to-gas as own flexibility options) and yet there is no consistent categorization. In the following, four main technical flexibility options will be distinguished: Demand side flexibility, supply side flexibility, storage flexibility and grid flexibility. It is possible to summarize all other flexibility options discussed in literature under at least one of these four categories and therefore they do not need separate consideration. Regardless of each flexibility option's role, the required flexibility will rise with increasing RES and decreasing fossil power plants as the "traditional" source of flexibility, which results in an increasing "flexibility gap" (Papaefthymiou et al. 2018).

The second major transformation stems from the increasingly decentral electricity generation: Traditionally, different large power plants were classified according to their ability to adjust their power supply into base-, intermediate- and peak load power plants (Diesendorf 2010). The behavior of the power consumers was estimated on the basis of load models and daily load profiles, which allowed a good prediction of the power situation in the grid and the corresponding operation of the power plants (McLoughlin et al. 2015; Milanovic et al. 2012). With growing RES share, feed-in increasingly stems from small decentral RES power plants, which are typically connected to low voltage level distribution grids. Thus, the traditional top-down oriented electricity flow from few large power plants connected to the transmission grids down to individual consumers via distribution grids dissolves and will turn opposite (Slootweg et al. 2011). Consequently, both electricity grids and information exchange in the electricity system face new challenges. To address these challenges, the term "Smart Grid" has been established in electricity system research. It has the core idea of converging "the actual electrical power infrastructure (Energy) with the telecommunications (Telecom) and information technology (IT) sectors in order to create a more aware and intelligent electrical power system" (Slootweg et al. 2011). This idea also entails the concept of intelligence, which allows the shift from mostly manual control of electrical grids towards a highly automated control of loads and a grid integration of energy storage devices (Slootweg et al. 2011).

I.2 Research aim

Combining both developments, the smart grid may therefore serve as the technical backbone which orchestrates the RES feed-in and the four different flexibility options. Despite the promising technical benefits of a smart grid – that are e.g. described by (Hu et al. 2014) – the viability of this concept within liberalized electricity systems is still challenging, as the smart grid benefits might not directly translate into a private business case (Lunde et al. 2016). This statement of (Lunde et al. 2016) offers a good indication about the difficulties in a liberalized electricity system, as incentives for investments in the flexibility assets for smart grid infrastructure and flexibility options are insufficient or uncertain in many national electricity systems (Alcázar-Ortega et al. 2015; Paterakis et al. 2017).

One reason for this uncertainty is, that electricity systems are designed in alignment with the political goals in an energy system and are therefore subject to change. These goals may for instance consist of the factors sustainability, energy security and economic efficiency, with different weightings or additional factors, dependent on the specific design of national energy systems. Political goals in turn both depend on societal goals as well as on different technologies and their respective potential. As a result, political goals, societal goals, incentives for flexibility options and the uncertain potential of technologies influence each other (see figure 1). The integration of RES intensifies interdependencies between such technical and institutional elements (Verzijlbergh et al. 2017).

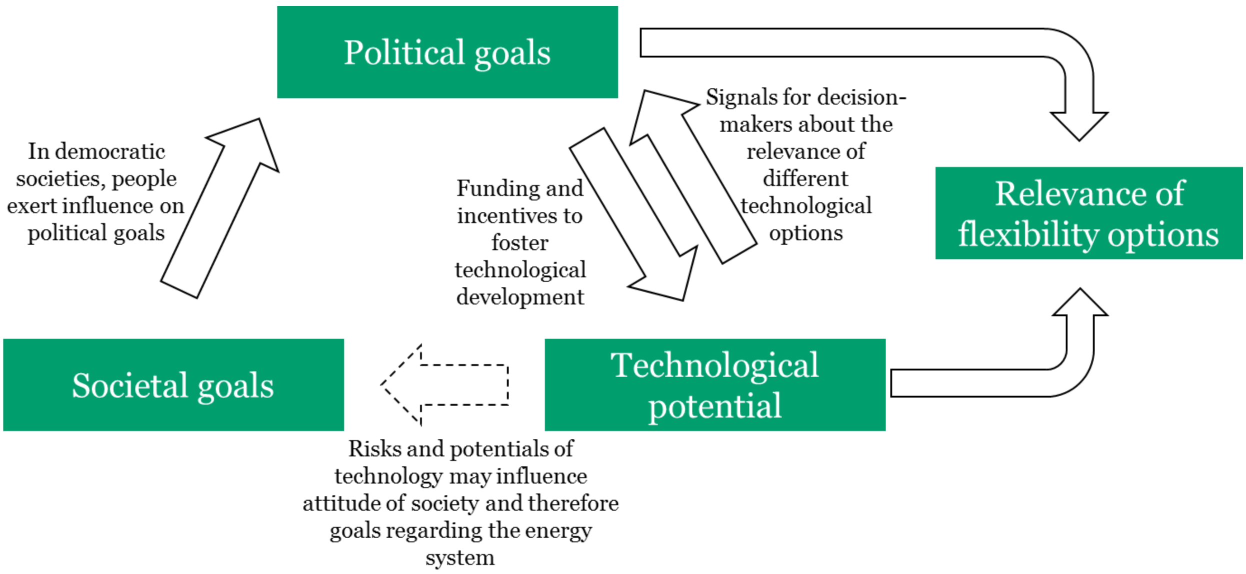

Figure 1: Exemplary interrelations between societal goals, political goals, technological potential and relevance of flexibility options. Source: own representation

Therefore, an isolated consideration of each factor would fall short of designing an energy system that fulfills underlying goals at the best. To make an approach towards a more comprehensive and coherent perspective on the interplay of the different components, this thesis analyzes how the economic viability of different flexibility options for the electricity system is influenced by different exogenous aspects that are not specific to the technology of the flexibility option itself. This includes economic, technological and regulatory aspects. Attractive economic incentives within the regulatory framework are the prerequisite for the widespread diffusion of flexibility options. Information system (IS) and information and communication technology (ICT) have an outstanding influence on technological development (Heeks 2010).

While the term ICT refers to technological goods, which process, transmit and display information electronically (Ruddock 2006; OECD 2015), IS research has a broader focus, by examining phenomena that emerge when such technological systems interact with social systems (Lee 2001; Gregor 2006).

Therefore, this thesis puts a special focus on economic incentives for flexibility options and how IS and ICT can improve these incentives. First, IS and ICT may serve as enablers that mitigate the implementation of technologies, e.g. by reducing planning costs. In this context, IS and ICT act as a catalyst for different flexibility options. Second, IS and ICT may change the "merit order" of flexibilities from resource incentive flexibility options like grid expansion and storages to information-intensive flexibility options like demand response. IS and ICT may serve as a "disruptive" technology that influence the structure and even the goals of the energy system. Facing these two kinds of impacts, a differentiation of short- and long-term perspective helps to structure different potentials of IS and ICT on flexibility incentives over different levels of policy, market design and techno-economic feasibility.

I.3 Structure of the thesis

The two perspectives for analyzing the potentials of information systems to incentivize flexibility options on the energy system are reflected in the structure of this doctoral thesis that is described in the following subchapter. This doctoral thesis is cumulative and refers to five research articles. The document at hand refers to these research articles in the different subchapters but does not contain them in full length. Instead, it provides a coherent analysis of the influence of IS and ICT on incentives for investments in flexibility options. Therefore, the document at hand puts an increased focus on the presentation of interrelations, while the five research papers give detailed information. Figure 2 gives an overview of the order of the corresponding research articles and illustrates the embedment in the chapters of this thesis. Appendix A contains the extended abstracts of the research articles.

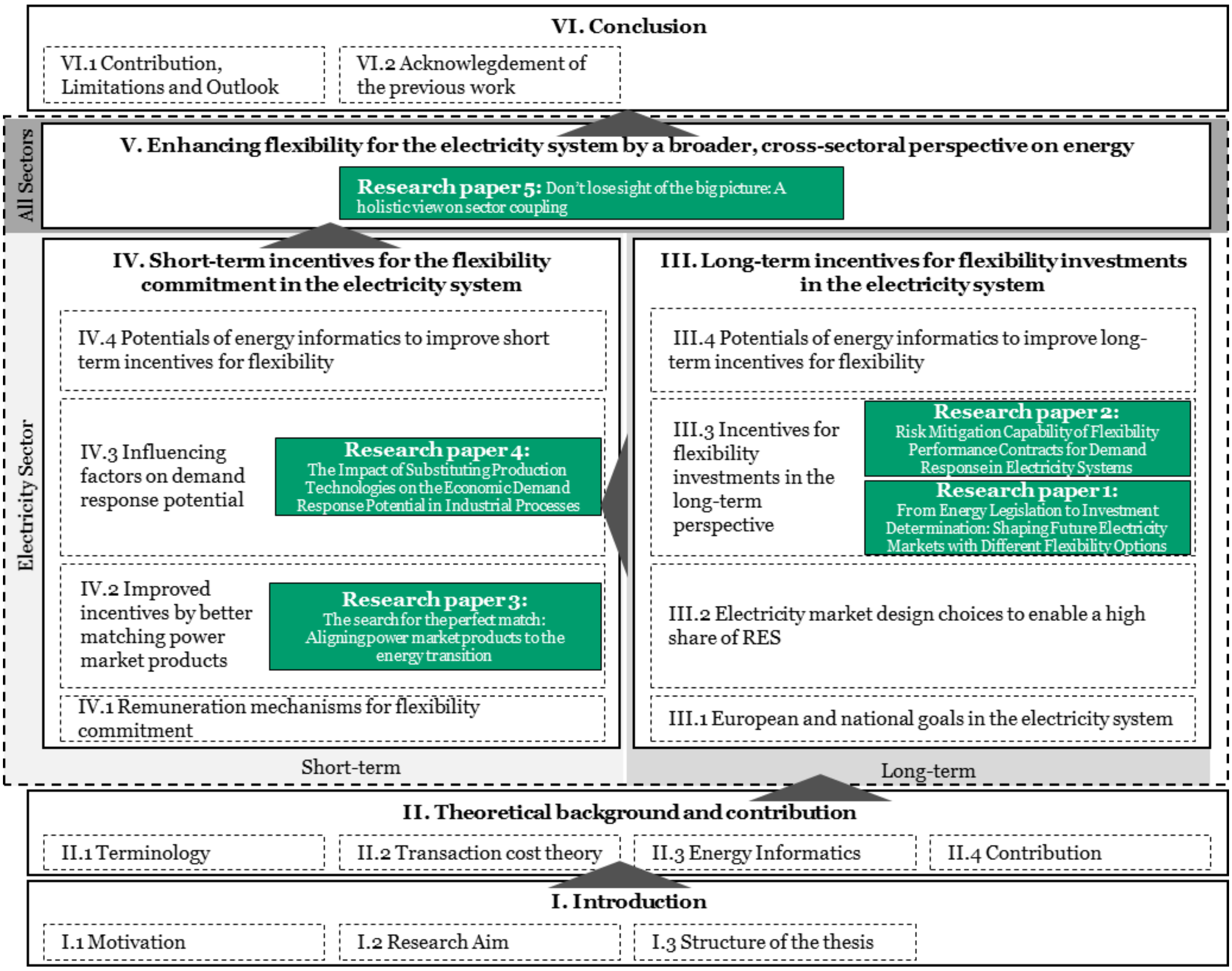

Figure 2: Structure of this thesis. Source: own representation

Chapter II elaborates on the theoretical foundation of energy informatics potentials based on the transaction cost theory, as well as on the specific contribution of this thesis in this research domain.

Chapter III then describes the long-term perspective on promoting flexibility options by analyzing incentives for flexibility in the energy system on different levels and by presenting possibilities to strengthen market incentives. The chapter provides a summary of goals and requirements regarding the energy transition as well as the existing regulatory framework for fostering flexibility options on a European and national level. Due to the prevailing uncertainty regarding the future design of the energy system, regulatory interventions and subsidies are necessary to initiate the expansion of flexibility options. Nevertheless, to pursue a more market-based approach in the future, chapter III presents another approach for uncertainty reduction and concludes by analyzing which role IS and ICT play in these specific domains.

Chapter IV then structures the potentials of IS and ICT to support flexibility options in the short-term. The more short-term decisions are, the higher the role of ICT in comparison to IS for flexibility support is. After giving an overview of existing remuneration mechanisms for flexibility options, the thesis describes options for power market redesign to support the expansion of flexibility options using the possibilities of ICT. This chapter also puts a special focus on demand response as information intensive flexibility option with corresponding influence factors. This case also illustrates the need for the exploitation of automation, optimization and integration.

To tackle the energy transition also in other sectors apart from the electricity sector, chapter V gives an outlook on the cross-sectoral flexibility opportunities which may be enabled by IS and ICT and how they can contribute to leveling temporal and spatial imbalances in energy demand and energy supply, efficiently. Chapter VI concludes this thesis by summarizing the key findings from the previous sections before identifying limitations and giving an outlook on future research.

II. Theoretical background and contribution

II.1 Terminology

The following chapter gives a brief presentation of the generic theoretic fundaments of information systems in order to be able to better assess the potential benefits for the specific domain of energy systems. Building on that, the established research stream of energy informatics is presented, followed by a description of the specific contribution of this thesis within this domain.

The term *information system* has been existing for several decades and the corresponding research discipline had its origins in a variety of different reference disciplines with distinct theoretical research perspectives (Kaplan and Duchon 1988). Allen Lee describes information systems as a research field that "[…] examines more than just the technological system, or just the social system, or even the two side by side; in addition, it investigates the phenomena that emerge when the two interact" (Lee 2001). Coming from that background, information systems research goes far beyond the field of information technology and consists of "interrelated components working together to collect, process, store, and disseminate information to support decision making, coordination, control, analysis, and visualization in an organization" (Laudon and Traver 1994). During the last decades, the role of information systems within an organization has shifted from being "relegated in the back office" towards being "concern of every manager in the organization" (Brancheau and Wetherbe 1987) and fulfill the purpose of improving the effectiveness and efficiency of that organization" (Hevner et al. 2004). The presented perceptions of information systems by Laudon, Brancheau and Hevner all target an individual organization's perspective on information systems.

With organizational goals as one purpose of information systems, impacts of information systems strategy have widely been investigated on the fundament of well-established economic theories for individual organizations and organizational strategy. More thoroughly, most effects are associated with the improvement of advanced information and communication technology (ICT) (or simply information technology (IT), the term ICT includes IT in the following) as the technological enabler of IS. The cost-saving potential of IT through mechanization of data processing activities has accelerated the adoption of IT and IS in the early second half of the 20th century

(Kriebel 1968). An increase in data quality, information quality and therefore knowledge can contribute to an improved decision making and improved management of processes (Kriebel 1968). This again may influence the physical environment.

II.2 A transaction cost approach to assess the structural impact of IS and ICT

The raised efficiencies enabled by the automated data processing opportunities of IT and the better availability of information by IS reduce the transaction costs within an organization but also across organizations. This transaction cost theoretic approach is common in the existing literature to describe the possible impacts of information systems.

The transaction cost model analyzes the increase of required resources for economic exchange between at least two individual participants when certain imperfections appear (Cordella 2006). Inefficiencies and imperfections in the organization of transactions, also denoted as *market failures*, are the result of information- and behavioral-related problems, with these imperfections defining the complexity of the transaction (Ciborra 1983). Economic agents invest in resources to mitigate the effects of these imperfections in the execution of the exchange. These investments are the costs associated with the transactions, the so-called transaction costs. Structured according to the phases of a transaction life cycle, one may distinguish search costs, negotiation costs and enforcement costs (Reed 1973; Cordella 2006). From an information-oriented perspective, transaction costs for a specific exchange can be captured by a function of the constructs *coordination costs, bounded rationality, information asymmetry, opportunistic behavior, asset specificity, complexity and uncertainty* (Cordella 2006). The first six constructs can be found as factors (partially under a different denomination) in the early publications of (Williamson 1973) and (Williamson 1975) who provide a corresponding definition. In a later publication the notion of variations in asset specificity as the principal factors for transaction cost differs among transactions (Riordan and Williamson 1985).

In the sense of the transaction theory, the necessary information for assessing an exchange's equity is a critical prerequisite for a successful transaction (Cordella 2006). With increasing costs for assuring the necessary information, the option of re-organizing the exchange process (i.e. the transaction) within a structure that more adequately addresses uncertainty and information asymmetry becomes more advantageous for all the involved parties (Cordella 2006). The organization of the transaction always ranges within a spectrum between the two antipodes of market and hierarchic coordination. In the logic of market coordination, transactions materialize between different individuals and firms as a result of supply and demand forces for a product with a certain design, price, quantity and target delivery schedule (Malone et al. 1987). The extreme case of pure market coordination (decentralized market) amounts in an entire dissolution of organizations, as all transactions are fulfilled by individuals on market-based mechanisms (e.g. peer-to-peer trading). Hierarchic coordination, on the other side, describes the logic of coordinating material flow by adjacent steps by controlling and directing it at a higher level in the managerial hierarchy (Malone et al. 1987). Market coordination allows low production costs but comes with high coordination costs – for hierarchic coordination, the assignment is vice versa (Malone and Smith 1984). The advent of technologies might nevertheless change the role of transaction costs in the tradeoff between market and hierarchic coordination. ICT may, for instance, tie together adjacent value-chain steps and therefore may shift transactions from hierarchic coordination towards more market coordination (Malone et al. 1987). This results for instance in a decrease in firm size (Brynjolfsson et al. 1994). While these theoretical fundaments had a special focus on the reducing effects of ICT on coordination costs, the effect on the remaining constructs of transaction cost theory still needs to be taken into consideration as well.

Bounded rationality: The concept of bounded rationality goes back to (Simon 1972) and (March 1982) who suggest that decision-makers face incomplete information, limited time, limited skills, limited resources, ambiguity and lack of definition and therefore only have limited capabilities to make rational decisions (Forester 1984). Bounded rationality has been a key concept in the development of organizational theory and can provide a link to better understanding impacts of information technology on organizational design (Bakos and Treacy 1986). Based on a possible information completion, ICT and IS may enable a reduction of bounded rationality, which – under the transaction cost paradigm – also results in a more market-based organization of transactions.

Information asymmetry: ICT may help to reduce the information asymmetry between two parties (e.g. supplier and buyer) by providing better possibilities of monitoring

(Stump and Heide 1996). This may increase the opportunity for both parties to exert control themselves while reducing the motivation to control the partner in a transaction (Kim and Hsieh 2006; Ruey-Jer 2007). Nevertheless, a lack of willingness to disclose the relevant information by the involved parties may undermine the technical opportunities, which may have origin in the opportunistic behavior of one of the involved participants.

Opportunistic behavior: Opportunistic behavior entails "self-interest seeking with guile" and involves making threats and promises, which are self-disbelieved in hope of gaining an advantage over others (Williamson 1975; Kelley et al. 1989). Various control mechanisms like contracts in an inter-organizational transaction or inner-organizational control mechanisms may be used to reduce the risk of opportunistic behavior and to compensate for the lack of trust in transactions (Muris 1980; Ouchi 1979). Although not having a direct effect on opportunism, ICT and IS can be applied to design such control mechanisms efficiently by using blockchain and smart contracts. These recently emerged technologies may mitigate opportunism through incentives and crypto-economic mechanisms at relatively low transaction costs, and thus reduce transaction costs (Baron and Chaudey 2019).

Asset specificity: This concept describes the extent to which investments made to support a particular transaction, have a higher value for one organization than for others (Loukis et al. 2016). Transaction cost economics maintains that variations in asset specificity are even the principal for the existence of firms (Williamson 1975; Riordan and Williamson 1985). The concept can take the forms of site, physical, human and dedicated assets. In an empirical review, Rao (2001) observes an inverse relationship between ICT and asset specificity, thus ICT reduces the specific advantage of certain investments for firms. As a result, transaction costs may decrease.

Complexity and uncertainty: For the two constructs, *complexity* and *uncertainty*, the relation is not that distinct. The challenge is, that these two constructs are highly interdependent with the aforementioned constructs, with ICT effects and with themselves (Cordella 2006). Rapid change of technology – as common for ICT itself and diffused by ICT to other technologies – can thus be a source of uncertainty by itself (Lacity and Willcocks 1995). The same applies to the complexity where reduced search costs may lead to an abundance of information which then increases negotiation and enforcement costs as well as overall complexity (Bailey and Bakos 1997). As a result, the adoption of ICT in some settings may lead to significantly increased transaction costs due to high additional costs to accommodate the more complex environment (Cordella 2006). As such, the impact of ICT and IS is not an automatism that will occur in any case without external influence. To account for this limitation, this thesis uses the term *potential* instead of *impact* to describe the consequences of technological progress, which can but do not necessarily have to materialize. Still, utilizing ICT to increase information availability, to accelerate and to increase the amount of available information makes economic exchanges easier and more efficient by reducing transaction costs in all three phases of transaction costs (Cordella 2006).

To conclude, transaction cost theory is well established and empirically confirmed, despite still not entirely explored in all its complexity (Geyskens et al. 2006). Thereby ICT and IS may contribute towards a more market-based, a less hierarchical, way of coordinating transactions and, consequently, increase the number of individual parties involved. Comparing this intermediate result with the described developments in chapter I, the potential of ICT and IS to change organizational structures comes in alignment with the requirements of the energy transition for a decentralized supply of electricity. By the early 2010s, both disciplines were brought together to leverage their potentials. The next sub-chapter describes this development.

II.3 The research discipline energy informatics

Until 2010, the potentials of ICT and IS for the development of energy and especially sustainability-related applications were revealed by few, mostly unrelated research articles in different domains and research disciplines, as can be seen in the review by Kossahl et al. (2012) and Goebel et al. (2014). In 2010, Watson et al. (2010) merged the disciplines of IS and energy research to establish the new research discipline "energy informatics". This discipline encompasses the analysis, the design and the implementation of systems[1] to increase the efficiency of energy systems, following the paradigm that information enriched energy, amounts in less energy demand (Watson et al. 2010). This special role of data is apparent in the requirement of "collection and analysis of energy data sets to support optimization of energy distribution and

[1] Watson uses a rather broad definition of (information) systems as an "integrated and cooperating set of people, processes, software, and information technologies [working] to support individual, organizational, or societal goals" (Watson et al., 2010). Thereby, they also include ICT in his definition of IS.

consumption networks." In this context, Watson et al. (2010) lists eight connecting functions of information systems that shape an integrated system for an energy system that consists in general of data collection and transmission, information supplying and giving decision support and automation opportunities. The technical core of his proposed energy informatics framework consists of sensor networks, flow networks, sensitized objects and a central information system for coordination. The technical core is surrounded by eco-goals and stakeholders that propose policies, regulations, social norms and determine the economics both on-demand and supply-side (Watson et al. 2010). This generic framework gives various degrees of freedom for locating energy informatics research. Goebel et al. (2014) give a more specific idea of goals, research themes, use cases and involved disciplines in IS research. Still, there is a broad range of application domains that serve the two goals of energy efficiency via smart energy-saving systems and renewable energy supply via smart grids. There is a broad range of exemplary use cases for energy informatics:

- Peer-to-peer energy trading (Zhang et al. 2018a)
- Optimization of data center dispatch to support load balancing (Fridgen et al. 2017b)
- Cybersecurity issues in load balancing (Vernotte et al. 2018)
- The electric grid reliability research (Sultan and Hilton 2019)
- User interfaces for energy management (Xu et al. 2018)
- Simulation of energy use (Watson et al. 2018)
- Big data analysis in smart grids (Zhang et al. 2018b)
- Predictive energy data analytics (Hopf 2018)

Given this broad area of applications on different levels of abstraction in the research stream of energy informatics, the next sub-chapter arranges the contribution of this thesis into energy informatics.

II.4 Contribution of this thesis

The aim of this thesis is to analyze how energy informatics can contribute to incentivizing flexibility options in the energy system in a long- and short-term perspective. According to the framework of Goebel et al. (2014), this thesis falls into the categories of *renewable energy supply integration via smart grids* with use cases of *factories*, *energy storage*, *power systems* and *electricity markets* involved. Relevant research backgrounds are *IS economics*, *optimization* and *control*. Still, this domain-oriented perspective given by Goebel et al. (2014) might not be sufficient to understand the interdisciplinary orientation and the scope of this thesis.

For a better understanding of energy systems, multi-level representations such as frameworks are commonly used, as for example in (Zhang et al. 2018a) and (Sachs et al.). These representations were used to derive a six-level model, which illustrates the interplay between levels in the energy system, energy informatics, economic incentives, technological potentials and political as well societal goals (c.f. figure 3).

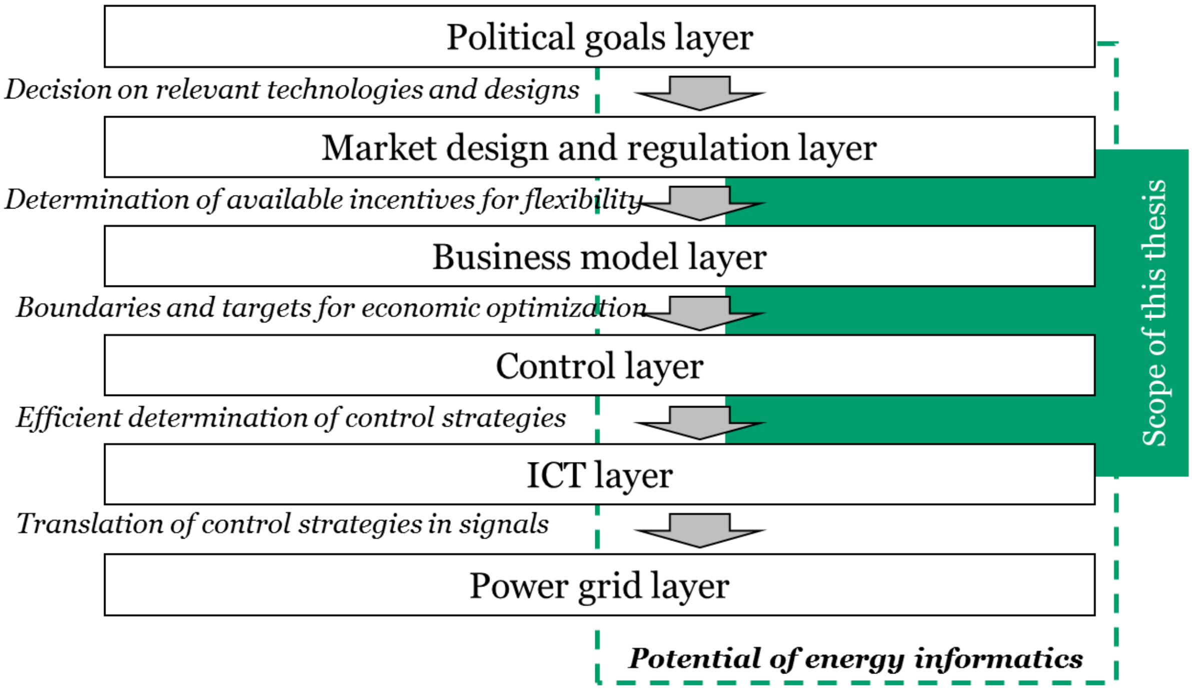

Figure 3: Scope of this thesis in a six-level model of the energy system. Source: own representation

This thesis depicts three layers of this representation to conduct a deeper analysis of the economic incentives for flexibility options and how energy informatics potentially influences these. While market design and regulation set long-term incentives for flexibility provision and are consequently elaborated on in chapter III, the control layer is used to decide on operational commitment of flexibilities and therefore part of chapter IV. The business model layer can be part of both perspectives and will correspondingly be part of both chapters. Political goal, ICT and power grid layer will not be analyzed in detail, as incentives – as core of this thesis – mainly appear on the market design, regulation, business and control level. Still, these remaining levels will be at least taken into account in the analysis of the potential influence of energy informatics.

Therefore, this thesis builds upon existing research in the domains of energy informatics, energy policy, energy economics and energy law and provides linkages as all four domains have flexibility incentives as part of their research scope. Especially the dissertation of Thimmel (2019) is a relevant groundwork, as it also links energy informatics, energy policy and energy economics to describe the potential of IS for demand flexibility. In more detail, it examines how the use of information systems can contribute to a successful energy transition by intelligently matching power demand to the fluctuating power supply. In the above described six-level representation, Thimmel (2019) focusses on the business and control layer from a demand flexibility perspective, while this thesis analyzes more levels from a general flexibility perspective.

III. Long-term incentives for flexibility investments in the electricity system

III.1 European and national goals in the electricity sector

To mitigate the impacts of climate change, a break down of global greenhouse gas reduction goals to a European and national level in Germany, is necessary.

The European goals for all member states in the European country are by now not sector-specific but focus on an overall reduction of greenhouse gas emissions and the increase of energy efficiency and share of energy demand from RES. The long-term goal for 2050 aims at a greenhouse gas reduction by 80 to 95 % compared to 1990 levels (European Commission 2019).

Germany as a member state of the European Union has set more specific goals for the electricity sector. The country has gained first attention by terms of the "Energiewende" as the first major country to commit itself to an electricity system transition based on decentralized RES (Antal and Karhunmaa 2018). A detailed description of the historical genesis of this term and the underlying political processes and goals are described by (Hake et al. 2015). The first key milestone for the scope of this thesis is the liberalization of the electricity markets by 1998, which replaced the monopoly of energy companies and led to a sharp decline in electricity prices. While a mechanism for RES fostering had already been existing since 1990 (Act on the Supply of Electricity from Renewable Energy Sources into the Grid, "Stromeinspeisungsgesetz, StrEG"), the key milestone for fostering RES was the introduction of the Renewable Energy Act, EEG. This act decoupled the premium for RES feed-in from electricity market prices by guaranteeing fixed feed-in tariffs for a period of 20 years (Hake et al. 2015). In 2010, the "Energiekonzept" was the first time when concrete goals for a path to increase the share of RES in gross electricity consumption were committed, aiming to reach a 50 percent share in 2030 and an 80 percent share in 2050 (Bundesregierung 2010). The goal of reaching a 50 percent share was intensified later in the coalition agreement of 2018 to reach a 65 percent share of RES in gross electricity consumption by 2030 (Bundesregierung 2018). By 2018, Germany has reached a share of 37.8 % RES supply in gross electricity consumption (Statista 2019).

Still, as sectors of traffic and heat lag behind, the carbon dioxide reduction does not go along the planned pathway in Germany (Pichlmaier et al. 2019). Future transport and heating will require increased cross-sectoral linkages, with electrification as one example for such linkages (Verzijlbergh et al. 2017). The potentials of energy informatics to contribute to more cross-sectoral actions for carbon-dioxide reductions will be further elaborated on in chapter V. This consideration is furthermore relevant from a perspective of technologic neutrality, as it is not clear yet, which technologies on supply and demand side will determine the future energy system and whether certain sectors may exhaust more carbon dioxide than others. Political goals regarding the support for certain technologies and sectors are always influenced by the current and by the expected potential, as well by societal acceptance and societal goals. The process of nuclear phase-out or the discussion about the high-power transmission lines in Germany well illustrate the immense significance of policy-society interdependencies for the energy system. Nevertheless, this interdependency also causes uncertainty and may lead to myopic planning. Heuberger et al. (2017) expect an increase of the cumulative power system cost from 2015 to 2050 by up to 14 % due to this lack of foresight regarding the relevant technologies for energy transition.

III.2 Electricity market design choices to enable a high share of RES

Given the politically and societally desired increase of RES share in the electricity system, an expansion of flexibility options (described in chapter I) is necessary, in order to balance the increasingly fluctuating supply. In the course of electricity market liberalization, grid operators and private stakeholders in the electricity market operate flexibility options.

Thereby, the flexibility options must have the perspective of a positive return-on-investment in order to be attractive for private stakeholders. Besides the possibility of individual agreements, electricity markets give incentives for flexibility by two principles: Either electricity markets provide volatile price signals, that allow using the technical flexibility to exploit the arbitrage between cheap and expensive trading periods, or markets give certain premiums for holding flexibility available over a certain time period. The latter mechanism is mostly used in order to sustain the grid frequency (balancing power) or to counteract grid congestions (curtailable loads). Curtailable loads are specific for Germany, where also regulatory non-market-based mechanisms like the grid reserve are implemented in order to guarantee secure supply.

Subchapter IV.1 provides a further analysis of how these mechanisms provide revenues for flexibility provision in the short term.

The arrangement of different market mechanisms in an electricity system is describable with the term market design. According to (Boisseleau 2004), this term has been used in different notions and entails three levels with corresponding design choices:

- Organizational structure: Degree of market integration, degree of competition and regulation, access policies
- Wholesale markets: Bilateral markets vs. pooling or exchanges, market integration, transmission pricing
- Marketplace: Auction design, Prices and behaviors, admissible participants, competition

From a local perspective, Ampatzis et al. (2014) propose a more simplified perspective on market design, incorporating the three dimensions , *trading horizon and dispatch intervals* as well as *market mechanisms* as its determinants. As described above, market design underlies influences of e.g. political goals and technological potentials and is for this reason subject to changes.

Common discussions on market design target on questions of congestion management and the preference of a nodal, zonal or uniform pricing regime or on the decision whether a capacity- or an energy-only market will be advantageous for high RES shares; see e.g. (Cramton et al. 2013) or (Weibelzahl 2017). For instance, Kraan et al. (2019) argue that pure energy-only markets do not incentivize investors to deliver a fully RES-based energy system with the imperative for policymakers to develop capacity remuneration mechanisms. When a certain arrangement of market design is determined, it is necessary to align regulation in order to implement market design into practice. The role of regulation as translator between abstract market design concepts and the implementation of the desired results must not be underestimated. Ringler et al. (2017) therefore recommend a stable and transparent regulatory framework on a European level with cross-border market coupling to enable a common European electricity market. Only a stable framework sets the necessary conditions for private investors to invest in flexibility options in the long term. The next sub-chapter further elaborates these incentives.

III.3 Incentives for flexibility investments in the long-term perspective

Private investors need to take into account potential revenues and expenditures when deciding on investments in flexibility options. One possibility, to subdivide expenditures is the splitting in capital expenditures (CAPEX) and operating expenditures (OPEX). The amount of CAPEX for a flexibility option increases the complexity and uncertainty in an investment project and therefore the willingness of an investor to undertake investments (Weaver 2012). The OPEX of flexibility options relates on the other hand to the marginal costs for flexibility provision and therefore influences the commitment of the flexibility options on the different electricity markets.

Flexibility options have a different structure regarding CAPEX and OPEX (Steffen 2018). For instance, demand flexibility measures may have comparatively low CAPEX but may induce high OPEX when industrial production planning needs to intervene in their processes. Currently, especially flexibility options with low additional CAPEX for flexibility take part in the markets for flexibility due to the planning uncertainty. In general, the higher the share of CAPEX is, the more stability of incentives in a long – term perspective is necessary (Weaver 2012). This subsection describes two perspectives on these long-term incentives:

Ländner et al. (2019) is the first research article in this cumulative dissertation and presents an overview of the current investment barriers for flexibility options and the existing legal energy investment framework. More specifically, the article identifies obstacles for private investors and provides an analysis of the current regulation that increases or decreases incentives for flexibility on the European and the national German level. The article undertakes this analysis for the flexibility options network expansion, supply flexibility, storage and demand flexibility. *Research article 1* then summarizes the challenges of future energy law with the three domains *uncertainty regarding future energy goals*, *energy law distortion towards specific flexibility options* and *law complexity*. Ignoring these challenges might lead towards a system deadlock where regulatory interventions to grant necessary flexibility incentives only lead to an increase of complexity and uncertainty, thereby lead to market failure and in turn to decreasing market-based incentives.

This conclusion corresponds with the assessment of other research articles. (Newbery et al. 2018) mention political risks due to increased concerns over climate change and sustainability which are difficult to hedge and lead to missing markets. (Schachter et al. 2016) emphasize the pivotal role of uncertainty in the decision making on flexibility options: “There is a need to account appropriately for uncertainty in long-term decision making and the valuation of network investment plans, as accounting for uncertainty can significantly change the business case for flexible capacity-based services for postponing or even avoiding costly irreversible reinforcements.” The risks for private investors associated with this uncertainty can, therefore eliminate business cases simply by preventing them from being bankable.

An instrument to reduce such risks on a market-based approach is subject of research article 2: Jäckle et al. (2019) present an approach for the mitigation of risks associated with flexibility provision for a private investor. Although promoting a special demand flexibility use case, the method can be generalized in order to be also applied for storage and supply flexibility. Returns for flexibility commitment from electricity spot markets are uncertain and volatile, in addition to operational, technological, contextual, measurement and verification risks.

The idea of this article is the explicit design of Flexibility Performance Contracts (FPCs). An FPC issuer, therefore, grants a certain remuneration for the use of the flexibility to a flexibility provider, independent of the market results. To issue FPCs with appealing incentives for flexibility providers and meanwhile an expectable positive business case for the FPC issuer, advanced IS for data collection, processing and analyzing are necessary. This reflects in the following sub-chapter, which describes the potential of information systems to improve the long-term flexibility incentives.

III.4 Potentials of energy informatics to improve long-term incentives for flexibility

To conclude chapter III, this sub-chapter summarizes the potentials of information systems and ICT in the context of energy informatics.

On the *political layer*, IS can contribute towards the finding of effective and socially accepted solutions in terms of mitigating climate change. For instance, processing of high data amounts is necessary in order to simulate the possible impacts of greenhouse gas emissions. IS and ICT can be used to analyze the social acceptance of certain goals and measures, as in the study of Tiefenbeck et al. (2019). Derived from the political goals, it is necessary to derive and simulate energy transition pathways by the aid of energy system models in order to gain information on the possible relevance of the different technology options in the electricity system (Bolwig et al. 2019; Lopion et al. 2018). Such simulations support decision making by creating transparency and reducing uncertainty. Although this has no direct influence on the design or amount of flexibility incentives, such decisions significantly influence the flexibility requirements in an energy system and thereby indirectly also the corresponding incentives.

These incentives are determined especially on the *market design and regulation layer*. The organizational structure as part of market design (see sub-chapter III.2) may especially be affected by the potential to reorganize the most efficient market structure in the sense of the transaction theory described in chapter II. The transaction cost-decreasing effect of IS and ICT leads by trend to a more decentralized energy system with smaller participants, which is in alignment with the increasing role of small decentral RES suppliers (Slootweg et al. 2011). ICT enabled technologies like blockchain, distributed ledger and smart contracts offer disintermediation, transparency and tamper-proof transactions (Andoni et al. 2019). These can act as the central enabler to decrease the transaction costs at that amount, which empowers consumers and small renewable generators to play a more active role in the energy market and monetize their assets (Mylrea and Gourisetti 2017). Nevertheless, to put these potentials into practical application, the legal framework needs to keep up with the created technological potentials.

The constructs of *complexity* and *uncertainty* from transaction theory also exist as challenges for the design of energy legislation. The challenge of legal complexity may be faced by increased legal automation, similar to the developments described by Pasquale (2019). So-called “Legal-tech” already allows an automated execution of certain legal processes, whereas it is questionable if the complex niche domain of energy law is attractive enough for legal tech to develop solutions in the next years.

For the challenge of uncertainty, more mature solutions may already exist: In this context, the agent-based simulations as one domain of energy informatics research can help to better understand the individual behavior of participants and therefore contribute to higher certainty regarding market design and regulation decisions. Kraan et al. (2019) give an example of agent-based simulations in energy systems.

The layer of *business models* may profit from the created certainty in the long-term, as this allows more stable revenue streams as a return for flexibility investments. Still, from the perspective of an individual investor, energy informatics can foster other incentive mechanisms as a substitute for long-term certainty. As described in sub-chapter III.4, IS can support flexibility investments by enabling FPCs. FPC-design requires the gathering of many different information sources. Vice versa an effective usage of IS can deliver a significant competitive advantage for FPC issuers. The role of an FPC issuer is by now already captured by some aggregators, who facilitate (especially smaller) consumers' and market participants' access to energy and flexibility markets (Polgári et al. 2017). Aggregators utilize technical assets of their partners (flexibility providers) and focus on processing of information to send the "right signals at the right time". In return, they guarantee certain remuneration schemes for flexibility provision. Using the notion of transaction cost theory of chapter II, the ICT-enabled reduction of asset specificity enables aggregators to pursue their information focused business model.

On the *power system layer*, simulations can also help in the long-term to determine investments in certain assets under uncertainty. Examples are the determination of investments in smart distribution networks (Schachter et al. 2016) or the dimensioning of energy storage systems (Liu et al. 2018).

IV. Short-term incentives for the flexibility commitment in the electricity system

IV.1 Remuneration mechanisms for flexibility commitment

The long-term decisions on electricity market design determine the number and the characteristics of available markets for flexibility. In turn, the revenue potentials from short-term flexibility commitment on these markets determine the market-based investment incentives for flexibility. This sub-chapter, therefore, gives a brief overview of the existing remuneration mechanisms to monetize flexibility.

Albadi and El-Saadany (2007) as well as Albadi and El-Saadany (2008) provide a well-recognized categorization scheme for flexibility[2]. In accordance with the introduced categorization in sub-chapter III.2, they distinguish between price-based and incentive-based programs, whereas one can subdivide the latter category into:

- Classical programs (Direct Control, Interruptible Curtailable Programs)
- Market-based (Demand Bidding, Emergency Flexibility, Capacity Market, Ancilliary Services Market)

In contrast to this, price-based programs reward participants for their performance to adapt electricity based on price signals and consist of Time of Use (TOU), Critical Peak Pricing (CPP) Extreme Day CPP, Extreme Day Pricing and Real Time Pricing (RTP).

Despite this well-recognized framework, the assessment of grid flexibility does not match into these given categories. Grid flexibility may be evaluated with the prevented costs, that a transmission system operator (TSO) or distribution system operator (DSO) would have spent for congestion management otherwise (e.g. by reciprocal ramping-up and ramping down distant power plants). Congestion management regimes highly depend on the prevailing market. A nodal pricing regime, for instance, includes congestions into the market price signals. Under a zonal or uniform pricing regime, most of the above-described programs imply a “copperplate” and do not account for possible grid congestions. To better integrate the grid perspective, local flexibility markets are in discussion. Olivella-Rosell et al. (2018) provide an overview of ten possible flexibility services for DSOs, balancing responsible parties (BRP) and prosumers as flexibility customers in three different possible grid states. As the TSO is

[2] 841, respectively 1522 citations of the underlying research article in Google Scholar by 05.08.2019

not among the flexibility customers in this perspective, opportunities to provide balancing power and load curtailment are not in the scope of their research article.

To integrate both the global and local perspective, figure 4 provides a representation of flexibility remuneration schemes for the case of Germany.

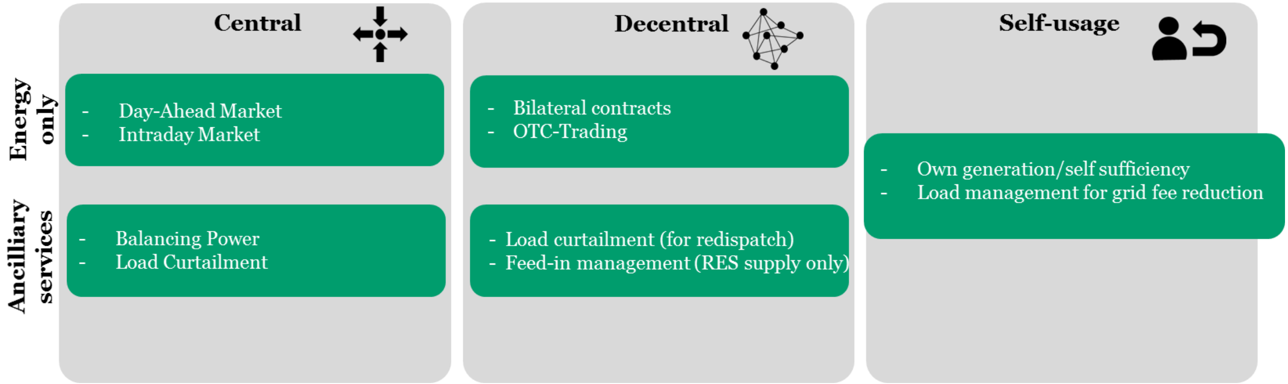

Figure 4: Flexibility remuneration potentials for the German case. Source: own representation

It's quite remarkable that both perspectives of Albadi and El-Saadany (2007) and Olivella-Rosell et al. (2018) et al. presume that participants do not have own access to the electricity markets and therefore use an intermediary like the utility, aggregators or the BRP, transferring the market incentives with the described programs. Intermediaries help to provide access to these markets, as trading volumes of the flexibility providers may be insufficient, or as power market product might not match the requirements of a flexibility provider. The next sub-chapter will therefore analyze possible adjustments of power market products to better match such requirements.

IV.2 Improved incentives for flexibility by better matching of power market products

The design of electricity spot markets accounts for the trade-off between planning certainty and flexibility by consecutive auction mechanisms. The EPEX Spot for the market region Germany/Luxemburg has, for instance, three different types of auctions (*Day-Ahead*, *Intraday-Auction* and *Intraday-Continuous*). This allows both planning certainty regarding the operations of assets at the following day and flexibility to address short-term changes. While Intraday-Auction and Continuous in Germany/Luxemburg allow the trading of 15-minutes time steps, other countries still rely on one-hour duration as minimum product length (Märkle-Huß et al. 2018). Verzijlbergh et al. (2017) propose the reduction of time-steps in Day-Ahead and Intraday markets (e.g. to 5 minutes). Märkle-Huß et al. (2018) conclude that 15-minute trading can increase power generation from RES and meanwhile decrease electricity prices, while it is necessary for future research to find the optimal duration of power trading contracts. On this basis, *research article 3* analyses the possible degrees of freedom in the design of power market products and their impact on different stakeholders in the electricity system to prepare for further possible product adjustments. Adjustments for power market products are possible regarding the strengthening of locational pricing, shorter duration of power trading contracts, shorter gate closure times, and smaller minimum trading volumes. The evaluation of these adjustments leads to the tradeoff of increased enablement of small and flexible participant involvement that may increase market efficiency versus an increase in transaction costs. Furthermore, adjusting these parameters inherits interdependencies with other dimensions of market design like the congestion management regime for the adding of local pricing components or the delimitation between balancing power and spot markets for a shortening of gate closure time. The costs for the necessary infrastructure to implement these changes will oppose the potential benefits of higher market efficiency. Still, the question about the reallocation of gains in market efficiency to increase incentives for flexibility providers remains unanswered. Therefore, the design of adjusted power market products offers a large potential for further research.

Besides such product design-related questions, various other parameters influence the economic viability of flexibility provision as the next sub-chapter illustrates.

IV.3 Influencing factors on provided flexibility in the case of industrial demand response

Flexibility assets need to refinance the initial investments with earnings earned from committing the flexibility to the remuneration mechanisms described in sub-chapter IV.1. From an economic perspective, an asset owner performs the operational commitment of a flexibility option when the expected revenues overweigh the costs for flexibility. The difference between both amounts is necessary to generate return-on-investment and to gain a profit margin. The challenge of committing flexibility is, therefore, to overview the complex remuneration mechanisms, while assessing costs for providing flexibility, which depend on various influencing factors.

Costs for supply flexibility of thermal power plants highly depend on the overall number of startups and the number of full load hours (Schill et al. 2017). Storage flexibility costs may appear e.g. for battery storage systems in terms of a shortened life-time due to degradation, which largely depends on the battery charging (Pelletier et al. 2017). In the case of demand flexibility (in the following, this thesis uses the term demand response according to the framework of (Palensky and Dietrich 2011), fluctuations in electricity consumption delimit the availability of this potential (Müller and Möst 2018). The demand response potential can be subdivided in the theoretical potential as the absolute maximum demand response potential, the technical potential which takes into account technical restrictions, the economic potential to comprise only the cost-effective potential and the achievable potential as smallest potential subset which also takes into account the acceptance of load interventions (Dranka and Ferreira 2019). Industrial processes have a high demand response potential (Paulus and Borggrefe 2011). Still, a central constraint restricts the potential: In industrial processes, when aiming to be cost-effective which means to avoid opportunity costs for lost production, the economic potential depends on the capacity utilization of process plants. A 100 percent capacity utilization inherits no flexibility at all (Ausfelder 2018). As a result, overcapacities are necessary for industrial demand response for flexibility provision at competitive costs. Such overcapacities may stem from seasonal fluctuations, declining conjuncture, raised material efficiencies or safety redundancies. Although the actual potential provided is – as the smallest subset – directly bounded by the achievable potential, the economic potential might be – at least in the highly energy intensive processes with adequate transparency – the highest delimiter for the provided DR potential.

For the case of a paper mill, *research article 4* (Schoepf et al. 2018) analyses how the demand response depends on the relation of two raw material prices of pulp and recovered paper. The article finds that the demand response potential significantly depends on the relation of both raw material prices. This underlines the importance of considering the relevant internal and external influence factors both in the case of long-term decisions on the role of certain technologies in the energy system and in the case of short-term flexibility commitment, as well as the interdependencies between the two perspectives.

IV.4 Potentials of energy informatics to improve short term incentives for flexibility

The potentials of energy informatics on the business model layer also apply for the short-term perspective by terms of redesigning power trading contracts, as *research article 3* in sub-chapter IV.2 illustrates. The capabilities of automated processing and analyzing a large amount of data are the prerequisite for an adjustment of power trading towards the shorter duration of power trading contracts, shorter gate closure times and smaller minimum trading volumes. Energy informatics shifts the tradeoff between increased market efficiency due to a better matching of trading products with the technical requirements of the individual participants and increased transaction costs due to higher coordination efforts towards a better match of contracts. ICT also allows for more efficient contracting by providing the possibility of short-term smart contracts (Thomas et al. 2019). Moreover, ICT can improve access to electricity markets by providing services on platforms like the "Energy Synchronization Platform" (Schott et al. 2018).

It is also possible to implement platform-based services for the control layer, where energy informatics offers opportunities to improve flexibility incentives by maximizing the economic profit earned from the commitment of the flexibility option. Facing the variety of external and internal influence factors that determine costs and revenue potentials of flexibility options, the exploitation of IS and ICT enabled automation potentials is imperative for flexibility provision at reasonable transaction costs. By that, both IS and ICT play an important role, as information about the relevant parameters needs to be gathered, optimized and translated into control signals for the technical flexibility assets. *Research article 4* in subchapter IV.3 illustrates the influence of raw material prices as external factors on the economic demand response potential in a (comparatively simple) real-world case. That case offers high potentials for automated control of the production quantities of the electricity-intensive processes in order to minimize summed costs of electricity and production in an integrated manner.

A yet not mentioned but meanwhile crucial issue for the commitment of flexibility is the forecasting of electricity feed-in and electricity prices. Energy informatics allows the steady improvement of forecasting technologies, based on permanent training of models with the steadily increasing data amount. Machine Learning models, therefore, improve Day-Ahead electricity price forecasting accuracy and may outperform statistical methods (Lago et al. 2018).

On the infrastructure level, the use of ICT improves the possibilities of controlling grids and the technical power infrastructure, which increases the efficiency of grid and asset operation and may reduce grid congestions. Lampropoulos et al. (2019) propose an ICT-based hierarchical framework to control the flexibilities by a TSO or a DSO. By better control of grid and flexible resources, a more efficient commitment of flexibilities can be attained (Nainar et al. 2019). Data standardization initiatives like generic load and data provision management (GLDPM) aim to improve data availability and especially the coordination between the distribution and transmission grid level (ENTSO-E 2017; Schönheit and Sikora 2018). Improved coordination between TSOs and DSOs can substantially increase welfare of system operators (Vicente-Pastor et al. 2018). Energy informatics has the tasks of providing the foundations for standardization e.g. by developing generic data models for flexibility in an electricity system, as provided e.g. by (Schott et al. 2019).

V. Enhancing flexibility for the electricity system by a broader, cross-sectoral perspective on energy

After the challenges of decarbonizing the electricity sector as pioneering sectors have been described, still other sectors like traffic and heating need to be considered in the transformation due to their high energy demand. The concept of sector coupling promotes the purposeful interaction of different grids, as this potentially mitigates problems associated with RES feed-in like balancing demand and supply or grid congestions.

Research article 5 addresses this topic by suggesting a broader perspective on the energy system, also incorporating the outcomes of energy transformation chains into the scope of energy systems and as a possibility to transport energy. Following this perspective, not only the primary, secondary and tertiary energy carriers are under consideration, but instead also the consumable products, which are the outcome of an energy-demanding process. For instance, the road transport of aluminum as an electricity-intensive good may be an alternative to power grids for electricity to a certain degree. Given sufficient production capacities, the traffic sector may offer possibilities to dissolve grid congestions or even to transport energy more efficiently. To determine the transportation-loss-minimal pathway for energy transportation between geographically distant locations, the research article uses the traffic assignment problem from logistics research. Next to the possibility of physical energy transportation of energy inherent products, the perspective also includes the opportunity of virtual energy transportation by dispatching capacity of data centers or by using distributed manufacturing resources for production.

Implementing this perspective into practice nevertheless requires certain regulatory mechanisms and the exploitation of energy informatics' potential. As no central coordinator directs the energy flows in liberalized energy systems, it is necessary to implement adequate market mechanisms. The fee structure for the usage of public grids must then set the corresponding incentives to promote the usage of grids that are most beneficial to an overall system of goals (e.g. reduction of greenhouse gases). The role of energy informatics can hereby cover the support of all layers. Examples are the development of scenarios and simulations to develop adequate incentives, the implementation of efficient contracting in cross-sectoral transactions or the provision of sectoral pathway optimization tools.

VI. Conclusion

VI.1 Contribution, Limitations and Outlook

A significant RES share-increase in the energy system is important for the decarbonization of societies that highly depend on energy supply. Therefore, especially the electricity system requires flexibility options to compensate the volatile feed-in characteristics of RES. Liberalized electricity systems require incentives for private market participants to invest in the expansion of technical assets as flexibility options. Yet, the incentives for flexibility in many countries are uncertain, too low, or both (Alcázar-Ortega et al. 2015; Paterakis et al. 2017). To provide guidance for the design of future electricity systems with improved flexibility incentives, a more holistic perspective is necessary, which also includes reasons, needs and shaping elements for market design change (Ela et al. 2016). This thesis, therefore, analyzed, which potential role energy informatics could play in this context.

Specifically, the aim of this doctoral thesis was to analyze economic incentives for investments and for the commitment of the different flexibility options demand flexibility, storages, supply flexibility, and grid expansion and how these options are potentially influenced by energy informatics. Different research approaches, which included mathematic models, simulations, conceptual work and literature, and legislative text research were performed in interdisciplinary research teams in order to cope with the various interdependencies in the electricity system. The research articles had a different level of abstraction but were all related to the topic of flexibility incentives. These aspects allow integrating a unique variety of perspectives into one doctoral thesis.

The analysis started with a consideration of the theoretical background on advantages of IS and ICT using the transaction cost theory and the introduction of energy informatics as a combination of IS and ICT applications for a sustainable energy system. Subsequently, the long-term perspective on RES-induced necessities for flexibility options were described, as well as applications for IS in energy system modeling. This especially included changes in the layer of market design and regulation, as well as the derived business model layer. *Research article 1* gave an overview of the current regulatory framework for flexibility incentives on a European and a national level, followed by *research article 2* that describes a market-based instrument to mitigate the risks of flexibility investments.

In the short-term consideration of flexibility, the focus lied on the operational improvement of flexibility commitment. Thereby, *research article 3 introduces* potential new products on the spot market. *Research article* 4 analyzed how external factors influence the economic demand response potential. *Research articles 5* finalized by promoting a broader perspective for the consideration of energy sectors in the entire energy system. Summarizing the key potentials of energy informatics according to the focused layers (policy goals, market design and regulation, business model, control), it is possible to emphasize following issues:

- Energy informatics already plays a major role in the layer of political goal setting. Despite not being immediate focus of this thesis, this topic gains increasing importance as diverging interests and high uncertainties regarding the decarbonization pathway are observable. In order to fill these gaps, scenario building with a neutral and transparent assessment of different outcomes regarding climate impact, economics, supply security and social acceptance is necessary. Energy informatics has the important role of providing realistic data and simulation frameworks for this assessment. Therefore, the energy informatics framework by Goebel et al. (2014) possibly needs an extension by the topic energy system modeling to also account for the strategic implications of energy informatics.
- On the market design layer, IS and ICT (in general) have the potential to change the most efficient forms of coordinating transactions from hierarchal coordination towards more decentralized and market-based coordination. This goes in alignment with the planned shift in the electricity sector from a centralized top-down electricity flow towards a decentral bottom-up interaction of RES and flexibility options. Presuming this logic of the transaction cost theory, a shift towards a more market-based and decentral approach is expectable. Nevertheless, other non-market based factors that restrict the applicability of the transaction cost theory in this domain influence the energy and electricity system as critical infrastructure.
- Energy informatics enables business models like aggregators who process information to facilitate flexibility provision for technical assets. Sometimes aggregators also overtake the role of risk mitigation, which requires a thorough

risk evaluation and portfolio creation for the aggregator, based on market data. To mitigate these risks already in the process of power market trading, energy informatics also allows efficient processing of power market products that match better the technical characteristics of flexibilities.

- On the control level, energy informatics can mitigate the negative effects of interdependencies and complexity on the efficient commitment of flexibility. Automated control and decision support system that integrate the influence of external factors are the keys towards an increased provision of flexibility. This especially applies to the case of demand response as illustrated in the case of research article 4 but also applies for other cases like e.g. electric vehicle charging.

For a valid evaluation of these findings, it is nevertheless necessary to consider the associated limitations. The transaction cost theory was the only considered approach to analyze the structural change potentials of energy informatics. Although this theory already includes some observable phenomena like bounded rationality, a simple lack of information cannot explain some societal effects like NIMBYism[3]. Instead, other more recent approaches from behavioral economics like the prospect theory by Kahneman and Tversky (1979) may be used to better predict the irrational behavior of some participants in the energy system to derive better decisions. Furthermore, there is not necessarily a causality between the adoption of IS and ICT and – if even realized – a reduction of transaction costs. It is, therefore, necessary to consider the overall consequences of IS and ICT adaption instead of only direct effects (Cordella 2006).

Still, this thesis cannot describe all associated consequences with IS and ICT use in the energy system either, as a high amount and variety of interdependencies exists in the domain of energy informatics. Therefore, this thesis described some relevant interdependencies and arranged them in a framework considering the topic of the role of energy informatics for flexibility incentives on different abstraction levels.

The described interdependencies in this thesis already illustrate the complex interplay of ecologic, regulatory, economic and technologic questions. On the technological level, a variety of solutions is potentially available, but on the subordinate levels, high uncertainty and complexity regarding policy goals and the role of each flexibility option

[3] see e.g. Hankinson 2018 for explanation

are prevalent in many countries. Energy informatics-enabled decision support is thus not just necessary for operational decisions like the commitment of technical flexibility assets, but also for the provision of guidance for societal and political goals.

Moreover, energy informatics has the potential to change existing market structures and to allow an efficient interplay of small decentralized and decarbonized RES sources and flexibilities in the power markets. To unleash and to manage this potential, I promote fostering the sub-discipline of *strategic energy informatics* combining both broad and deepened perspectives from different disciplines in a long-term view to gain a big picture of a sustainable energy system. It is not possible to understand the energy system as a whole by approaching it from one single research discipline, neither can a single person capture its whole complexity. To close the flexibility gap and the increasing gaps of political and societal opinions on the energy system, it is therefore imperative to close the gap between researchers in different disciplines and to join forces for the design of the future energy system.

VI.2 Acknowledgement of previous work

I conducted all my research with colleagues at the Finance and Information Management (FIM) Research Center and the Project Group Business and Information Systems Engineering of the Fraunhofer Institute for Applied Information Technology (FIT). Thus, I point out how my research builds on these organizations' previous work.

Several research papers in the mentioned organizations examined the general topic of flexibility in the energy system. The experience and the knowledge of these authors helped to identify research gaps and to create new ideas. The most important research articles in this context were the work of Fridgen et al. (2014), Fridgen et al. (2016) and Fridgen et al. (2018). Additionally, r*esearch article 2* builds upon a research stream regarding insurance of energy efficiency investments. In particular, the work by Buhl et al. (2018) as well as Töppel and Tränkler (2019) has set the path for this research. Finally, the extended perspective on sector coupling as described by *research article 5* grounds in the work of Fridgen et al. (2017b), where data centers provide flexibility.

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VIII. Appendix A: Extended abstracts of the research articles

VIII.1 Research article 1: From Energy Legislation to Investment Determination: Shaping Future Electricity Markets with Different Flexibility Options

Authors:

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Extended abstract:

As the share of renewables increases, flexibility options in the power grid will have to keep up with this fundamental change in the power supply structure over the next decades. In liberalized electricity systems, this includes, securing investments to supply the necessary flexibility in future. In the context of flexibility investments in the transportation of energy throughout the grid is the crucial backbone in maintaining a stable and efficient energy system. However, as it is argued in Steinke et al. (2013) or Weibelzahl and Märtz (2018), adequate storage investments may potentially lower the need for large-scale grid extensions. Similar arguments also apply for conventional power plants built at the required network locations as well as for installed demand-side management systems, both of which are usable as options for grid stabilization with possibly reduced grid investments through a better balance of intermittent electricity supply and demand.

Despite their importance for a successful energy transition, there are still severe obstacles that may keep investors from undertaking the needed investments in flexibility options. The article identifies five obstacles that prevent possible private actors in the electricity system from investing in flexibility options:

- Market design & congestion management regimes

- Interdependent decision making in anticipative markets
- Emergence & penetration of renewable energy production
- Market power & imperfect competition
- Unknown regulatory changes and market outcomes

These obstacles emphasize the importance of a political legislation framework that increases the incentives for investments in flexibility options. Following this conclusion, the article provides an analysis of the current regulation for incentives for flexibility on the European and the national German level.

The flexibility option of network investments and network expansion is regulated in the Ten-Year Network Development Plan (TYNDP) by the organization ENTSO-E (European Network of Transmission System Operators for Electricity), which determines the future demand of grid expansion. A sum of about 180 billion euros is estimated, to be necessary until 2030, to modernize and expand European grids. This plan is pursued by the German TSOs to develop different scenarios for the grid expansion under different long-term energy-policy perspectives.

The flexibility option back-up generating capacities is not explicitly regulated on the European level, despite a directive allowing member states to grant state subsidies for generation capacities in the case of market failure. The incentives for supply flexibility are restricted to investment support for power plants when security of supply is in danger, which has its origin in the political decision against capacity market design.

Storage facility investments are not directly incentivized under European regulation. Still, there is a directive that obligates the EU Member States to take the necessary and appropriate steps for storage expansion to ensure a stable electricity system. The regulatory framework to support investment in flexibility in Germany is inconsistent and does currently not give sufficient incentives for a large scale expansion of storage, which can also be traced back to the calculation of grid fees and levies for end consumers.

Investments in demand side management are especially promoted via the option of increased energy efficiency on the European level. The need for more flexibility and for an increase in flexibility potential investment was recognized by a proposal for regulation in 2017. On the national level, regulations on necessary energy efficiency increase and grid fees are an additional obstacle for the implementation of demand flexibility measures.

The article finally summarizes the challenges of future energy law with the three domains *uncertainty regarding future energy goals*, *energy law distortion towards specific flexibility options* and *law complexity*. Ignoring these challenges might lead towards a system deadlock where regulatory interventions to grant necessary flexibility incentives only lead to an increase of complexity and uncertainty, thereby lead to market failure and in turn to decreasing market-based incentives. As a result, policy makers need to lower investment uncertainty for private investors, avoid a distortion of energy investment law towards specific flexibility options and technologies, and reduce the complexity of the current legislation.

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VIII.2 Research article 2: Risk Mitigation Capability of Flexibility Performance Contracts for Demand Response in Electricity Systems

Authors:

Florian Jäckle, Michael Schöpf, Jannick Töppel, Felix Wagon

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Citation:

Jäckle, F.; Schoepf, M.; Töppel, J. & Wagon, F., (2019). Risk Mitigation Capability of Flexibility Performance Contracts for Demand Response in Electricity Systems. In Proceedings of the 27th European Conference on Information Systems (ECIS), Stockholm & Uppsala, Sweden, June 8-14, 2019.

Extended abstract:

The transition of the energy system increases the urgency to cope with the intermittency of renewable energy sources to keep the electricity network balanced. Demand Response (DR) measures are a promising approach to align the electricity consumption, especially of industrial consumers, with current electricity supply. Although demand response (DR) benefits are widely acknowledged from a practical perspective, industrial consumers are still reluctant to participate in DR measures. Within electricity systems, flexibility aggregators support industrial consumers in utilizing their flexibility potential and in overcoming these barriers. Besides technical installation and system maintenance, flexibility aggregators provide expertise in assessing and exploiting financial benefits as well as in fulfilling necessary requirements, e.g. the prequalification process for participation in DR measures (Ikäheimo et al. 2010). As most existing markets for flexibility require certain minimum trading volumes, flexibility aggregators help providers of small flexibility capacities, by combining individual flexibilities (pooling) and reducing transaction costs for all industrial consumers (Ottesen et al. 2018). Additionally, prices on these markets are usually exposed to a certain volatility and uncertainty. Therefore, revenues from the provision of flexibility are uncertain and represent an economic risk for flexibility providers. The decision-makers of industrial consumers are usually risk-

averse (Gambardella and Pahle, 2018). For this reason, investments in expanding the potential for DR provision might be omitted, although being profitable in the long term. Flexibility aggregators may mitigate these risks for an industrial consumer acting as flexibility provider by assuring guaranteed revenues for DR provision. The flexibility aggregator receives a share of the DR measure revenues in return for providing services and taking financial risks. Literature usually calls the amount of reduced risks with such guarantees by the term risk mitigation capability (Töppel and Tränkler, 2019).

Nevertheless, studies on risk transfer instruments related to DR investments are still scarce. To contribute to the closure of this research gap, we examine the risk transfer capability of Flexibility Performance Contracts (FPC). An FPC issuer, therefore, grants a certain remuneration to a flexibility provider for the use of the flexibility, independent of the market results. Two FPC types are derived in the research article, a flexibility performance insurance contract (FPIC) which only activates when flexibility remuneration falls below a predefined level and a flexibility savings guarantee (FSG) which guarantees a certain level of flexibility remuneration. For the two FPC designs, the corresponding cash flow structures were derived. Evaluation is based on Value-at-risk in order to identify the FPC, which minimized the financial performance risk for a risk averse decision maker. For the evaluation, we conduct a simulation-based model for an industrial refrigeration system, which provides flexibility through the application of a ToU tariff. Forecasted electricity prices are processed within a linear programming model to derive the optimal electricity consumption strategy of the refrigeration system. Finally, we perform a simulation for the present value of annual electricity bill savings. Our results reveal that the implementation of a ToU tariff entails high risks as electricity market price developments lead to temporarily or permanently increasing electricity prices for the ToU tariff. In some cases, electricity bill savings do not materialize at all for the flexibility provider. Hence, the ToU tariff can be even unfavorable compared to a conventional constant electricity tariff.

The results of the performed simulation study finally illustrate, that FPC are-well suited instruments to reduce risks associated with flexibility provision, though the risk mitigation capability of FPCs is very sensitive to the determination of individual contract parameters. Thereby, the FSG is beneficial with respect to the applied risk measure and is even superior to the FPIC. Only for very high guaranteed electricity bill savings, the preference will be in favor of the FPIC.

As the results are very sensitive, the importance of determining contract parameters with appropriate risk mitigation increases. Although existing IS already provide the technological foundation that enables the efficient execution of DR measures, these findings underline the necessity for risk transfer instruments to foster a broad implementation of DR measures. To issue FPCs with appealing incentives for flexibility providers and meanwhile an expectable positive business case for the FPC issuer, advanced IS for data collection, processing and analyzing are necessary.

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VIII.3 Research article 3: The search for the perfect match: Aligning power market products to the energy transition

Authors:

Gilbert Fridgen, Anne Michaelis, Maximilian Rinck, Michael Schöpf, Martin Weibelzahl

Currently under review

Citation:

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Extended abstract:

In the past decades, most countries liberalized their wholesale electricity markets (Graf and Wozabal 2013). In contrast to a traditional independent system operator that centrally managed and controlled the entire power system as kind of omniscient planner in the pre-liberalization era, information asymmetries typically imply that liberalized markets can realize an increased efficiency compared to a traditional centralized dispatch (Arentsen and Künneke 1996). To tackle this general problem of information asymmetry, markets set explicit monetary incentives in form of market prices to disclose such relevant private information on the available flexibility options using corresponding bids. Given the general existence of information asymmetries, the current development of renewables significantly increases the need for appropriate market structures to incentivize market participants to disclose their individual and asset-specific information. In particular, due to the highly fluctuating generation of renewables, flexibility gained growing importance (Kubli et al. 2018). To address the growing flexibility gap associated with the increasing share of renewables and the planned phase-out of conventional power plants like nuclear or coal, the length and gate closure time of intraday market products were already shortened in many countries over the past years. Notwithstanding these attempts on intraday markets to better balance demand and fluctuating supply, the current product design still bases on average power volumes that are contracted by the market participants. Thus, in contrast to self-designable products that are traded over-the-counter, products merchandised on the power exchange cannot be defined individually by the market participants and are instead specified by the power exchange operator itself. The

trading of such standardized products typically ensured low transaction costs as well as a corresponding power-consumption measurement and billing in an easy-to-implement fashion in the past.

On a grid level, renewables are inherently characterized by specific power profiles like solar ramps whose concrete shape depends on unknown weather conditions (Goutte and Vassilopoulos 2019). These new power profiles result in rapid changes of residual load, which occur increasingly in the morning and evening hours. As power market trade is still often organized on an hourly basis, corresponding challenges for grid operation due to frequency fluctuations occur daily and typically during hour changes (Weissbach and Welfonder 2009). Especially during changes of the hour, there are large imbalances between the contracted average power and the actual power profile. The reason for such frequency deviations may lie – at least to some degree –in the described product design, which bases on average power volumes.

To ensure an economically efficient and stable future power system in times of an increased feed-in of renewable energies and an associated growing flexibility demand, adjustments to the existing power trading system will be necessary. Therefore, this paper elaborates in the first step on four different evolutionary adjustments of existing power market products at the power exchange. In particular, the focus of the described adjustments lies on various parameters that determine current power market products and corresponding trading. These parameters include (1) local pricing, (2) temporal granularity, (3) gate closure times, and (4) minimum volumes. Enabled by substantial advances in technologies for data collection and processing, in a second step we also highlight the need to change the current perspective of power trade and to bring trade much closer to the possible operating modes of power plants, including their underlying flexibility potentials.

We discuss a shift in power trade with market participants that are able to define products in form of individualized power profiles. In order to trade such individual power profiles, it will be necessary to include the actual profile of power consumption or feed-in as a new parameter in the design and pricing of power products. Such a shift in electricity trading will require a change in current matching procedures on intraday markets towards so-called cross-matching, i.e., the matching of multiple orders instead of current bilateral intraday trade and the introduction of power as a new product parameter. To be able to implement profile trading, it will be necessary to measure the actual quantity of power with a finer temporal granular resolution within the imbalance settlement period, for example by using smart meters.

The proposed new perspective on power trade opens up a number of technical, legal and economic questions that research and policy must address in the future. Overall, an important policy task will lie in the determination of the right balance between arising system transformation costs and the expected benefits of the new system by taking effects on the different stakeholders into account.

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VIII.4 Research article 4: The Impact of Substituting Production Technologies on the Economic Demand Response Potential in Industrial Processes

Authors:

Michael Schöpf, Martin Weibelzahl, Lisa Nowka

Published in: ***Energies***

(VHB-JOURQUAL 3 Category: -; 2018 Impact Factor: 2.71)

Citation:

Schoepf, M., Weibelzahl, M., & Nowka, L. (2018). The Impact of Substituting Production Technologies on the Economic Demand Response Potential in Industrial Processes. Energies, 11(9), 2217.

Extended abstract:

The industrial sector offers extensive research opportunities for demand response, as it is the most electricity-intensive sector in many countries., still, a large share of the demand response potential in industrial processes is still unexploited (Alcázar-Ortega et al. 2015) and (Müller and Möst 2018). One important barrier to a further exploitation of the demand response potential in the industrial sector concerns the fact that the monetary rewards for a demand response provision can often not compensate for the increased production costs associated with the respective flexibility supply, which will typically involve additional risks for the industrial enterprise. Therefore, existing research distinguishes between the theoretical, technical, economic, and practical demand response potential (Gils 2014) and (Grein and Pehnt 2012). Focusing on the economic potential, the authors of (Paulus et al. 2011) and (Grein and Pehnt 2012) indeed find the highest potential in large-scale and energy-intensive industrial processes. However, the economic potential of those processes always depends on the respective production utilization of the process or technology (Müller and Möst 2018). Obviously, if a process has a utilization of 100 percent, the remuneration for demand–response provision must exceed the opportunity costs for lost production in order to allow for an economically reasonable supply of demand response from the enterprises' point of view. Accordingly, the economic potential of demand response increases with sinking capacity utilization.

Therefore, we argue that a more comprehensive analysis of high energy-intensive production processes is necessary to understand their economic demand response potential better. We consider an industrial production process with substituting technologies that differ in their required input factors. For such a production setting, we provide a generic, linear optimization model, where under certain input-price combinations a given production technology may possibly be substituted by another technology in the derived optimal production schedule. For an analysis of the effects of a substitution of production technologies in the paper industry, we collected real-world data for a production site of a large, international paper producer. We consider two production stages with a special focus on the production of pulp in the first stage, which involves the technologies TMP and DIP. The aggregated production capacity of the two technologies TMP and DIP amounts to around 112 percent of the given final demand implying that there are indeed production overcapacities in the system. While electricity is used as an input factor for both technologies, we only take the input materials wood chips for TMP and recovered paper for DIP into account. We consider 26,304 time periods that correspond to the different hours of the past three years. Electricity prices vary between time periods according to real-world data, where we use fluctuating day-ahead spot prices (historical time series of prices for the German/Austrian EPEX Spot Market from 6 January 2015 to 5 January 2018 are used). The prices for the input materials wood chips and recovered paper are assumed to be constant over the time horizon and only vary between different simulation scenarios.

The described results illustrate, that the economic demand response potential significantly depends on the absolute level of input-material prices as well as on their relative relation between each other. In fact, industrial enterprises must account for such influencing factors including all relevant input parameter constellations in their decision-making processes. This applies both on the operational (e.g., production planning based on input prices) as well on the strategic level (e.g., planning of investments in processing-capacity) in order to react to current energy-market developments. Ultimately, it is therefore necessary to adjust and extend current decision-support systems of industrial enterprises to maximize the realized, economic demand response potential on a micro-economic level. For industrial enterprises, these findings have implications in the short- as well as in the long-run. While operational short-run decisions of industrial enterprises regarding an efficient supply of demand flexibility may highly be driven by price fluctuations of input materials, long-run investments in flexibility options may be affected by expected price developments and fluctuations of main input factors in the future. The latter long-run consideration of the demand response potential is not only relevant for individual enterprises, but also for decisions on a macroeconomic and policy level. As the future power system with a steadily growing penetration of renewables requires additional flexibility, information on the availability of the demand response potential as well as on its main influencing factors is crucial. Research on demand response should therefore account for the relevant scenarios with respect to input factor price developments in order to make valid projections about the available demand response potential in the future.

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VIII.5 Research article 5: Don't lose sight of the big picture: A holistic view on sector coupling

Authors:

Gilbert Fridgen, Robert Keller, Marc-Fabian Körner Michael Schöpf

Currently under review

Citation:

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Extended abstract:

Sector coupling (SC) describes the concept of a purposeful connection and interaction of energy sectors to increase the flexibility of supply, demand and storing. While it currently focusses on counteracting the challenge of temporal energy balancing induced by the volatile feed-in of renewable energy sources, research considers SC as one of the most promising concepts to succeed the energy transition.

The currently prevailing understanding of SC, however, focusses on counteracting temporal RES challenges (Robinius et al. 2017), while it does not encompass the dimension of spatial energy balancing. We, therefore, reflect that the current understanding of SC – which we hereinafter refer to as *inter-sectoral energy flow* – should only be considered as a subpart of SC. In contrast, most approaches that consider spatial energy transportation (Lund and Kempton 2008; Brown et al. 2018) reflect one sector only (hereinafter referred to as *intra-sectoral energy flow*) (Lund et al. 2017; Mancarella 2014).

Moreover, since prevailing research on SC considers separate approaches consisting of inter-sectoral couplings, it does not examine the requirements and challenges induced by an efficient coordination of several sectors, grids and energy flows. Applying a holistic view – including cross-sectoral coupling for spatial energy transportation – consequently lead to the reflection of all grids that transport energy in any form. We broaden the scope of the current perception of energy carriers and energy grids by including energy that is bound by its conversion to the consumer for its respective use: The power-to-product concept provides the idea of a purposeful usage of physical products as means of energy storage (Schumm et al. 2018; Khripko et al. 2017).

Extending this idea further to non-physical products (like digital commodities), we also reflect communication grids to be part of SC for the virtual transportation of energy (Fridgen et al. 2017a). Therefore, we introduce a holistic view on sector coupling, which incorporates cross-sectoral energy flows, i.e. the coupling of several sectors, thereby merging intra- and inter-sectoral energy flows.

This view provides an opportunity to establish new methods for minimizing losses or costs of spatial energy transportation by cross-sectoral energy flows, thereby leading to an enhanced definition of SC. For modelling energy flows in a holistic view on SC, we adopt the traffic assignment problem (TAP) that research on logistics and routing optimization widely uses to calculate the most efficient allocation of (spatial) traffic flows (Sheffi 1985). By using different loss structures, we illustrate how a holistic view on SC minimizes transportation losses.

We demonstrate two scenarios to illustrate possible cross-sectoral energy flows. Scenario 1 encompasses the coupling of an electricity grid with a transportation grid. Scenario 2 encompasses the coupling of an electricity grid with a communication grid. Based on this model, we derive the implications that SC can minimize losses of a spatial energy transportation by reflecting cross-sectoral energy flows, SC should include all grids that transport energy in any form and that SC can reduce the planning of infrastructural excess capacities.

Still, to allow these potential to be realized, policy makers need to shape incentivizing market mechanisms and – where necessary – according to the desired goals of the energy system. A further challenge arises from the fact, that national borders do not stop energy flows. As there are different goals in the energy systems and different degrees of competition allowed, it is currently not feasible to build a consistent framework of incentives on a transnational level. Facing increasing efforts on climate change mitigation, also an increasing harmonization of energy policy and an international view on cross-sectoral energy flows is necessary.

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