Shaping and Evaluating Information Systems Enabled Demand Flexibility in Markets for Nonstorable Exchange-Traded Goods

Dissertation

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Abstract

The insight that demand flexibility bears value under uncertain price development is fundamental to this thesis, which studies such flexibility in timing the procurement of exchange-traded goods. When market prices vary, it can be possible to fulfill time-independent requests for a given product or service at lower prices. In that sense, the thesis addresses electricity and cloud computing, which both can be considered non-storable goods that require immediate consumption. Therefore, both the established, liberalized electricity market and the rapidly growing cloud computing market could make beneficial use of short-term demand flexibility. The involvement of information systems and technology facilitates that use and makes it likely for these two markets to be more closely interrelated in the future.

Consequently, this thesis provides an outlook on market structures that may become more relevant in the future. It unites four research papers and contextualizes their contribution. Two research papers advise on scheduling flexible demand in electricity markets (Paper 1 — *Providing Utility to Utilities: The Value of Information Systems Enabled Flexibility in Electricity Consumption*) and a cloud computing market (Paper 4 — *Scheduling Flexible Demand in Cloud Computing Spot Markets: A Real Options Approach*). Both papers introduce real option models and analytical algorithms for evaluating temporal demand flexibility in the respective markets.

Options to reduce electricity costs or to join microgrids as decentralized consumption structures can shape demand flexibility. In a mixed methods research approach, Paper 2 — *Electronic Markets for Electricity Procurement by SMEs: Determining Price-Impacting Factors and their Influence on the Outcome of Electronic Reverse Auctions* — investigates price-impacting factors when companies auction their electricity supply in an innovative form of electricity procurement. Paper 3 — *Framing Microgrid Design from a Business and Information Systems Engineering Perspective: A Framework and Agenda for Research* — systematizes the microgrid construct. This thesis thus contributes to understanding and embracing new possibilities opened up by information systems, such as electronic spot markets and exchange trade, electronic reverse auctions, automated load shifting decisions, and microgrids.

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1 Introduction

1.1 Temporal Character of Demand Flexibility

In economic theory and practice, the flexibility of market participants is what enables negotiations (Druckman and Mitchell 1995). Flexibility is the characteristic that lets them adjust their supply-side offers or demand-side bids to conclude contracts and conduct trade. Any willingness of suppliers and customers to adapt these offers or bids will facilitate reaching consensus. As prices are formed through matching offers and bids, price expectations and the price sensitivity of the market participants contribute a vital part to their flexibility (Nishimura 1989).

Depending on which goods or services a supplier and customer negotiate about, different types of flexibility can apply and could be necessary (Fridgen et al. 2016a). Accordingly, there can be price-influencing flexibility components regarding

- The product or service itself considering a substitute thereof,
- The quality and variants of a product or service,
- The quantity, size, or extent of the product or service,
- The place of fulfillment or a spatial/shipment surcharge, and
- The timing regarding start, duration, intervals, and end of fulfillment.

The latter — temporal flexibility — represents an integral and market-enabling flexibility component, because fulfillment to the customer applies to most goods and services.[1] When market prices vary (i.e., offers and bids match at frequently differing prices), producing or consuming a given product or service at a sooner, a later time or at a varying pace can markedly affect the applicable price and save money. The term *temporal demand flexibility* (Ross 2017) has been coined to refer to customers' willingness to bring their demand forward, to interrupt, or to postpone it (Fridgen et al. 2016a, p. 3).

Recognizing the value temporal demand flexibility carries is crucial to deploy it consciously. Based on market signals, such flexibility serves to control supply or consumption. The fulfillment of product orders or service requests can be cheaper when such

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[1] Commonly used in plural only, *goods* mean "products that are bought and sold in business"; *products* depict "something produced by physical or intellectual effort" — both definitions cited according to Schönsleben (2019, p. 28). Generally, this thesis refers to "goods" (in plural) or "a product" (in singular) synonymously. It distinguishes *services* in section 2.1.2.

orders or requests are time-independent. Suppliers are likely to be interested in contracting with consumers whose elastic demand can help them cut production costs or purchase prices. They could also benefit from better capacity utilization and possibly increased overall customer satisfaction (Klaus et al. 2014). If they charge lower prices or offer compensation to customers who furnish the required portion of their temporal demand flexibility, a customer benefit can result as well. In order to realistically shape elastic demand, consumption behavior thus needs control and adequate incentives (Strbac 2008).

As a buffer, both suppliers and customers could stockpile goods in order either to fulfill deliveries or to make their demand at a later time, if applicable. However, this is not possible for all goods; with *nonstorable* goods or services, stockpiling is not an option. Therefore, it appears appropriate to develop strategies regarding seizing temporal demand flexibility for nonstorable goods or services that require immediate consumption. This thesis investigates such strategizing.

1.2 Benefits of Temporal Demand Flexibility in Electricity and Cloud Computing

This thesis selects two markets for studying nonstorable goods or services that could make beneficial use of temporal demand flexibility — an obvious one, namely electricity, and one that is shaping the future, namely cloud computing. These markets have a *real-time market* character in common, sharing the feature of frequently quoting prices in exchange-like trade (Papers 1 and 4). The thesis attaches great importance to the involvement of information systems (IS), which facilitate such trade and the development of the selected electronic markets. Cloud computing services represent a digital product in itself, but also in the electricity market, IS enable higher productivity and new operating models. In the future, these two markets will likely be more closely interrelated or connected (e.g., Markovic et al. 2013; Thimmel et al. 2019).

The nonstorability feature mentioned above holds for **electricity**, which is electrical energy flowing from a generating unit to a place of consumption. Over a given period, it is metered in kilowatt-hours (kWh) or megawatt-hours (MWh). Electricity is a complicated product, as, by its nature, storage is complicated (Borenstein et al. 2002). Consumers need electricity to be instantly available and delivered appropriately at the time of consumption. Even so, electricity supply and demand vary continuously, so that a physical balance is fragile, but its maintenance requires coordination (Lund et al. 2012) — as expressed in an obligatory *system frequency* inside a close range.[2]

The term *electricity storage* is in common use; however, this general term obscures that, in a strict physical sense, electricity can only be stored for a short time, that is, as a load in a capacitor, which is customary in smaller scale circuits and electric relays (Bird 2017). Apart from such brief storage, electricity is fleeting. Any use, even ad hoc consumption, is subject to losses, which one measures in a degree of *energy conversion efficiency*. Although this characteristic complicates storing electricity, one can transform electrical energy into other energy forms that are easier or more economical to store. 'Electricity storage' therefore typically refers to its transformation and storage in another energy form (Komarnicki et al. 2017). Storage forms include batteries and fuel cells, pumped water, heat, ice, compressed air, electrolytic hydrogen, mechanical spring systems, and flywheels (Chen et al. 2009).

These modes of transformation can conserve parts of the original energy, despite two associated drawbacks. First, some conservation technologies entail environmental, social, or economic disadvantages. For example, batteries formerly required toxic or rare earth elements, and had an insufficient capacity as well as a short lifespan despite high costs and space requirements (Chen et al. 2009, p. 297). New-generation, highly efficient batteries at large scale are currently under development. Second, regaining the electrical energy is lossy — i.e., costly in terms of what is lost in the process of regaining the stored energy. Even one of the more efficient conservation approaches — pumped hydro storage with turbines — is neither free of losses nor instantaneously available. Additionally, social acceptance is limited when pumped storage facilities fill mountainous areas, aesthetically damaging the landscape (Chen et al. 2009, p. 310).

Consequently, ordinary operating conditions preclude economically favorable stockpiling or rationing of electricity. This restriction contrasts starkly with other, storable goods. Temporal demand flexibility can therefore be a source of value and a support in controlling the physical balance in power grids (Fridgen et al. 2016a). Electricity suppliers and system operators can benefit from integrating flexible consumers, and in fact rely on such flexibility in return for compensation (Figure 1).

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[2] In Europe, this system frequency amounts to 50 Hertz (Hz); in North America, it is 60 Hz.

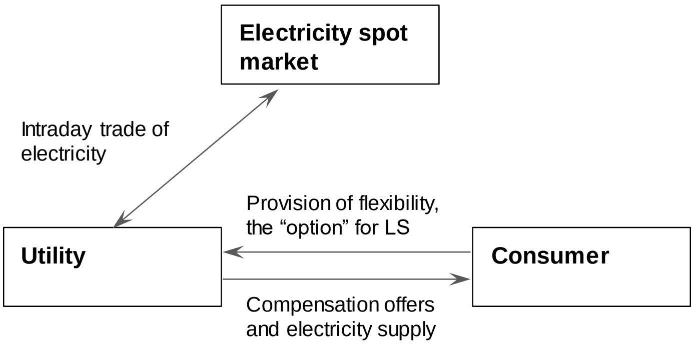

Figure 1. Flexibility Provision in Electricity Markets (Paper 1, Figure 1)

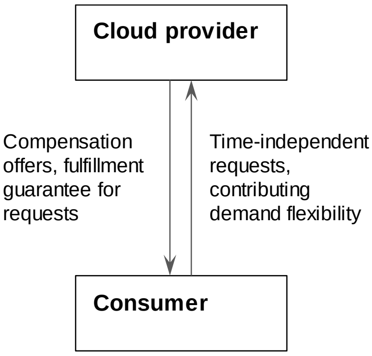

Figure 2. Flexibility Provision in Cloud Computing Markets

Next, despite a less ubiquitous use in comparison to electricity, there is a growing demand for **cloud computing**. This demand is expressed in continuously rising investments and leading service providers’ strong market positions (Costello 2019). Cloud services in high demand include on-demand data processing power and data storage in remote data centers around the world. The *cloud* metaphor denotes the nebular appearance of the provisioning resources and their physical location to customers. Nonetheless, a trend towards standardization has increased transparency (Keller and König 2014). This trend makes cloud computing a candidate for commoditization and fulfills at least one criterion of exchange trading concepts.

Nevertheless, in the light of all kinds of commodities, dynamic pricing and exchange trading of cloud services are an exception. Instead, current cloud pricing models mostly do not directly reflect variable costs the providers incur for operating cloud resources (Bestavros and Krieger 2014, p. 74). Temporal demand flexibility will be of value to cloud providers who could smoothen their service production costs and data center utilization (Paper 4). Customers would expect guaranteed fulfillment of their time-independent requests but could obtain incentives, allowing them to generate cost savings (Figure 2; Ishakian et al. 2012). Variable prices, which are a precondition to employing temporal demand flexibility in the cloud market, could result from the exchange trade of cloud services; additionally, pioneering providers have already introduced dynamic pricing mechanisms. If and when such developments continue, both providers and cloud customers can benefit from improving their cost position in the overall market.

1.3 Intended Contribution and Research Questions

This thesis intends to study demand flexibility in timing the procurement of nonstorable exchange-traded goods. It distinguishes traditional markets for electricity and the younger market for cloud computing services. Established electricity market structures provide efficient trading mechanisms, yet they are still evolving. In cloud computing, provider-neutral market structures are not a standard yet, as this thesis will illustrate.

Common to both of the studied environments is the insight that flexible, time-independent demand bears value and savings potential. Demand is the object of consideration, in its interaction with the supply on marketplaces, especially in exchange trading. Fluctuating market prices that arise in intraday trading on spot markets (an example being stock exchanges) are the prerequisite to realize savings.

First, the thesis focuses on evaluating such demand flexibility in real time — a role that models and analytical algorithms will be able to fulfill when integrated into information systems' automated decision support. The second focus is on the influences customers take through their choice of novel electronic procurement channels and their integration into local consumption structures. IS enable the platform character of such electronic marketplaces and control the balance of decentralized electricity grids (Slavova and Constantinides 2017).

For **evaluating information systems enabled demand flexibility** in the electricity market, this thesis contributes a formal evaluation model and an analytical algorithm (Paper 1). The relevant research question (RQ) is:

> *RQ 1: How can one quantify the monetary value of IS-enabled, short-term flexibility in consumer demand for electricity using real options analysis?*

This approach is mainly relevant for electricity suppliers (utilities)[3] in the wholesale electricity market, from which they procure electricity to supply their customers. Because they are likely to pass on higher wholesale prices but might also provide an incentive for sharing temporal demand flexibility, Paper 1's setting is also relevant to the prices consumers are to pay for their electricity supply.

It is not certain which factors additionally influence the electricity prices corporate consumers have to pay. For small and medium-sized enterprises (SMEs), the thesis

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[3] In this thesis, 'electricity supplier' and 'utility' are used synonymously unless otherwise specified.

investigates this question of additional influences by studying the data from electronic reverse auctions as an innovative form of electricity procurement (Paper 2). The two corresponding research questions are:

> *RQ 2: What factors impact the electricity price for SMEs on electronic electricity markets?*
>
> *RQ 3: What influence do the identified factors exert on the electricity price?*

Companies' or individuals' self-consumption of electricity is a factor **shaping information systems enabled demand flexibility**. The rationale behind this is that the opportunity to consume self-generated electricity increases flexibility when it comes to scheduling and sourcing the residual demand.

Scheduling generation and consumption is a central problem in microgrids. Microgrids are decentralized electricity grids restricted to enclosed premises and containing generation capacities, loads, and an intelligent controller. Paper 3 systematizes this construct and sets up a framework to guide subsequent microgrid research in the business and information systems research discipline.[4] The two specific research questions are:

> *RQ 4: What framework can structure design options that interdisciplinary literature describes for setting up a microgrid?*
>
> *RQ 5: To which aspects of the microgrid concept should BISE/IS researchers direct further effort?*

Back to the starting point, models to evaluate information systems enabled flexibility in electricity consumption can also be applied to other **markets for nonstorable exchange-traded goods** with fluctuating prices. In cloud computing, such dynamic pricing is a more recent approach that the provider Amazon Web Services has put into practice. Paper 4 therefore advises on scheduling flexible demand in cloud computing spot markets. It answers the research question:

> *RQ 6: How can cloud services customers quantify and exploit their demand flexibility's monetary value by using real options analysis and given uncertain short-term price development?*

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[4] Research paper with lead authorship of the thesis author, c.f. appendix, section 7.3.

2 Temporal Flexibility in Markets for Nonstorable Goods

2.1 Classes and Tangibility of Nonstorable Goods

When products are not suited to be stored, challenges to their sale and consumption arise. As such *nonstorable goods* are unfit to be held in storage or buffer, they need to be sold and consumed (or further processed) no later than their production is complete (if necessary, their delivery or transmission is included in transacting) because they would otherwise perish. This definition implies that consumers use nonstorable goods directly on receipt. Hence, nonstorable goods constitute a less flexible and contained class of products.

In their purest form, one cannot actually possess nonstorable goods in the sense of having or holding them. Consequently, nonstorable goods are identified as *non-stock items*. A company will never hold such in stock, although it may purchase the goods with a degree of regularity (Lomas 2019). However, one can own the infrastructure to generate or transmit such goods.

Due to their nonstorability, such goods are subject to ad hoc consumption. The designation *ad hoc goods*, however, is untypical — or a further specialization. The term could denote specific goods that a consumer procures on the exact occasion as it is needed (Lomas 2019). In contrast to non-stock items above, a company procures ad hoc goods less regularly, without planned consumption. “An example of an Ad Hoc item is a specialized item of diagnostic equipment which you would purchase on one occasion only” (Lomas 2019).

To structure nonstorable goods, distinguishing them based on their tangibility is appropriate: “Goods, products, and materials can be either *tangible* or *intangible*” (Schönsleben 2019, p. 29). In this context, tangible/physical and intangible/nonphysical categories are each considered a synonym pair.

The nonstorable goods electricity and cloud computing services, which are both subject to regular consumption, are the subject of this thesis. It necessarily excludes other markets, particularly those for storable goods. Storing goods enables buffering the goods’ in- and outflow and, therefore, buffering financial consequence too. This thesis does not intend to study such an arbitrage effect.

2.1.1 Tangible Nonstorable Goods

One can commonly hold tangible or physical goods in storage due to their material substance, which occupies physical space. In this class, nonstorability is an exception due to specific circumstances that are partially associated with *non-durability*. That is, the goods, such as raw meat (e.g., pork sides, which is an exchange-traded commodity), are perishable, or they are other agricultural products that spoil after a short period of storage. More generally, such goods' constitution transforms during storage, which affects their usability or appearance in an undesired way. Hence, one can classify such goods as nonstorable or 'low-storable'.

Other tangible products can be difficult to store economically if they have an exceptionally high or rapidly decreasing value, a large size, or distinct requirements, such as special caring and sheltering conditions (e.g., livestock).

2.1.2 Intangible Nonstorable Goods

Nonphysical goods take an intangible form. Due to their lack of material substance, one cannot physically hold intangible goods, whereas it is typically unproblematic to keep them in another, particularly digital form. Therefore, nonstorability rarely applies to intangible goods in their typical sense as products that are created to remain in virtual storage or on balance sheet. However, one can perceive and consume some intangible goods only by means of an instrument or a particular medium.

Consolidating concepts of investment, value creation, and intellectual achievement, intangibles are generally discussed in a variety of economic fields. Yet, "[t]here is not a unique nor unanimously accepted definition or classification of intangibles" (Grasenick and Low 2004, p. 268). Observable approaches group information, virtual goods, and services as intangibles:

- *Information* can be stored in written form or virtually in its building elements — as *data*. They are the subject of information systems.
- *Virtual goods* or *digital goods* (e.g., software, licenses, audio/video material) can be stored in the same way, because they "are disembodied goods in the sense that they can exist without embodiment in a physical form" according to Bhattacharjee et al. (2011, p. 2), who amend five "digital goods identifiers." Digital Rights Management ensures ownership or similar sufficient access rights.

- A *service*, historically and in its result-oriented definition (Buhl et al. 2008), is fulfilled interpersonally, face-to-face. On the one hand, services do not typically involve a transfer of ownership; instead, they are consumed when provided — a process-oriented definition (Buhl et al. 2008). (Excepting that a product created in the course of service delivery could be transferable.) In contrast, intangible goods differ from typical services in that, commonly, they are transferable and tradeable. On the other hand, services provide economic value and fulfill the lack of physical substance. These arguments justify lifting the classification restriction so that services are now classified as nonphysical, immaterial goods (Buhl et al. 2008). In a more precise distinction, these intangible services are "use-oriented" (Schönsleben 2019, p. 31). Given that, they are mostly nonstorable goods (Jansson 2013).

Consequently, only some nonphysical goods fulfill the definition of nonstorable goods. Observable evidence suggests this is limited to any services and goods that one can only consume on a specific occasion and time before they are void. Securitization in the form of an entitlement or a ticket can be an indicator.

Intangible nonstorable goods include **cloud computing services**, which encompass data processing and virtual machines, data storage, and rental software, amongst others. Cloud services can be measured in units of time, computing power, or similarly "on the basis of a performance indicator that is measured as a percentage" (Schönsleben 2019, p. 31). Under the necessary conditions, they can be traded in a harmonized way (section 4.3.2). This handling attributes them the character of virtual goods, although cloud computing services cannot be stored: a provider creates them at the moment of use (Buhl et al. 2008). Hence, they are "non-storable and time-critical" (Dorsch and Häckel 2012, p. 5), accessed at the time of creation.

It is not self-evident and justifies a closer look that this also applies to cloud services that themselves relate to the storage of data. The fact that such storage services cannot be easily interrupted or buffered counters their storability: At any moment, sufficient storage services allow for saving an amount of data. Interrupting or throttling these services would entail (partial) data loss. Likewise, for a given amount of data, there is no advantage in temporarily obtaining excess storage services. Consequently, data storage services need to be provided adequately in the moment of consumption. They are just as dated, perishable, and nonstorable as other cloud computing services.

Furthermore, the examples of transportation, entertainment, and **touristic products** or services are characteristic of intangible nonstorable goods (Wu et al. 2002). For instance, firmly reserved travel arrangements, flight seats, and event tickets are nonstorable according to the definition because one cannot sell or consume them later than on completion of their production. For further consideration, this distinction could incite an academic discourse on whether transportation and touristic products like flight seats predominantly resemble services or intangible goods.

2.1.3 Between Tangible and Intangible Nonstorable Goods

On the interface between tangible and intangible nonstorable goods, the characteristics of a distinguishable class of goods complicate assigning them clearly to one of the previous two categories. Concerning the prominent example relevant to this thesis, the literature assigns **electricity** ambiguously due to it exhibiting characteristics of both categories:

On the one hand, physically speaking, electricity is energy transmitted through electric current and electric potential. Therefore, one can physically observe the generation and distribution of electricity similarly to a completely tangible product. Additionally, electricity is an electric utility's product, which it differentiates in voltages and current.

On the other hand, electricity lacks material substance, and to consumers, procuring electricity often resembles service procurement: Consumers do not actively purchase electricity as an item in pieces or units; rather, a utility company they choose services them by supplying the total amount of electricity required and consumed without further notice. Distributing a product generally would not be a service in itself; nevertheless, consumers experience a product- or use-oriented service of operating their devices through the consumption of electricity (Schönsleben 2019, pp. 30 f.). This viewpoint "consider[s] the reason for using energy, […] and its reliability, i.e., the probability that supply would be available" (Fuentes-Bracamontes 2016, p. 17). Statements such as "the power is down" instead of "they deliver no power" or "power is out of stock" depict how consumers grasp consuming electricity as a service. Similarly, it appears in the history of power supply that consumers were "baffle[d] at the immaterial nature of electricity and the […] intangible consumption" (Gooday 2016, p. 3).

At the very least, many consumers perceive electricity as a commodity. Therefore, utilities strive to differentiate their energy product or service, for example, as ‘green power’. Overall, electricity supply features characteristics of both tangible and intangible goods. The introduction given above (section 1.2) has discussed electricity’s nonstorability. Electricity distribution is a servicing process in the utility’s ownership, while there is ownership transfer to the consumer. Wu et al. (2002) apply the same classification: their “model assumes that the good in question is non-storable, as in the case of such markets as electric power [...] and other service industries with dated/perishable goods” (Wu et al. 2002, p. 672).

2.2 Demand-Side Decision Flexibility under Uncertainty

2.2.1 Option Character and Value of Deferred Decisions

Customers who share their temporal demand flexibility with suppliers equip them with the right to decide on the time of fulfillment. A use-case from the electricity market illustrates that idea: Consumers who allow electricity suppliers or system operators to control their devices through load control agree to have them remotely started (e.g., washing machine, electric car charging[5]) or interrupted (e.g., freezer, air conditioning). Such *load shifting* implies earlier or later use of those devices, or another course of use, than consumers would intend to when free from external influence.

Load shifting succeeds because electricity (and cloud) markets feature times of day with higher and cheaper spot prices on average (Paper 1, Fig. 5; Paper 4, Fig. 1). Thus, there are price changes — particularly in a downward direction — of which load shifting can take advantage. Research has developed approaches to make such demand flexibility assessable in monetary terms, to calculate or estimate the achievable savings (Biegel et al. 2014).

Nonetheless, because the right to shift loads is not an obligation to the suppliers, they are equipped with an option of deciding and acting. Their decisions on initiating load shifting and on initiating delivery each are possible in one or more points of time. Although there may be conditions, such as a maximum deferral or excluded periods, a

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[5] For the description of load shifting in a plug-in electric vehicle instantiation, see Paper 1, pp. 551 f.

right to seize temporal demand flexibility increases suppliers' liberty and, in turn, their own flexibility. Decisionmaking should therefore take the value of such options into account (Crasselt and Lohmann 2016, p. 351).

As formalized methodological constructs, options (*financial options* and *real options*) enable grasping the value of such flexibility to act or decide at a later point in time. Modeling and evaluating such options is not trivial, as it means "to estimate option values at every decision point drawing on information from all future periods" (Crasselt and Lohmann 2016, p. 351). However, analytical solutions have long been available (Black and Scholes 1973; Cox et al. 1979). In research and business practice, it therefore is a common approach to employ option constructs to model complex situations. Particularly, "option-like situations in non-financial markets, often referred to as real options, are usually discussed and analyzed in the context of investment decisions [..., but] also frequently encountered in operating decisions" (Crasselt and Lohmann 2016, p. 351).

2.2.2 Application of Real Options Analysis

Real options reflect the managerial flexibility to act and decide under uncertain conditions. They represent different types of rights, including the option to postpone a decision and wait for changed conditions (*deferral option*). Modeling real options can thus grasp the option character of deferred decisions in the markets studied in this thesis. A benefit of real options is their analytical relationship with financial options, which allows replicating and evaluating a real option as a financial option (Copeland and Antikarov 2003). This method is called real options analysis (ROA).

In fact, real options theory originated from financial option valuation, an established methodology with a sound formal foundation (Paper 1, p. 540). The concept of real options is distinct in the type of underlying asset: any physical product or investment that is not an exchange-traded security can form the underlying. IS research applied ROA to cases from multiple sectors, with a focus on IT investment decisions (Benaroch and Kauffman 1999; Diepold et al. 2009; Ullrich 2013). With relevance to this thesis and with respect to uncertainty in electricity prices, ROA has been used for assessing investments in electricity generation capacities (Deng and Oren 2003; Martinez-Cesena et al. 2013; Ronn 2003) and flexible electricity consumption (Fridgen et al. 2015b; Oren 2001; Sezgen et al. 2007). Cloud computing research as well has applied ROA to support timing, staging, and termination decisions (Alzaghoul and Bahsoon 2014; Jede and Teuteberg 2016; Naldi and Mastroeni 2016; Yam et al. 2011). Paper 4 (p. 4) also gives instances of applications to general IT assets.

This thesis refers to deferral options, which is an established real option category (Papers 1 and 4). For analytic assessment, one can model a deferral option as a (financial) *call option*, which is "a right, but not an obligation, to buy an object (e.g., an asset) at a previously fixed price" (Paper 1, p. 552). A methodologically sound ROA approach fulfills formal prerequisites, as studied by Ullrich (2013). Primarily, it identifies an appropriate underlying that one is able to price dependably over the time of the real option's validity. The need for defining an underlying and, if its price is variable, for modeling that price movement is an initial step in establishing a real options model (Fridgen et al. 2014a; Fridgen et al. 2015b).

Developing adequate stochastic processes allows capturing the respective underlying's price development and assessing real options on both electricity and cloud computing services. Papers 1 and 4 have shown that this methodology subsequently permits evaluating a replicated call option through the binomial tree model (Cox et al. 1979) and variations thereof (Tian 1993).

3 Flexibility in Electricity Markets

3.1 Electricity Markets

3.1.1 Electricity Trading Mechanisms

Electricity markets allow for the trade of electricity: participants place offers to sell or bids to buy various forms of electricity contracts and derivatives. Under the relevant regulatory conditions, electricity markets match these offers and bids, determining an equilibrium price that is fundamentally subject to the principles of supply and demand (Buhl et al. 2019).[6]

The traded objects include predominantly standardized *physical electricity contracts*, which denote an obligation to deliver electricity, but may also be derivative financial instruments or contracts for difference. Their time standardization implies monthly, quarterly or annual delivery periods encompassing hourly, daily, or weekly time bands of continuous electricity delivery (e.g., *base load* for a day, *peak load* for twelve hours of daytime, c.f. Figure 3). Most instruments are similarly observable in European and North American electricity markets (Paper 1).[7]

Such markets take the organizational forms of energy/power exchanges or bilateral *over-the-counter* contracting (e.g., brokered via electronic platforms, Paper 2). This thesis focusses on exchange trading, such as it takes place on the European Energy Exchange (EEX) or the European Power Exchange (EPEX SPOT).

Historically, the Norwegian power exchange Foreningen Samkjøringen (literally 'Coordination Association') formed in 1932 was the pioneer. Through mergers by the 1970s, electricity suppliers from all over the country joined the eastern Norwegian founders (Skytte 2015). This exchange was the predecessor to today's all-Scandinavian electricity exchange Nord Pool established in 1996 after Norway and Sweden had deregulated and

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[6] *Acknowledgment:* Buhl et al. (2019) is a study (second edition) from the research project *SynErgie*'s work item IV.2.1. 'Synchronized and energy-adaptive production technology for flexible alignment of industrial processes towards a fluctuating energy supply' (SynErgie) has been a federally funded Kopernikus project for the energy transition since 2016. With the University of Bayreuth's participation, this research project has been striving to study and extend demand side management activities in the German manufacturing industry, to better adjust the electricity consumption in production processes to the fluctuating supply from renewable energy sources.

[7] On differences of European and North American electricity markets, see section 3.3 in Paper 1.

unified their electricity markets (subsequently joined by Denmark and Finland). Nord Pool also assisted in establishing German and French electricity markets, which have combined to form EEX and EPEX SPOT by today.

In the 1980s, other efforts to introduce electricity market structures included a South American model (Chile and Argentina) and pricing research at Bostonian universities by Schweppe et al. (1988) who suggested a framework for establishing such marketplaces. During that time, most European countries had a *monopolistic electricity supply*: suppliers and grid operators combined in one entity necessitated state regulation for consumer protection purposes (Jamasb and Pollitt 2005).

In Europe, former supply monopolies diminished in the course of the British electricity supply privatization and the continental *liberalization* of the electricity system. With a series of electricity market reforms since the mid-1990s, the European Union aimed to empower market structures (Helm 2014) and to promote competition in both the wholesale market and among ‘electricity retailers’ (Jamasb and Pollitt 2005). The liberalization indeed increased market efficiency and reduced electricity prices (Moreno et al. 2012). Germany implemented the reform in 1998.[8]

Hence, depending on the country and legislation, electricity markets have gained a competitive structure over the last 30 to 50 years. Electricity and balancing power trading has evolved and attracted participants. Today, not only electricity generating companies and electricity suppliers participate in electricity trading. With energy-intensive companies, renewable energy producers, and aggregators, non-traditional participants have entered the market, trading smaller aggregated volumes of electricity as compared to suppliers and traditional producers.

Over the decades, electricity supply thus experienced liberalization, the markets’ evolvement and their change of shape, increasing trading volumes and transaction numbers. Information systems have turned out to favor such dynamics, as market operators can realize smaller transactions in a shorter time only with the help of IS. Today, electricity marketplaces “represent some of the most information-intensive instantiations of markets due to the volatil[e]” electricity generation and consumption (Wörner et al. 2019, p. 3).

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[8] The revised *Energy Industry Act* („Energiewirtschaftsgesetz”) came into force on 29 April 1998 (BGBl. 1998 I, pp. 730–734).

3.1.2 Energy-only Market

It is typical for market participants to "secure medium- to long-term supply for base and, partially, peak loads far in advance through generation capacity, bilateral supply contracts, and/or acquired futures contracts. Nevertheless, ultimately, they need to bring fluctuating demand in line with supply in the short term" (Paper 1, p. 541; c.f. Figure 3). This sourcing is the motive for using a chronological sequence of electricity markets jointly forming the *energy-only market* (EOM): these markets allow for trading electricity from a long period in advance until shortly before its actual physical delivery (Buhl et al. 2019, p. 10).

The **futures market** opens the EOM sequence. It serves to secure supply and demand in the medium to long term, up to several years ahead. The traded futures are binding contracts on future physical electricity delivery or the financial equivalent. EEX's Power Derivatives market permits the trade of *Phelix* futures for up to six years ahead (e.g., in high volumes for the German power system, EEX 2019b). This EEX market also makes options available as derivative financial instruments on electricity. Again, options are a right, but not an obligation, to procure an amount of electricity at a fixed price and a time within or at the end of the option's validity (Buhl et al. 2019, p. 11; EEX 2019a). Market participants can use both instruments to protect themselves from price, volume, and availability risks (*risk-hedging*), by either procuring electricity in advance with futures (Dong and Liu 2007) or by preserving decision flexibility with options (c.f. section 2.2.1).

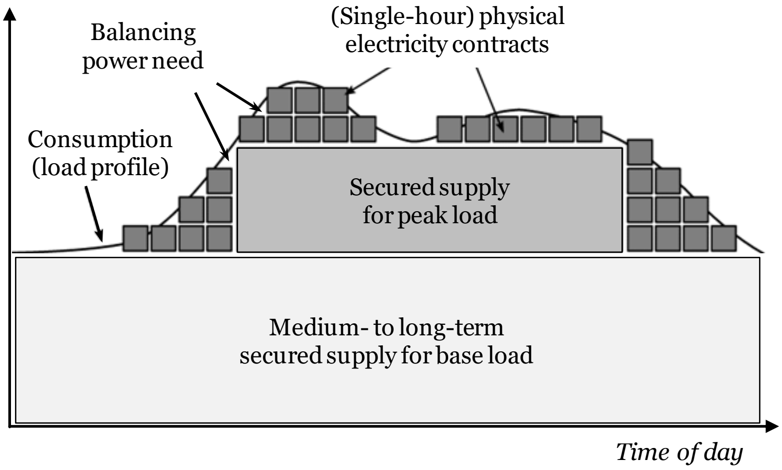

Figure 3. Market Instruments for Adjustment to Consumption
(Paper 1, Figure 2)

The **spot market** is closer to the time of delivery; therefore, it permits refining the approximations from previously entered long- and medium-term contracts: “market participants can further balance their schedules by selling or purchasing replacement [electricity contracts]” (Paper 1, p. 542). The spot market consists of one or more of three sequential subtypes for the short term: day-ahead, hour-ahead, and real-time markets (Umutlu et al. 2011). U.S. American systems are typically limited to real-time markets. “Day-ahead and hour-ahead markets are, technically speaking, forward markets in which participants trade electricity contracts in advance for specific times of the day” (Paper 1, p. 542) — similarly to futures markets but with a much shorter horizon.

In EPEX SPOT’s day-ahead market, participants offer or bid on electricity amounts in a two-sided blind auction (EPEX SPOT SE 2018, p. 4). The placed bids and offers relate to hours, quarters, or blocks of hours of the following day. Sorted by corresponding prices, the supply-side offers yield the so-called *merit order*: renewable energy sources typically feature low marginal costs, therefore take a prime place in the merit order. Similarly, the demand-side bids yield a demand curve. The market operator settles both supply and demand curves after the day-ahead market closes, determining market-clearing prices for each hour of the following day (Paper 1, p. 542).

The panel of day-ahead market-clearing prices can also form the opening prices for continuous trade in the intraday market, as it happens on EPEX SPOT. The closer to delivery, the more critical it gets for supplying and demanding parties to adjust any deviations from their previous predictions, particularly to increasingly accurate weather and renewable energy generation forecasts. For this reason, EPEX SPOT’s intraday market combines elements of both hour-ahead and real-time trading: participants can trade electricity for a future delivery hour of the day (hour-ahead) or for prompt, close to immediate delivery (real-time trade). The hour-ahead trade approaches real-time trade due to the allowed proximity of trading just minutes before physical delivery (Paper 1, p. 543).

In short, the critical reasons for this EOM market sequence are (Buhl et al. 2019):

- Concentrating liquidity over suitable time clusters or bands
- Setting transparent reference prices for continuous trade
- Permitting short-term adjustment to altering generation and consumption
- Adapting trading volumes to increasing forecasting accuracy up to delivery

3.1.3 Function and Characteristics of Spot Prices

Spot prices result as the market-clearing prices from day-ahead, hour-ahead, or real-time trade (in the electricity spot market). Spot prices function, firstly, as a price signal for demand-side market participants to alter their consumption if they have the chance to (c.f. section 3.2.1 on demand response). Secondly, and just as importantly (Umutlu et al. 2011), spot price signals lead energy producers to control their generation, and to dispatch power plants in particular. When the spot price exceeds their marginal costs of generation (including resources, emission rights, wear and tear), producing electricity is profitable. The development of such equilibrium prices over time reflects the relation of physical generation and consumption volumes. Accordingly, influencing factors of this relationship include the mix of energy sources (Moreno et al. 2012).

Nonetheless, technical and regulatory constraints restrict the flexibility of electricity generation, which can cause **negative spot prices**. Such can result when high supply from inflexible generation resources meets low demand (Schneider 2012). “At times, for example, a surge in wind power may coincide with little demand for electricity or slow reduction of conventional power plant capacity. The regulatory framework in Germany, which has given electricity generated from renewable sources feed-in guarantees and precedence over conventional sources, is an origin to such issues” (Paper 1, p. 542; Frondel et al. 2010). In Germany, the gross electricity production from renewable energy sources, the share of renewable energy sources in electricity consumption, and particularly the installed capacity of wind energy plants have risen continually (Federal Ministry for Economic Affairs and Energy and Federal Environment Agency 2019). Because of their intermittency, electricity feed-in from renewables, such as wind, increases supply volatility and, given static demand, price volatility (Moreno et al. 2012; Nicolosi and Fürsch 2009). Thus, in times of peak generation from renewable energy sources and low (industrial) consumption, the spot market for Germany has frequently seen negative prices, for instance on winter holidays (Stratmann 2020).

Highly **volatile prices** can occur in times of a significant supply surplus and deficit alike. For this reason, times of high demand and a supply deficit have been observable as triggering an opposite situation compared to negative prices: *spikes* designate spot price rises of a short period and comparatively large magnitude. They can occur in events that have been unpredicted or difficult to forecast, such as sudden weather changes, transmission grid or major plant outages (Kwoka and Sabodash 2011). It is not a spike when a price-influencing factor and thus the price level change for extended periods. In the EPEX SPOT market for Germany, positive and negative prices are limited and capped (EPEX SPOT SE 2018, p. 7). All of the above give reason for market participants to hedge the price risk inherent in electricity trade with futures contracts or derivative financial instruments.

3.1.4 Balancing Power

Market participants can actively resort to the aforementioned sections of the EOM to trade the adequate physical electricity contracts for settling an imbalance[9] (Figure 3). If their aggregated supply and demand do not equal at any time of physical delivery, transmission system operators will intervene with *balancing power*[10] to achieve the physically necessary balance (Biegel et al. 2014). A 50 Hertz (Hz) system frequency in Europe — or 60 Hz in American power systems — with a narrow tolerance range is required at any time to keep the power grid stable and electricity delivery operating. To achieve this supply-demand balance, the balancing power can be either positive if the demand exceeds the supply (*back-up generation capacities*), or negative vice versa (*interruptible loads*; Hirth and Ziegenhagen 2015).

The transmission system operators obtain balancing power from *reserve resources* (ENTSO-E 2019, p. 20) available from (to-date) non-harmonized markets (Ocker et al. 2016). It is timely reactiveness that distinguishes primary, secondary, and other reserve resources as well as the balancing power obtained from them (Buhl et al. 2019). The transmission system operators conclude long-term contracts with companies that furnish such balancing power. From additional resources auctioned in the short term, they or *reserve allocators*[11] select resources that meet reserve requirements at the lowest prices in real time, until they have achieved the necessary system frequency (Hirth and Ziegenhagen 2015; Ocker et al. 2016).

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[9] Harmonized as in ENTSO-E (2019), the *balance group* — an energy account for a market participant who is responsible for achieving a physical balance — is the object of consideration for equal supply and consumption (which this thesis does not intend to deepen).

[10] Balancing power is also labeled as ‘reactive power’, ‘reserve energy’, or similar – Ocker et al. (2016).

[11] A “Reserve Allocator [i]nforms the market of reserve requirements, receives tenders against the requirements and[,] in compliance with the prequalification criteria, […] assigns tenders” — ENTSO-E (2019, p. 15).

Balancing requirements have been expected to increase in countries with a "growth in renewables [...] as the wind penetration from fluctuating renewables increases" (Biegel et al. 2014, p. 355). To fulfill these requirements more effectively is a reason for a recent European *Electricity Balancing Guideline* (European Commission 2017) aiming at integrating previously national or regional balancing markets. A joint, cross-border balancing power market will combine the transmission system operators' resources, including fluctuating but inexpensive electricity generation from more renewable energy resources. An associated goal is to increasingly integrate flexible consumption incorporated in demand response (section 3.2.2).

3.2 Flexible Electricity Consumers and Suppliers

3.2.1 Market Roles Exchanging Information on Flexibility

Due to the market mechanisms of supply and demand outlined before, there are at least two market-participating groups who can seize temporal flexibility in an electricity supply contract. First, electricity suppliers (including utilities) can use flexibility potential to control their electricity production, if applicable. Since the 1998 market liberalization (section 3.1.1), they are also free to procure the electricity needed to supply consumers from the electricity markets without holding own generation capacities (Jamasb and Pollitt 2005). Second, consumers can make use of temporal demand flexibility to opt for adequate tariffs or to share it with suppliers who, in turn, incentivize and employ flexibility potential. Such flexibility only gains value when the actor able to generate immediate savings from it in the wholesale market, which in both cases is the electricity supplier, knows about the extent of available flexibility potential. Conversely, suppliers must let consumers know when they request or retrieve a portion of demand flexibility. Such a mutual need for information in electricity supply (Watson et al. 2010, pp. 26, 31) — an instance of initial information asymmetry — necessitates information exchange between consumers and suppliers (Fridgen et al. 2014b).

The *Harmonised Electricity Market Role Model*, which "covers both the wholesale and retail electricity markets" (ENTSO-E 2019, p. 5), distinguishes the groups of electricity market participants that exchange information on electricity production and consumption through IS. The groups "Producer" and "Consumer" are ultimately relevant to a market interaction based on supply and demand flexibility because they are entitled to exercise the control outlined above. Both are grid-connected parties “that contract[] for the right to consume or produce electricity at […] Accounting Point[s],” which are billed metering points[12] (ENTSO-E 2019, pp. 12, 15, 18). In accordance with the model, agents can and do take on a mediating role; such agents include consumers’ energy consultants or retail electricity suppliers without own generation who resell electricity.

Assuming an electricity provision settled in the EOM (no necessary balancing power), the following parties from the ENTSO-E market role model may support or realize the exchange of information on demand flexibility between consumers and producers or need to be involved themselves:

- The (Distribution) “System Operator” who runs and maintains the power grid distributing electricity in the area of a given consumer (flexible consumers — and particularly ‘prosumers’ — can contribute to the balance in the distribution grid, c.f. section 3.2.2 on self-consumption)
- The “Grid Access Provider” who provisions a metering point on which the consumer contributes demand flexibility; it could form an ‘advanced metering infrastructure’ encompassing smart meters and allowing for bidirectional information exchange (Paper 1, p. 538)
- A “Consent Administrator” who may register a consumers’ consent to contribute demand flexibility at a metering point
- A “Billing Agent” who issues invoices to the consumer that could remunerate contributed demand flexibility
- A “Resource Aggregator” who may gather the demand flexibility contributions of multiple consumers to offer that flexibility in aggregate to the wider energy system, namely to “a service provider for energy market services”

Supplemental to the role model, a party outside of the electricity market may support the necessary information exchange. This party could be a telecommunication or internet service provider to furnish the uni- or bidirectional communication stream from the smart meter to the electricity supplier.

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[12] To feed into or draw electricity from the power grid, consumers and producers access it through a metering point, which a *grid access provider* furnishes and a *metering point administrator* keeps on file. One needs to distinguish a *meter operator* who physically maintains metering devices at metering points and a *meter administrator* who registers those meters.

Other parties in the market role model are concerned with balancing power: only the electricity supplier would involve such in the information exchange, in instances of avoidable balancing power. With demand flexibility as a substitute for balancing power, consumers allow suppliers — and indirectly producers — to adjust their market position and their electricity balance.

3.2.2 Sourcing Electricity for Consumption

Analyzing consumers' demand flexibility suggests classifying their procurement strategies, which this section will lay out in further detail:

- Households and small commercial consumers conclude an electricity contract with one supplier for their entire electricity supply. This supplier can be their local utility or one they choose from a retail electricity market. Both groups have limited flexibility in loads and consumption patterns, but aggregation may help to achieve a significant magnitude of demand flexibility (Morstyn et al. 2018).
- Companies and other industrial or organizational consumers have several procurement options at their disposal, including electronic reverse auctions in a competitive retail electricity market (Paper 2). Their flexibility, which may be of considerable extent, depends on their sector and business model (Buhl et al. 2019; Roesch et al. 2019).
- Large companies can source electricity directly from generators or apply for admission to the wholesale market. A scale of consumption that would justify wholesale market access can imply considerable demand flexibility (except for rare cases of stable consumption, for instance, in data centers).
- Consumers of any size can consider installing sources of electricity generation and using the generated electricity for their needs (*self-consumption*).

Due to the market liberalization, most European consumers are free in selecting their electricity suppliers (Jamasb and Pollitt 2005). This liberty implies competitive **retail electricity markets** with *electricity choice*, a U.S.-originating term that denotes the right to choose an electricity supplier (Zhou 2017). SMEs can invite suppliers' competition in *electronic reverse auctions* considering their load profiles, by which the client companies can conclude cost-optimal supply contracts (Paper 2). Many electricity suppliers offer retail contracts with prices per kWh and potentially a basis charge, which are fixed for an extended contractual period. Opposed to that, fewer suppliers offer *real-time pricing*, which passes on the variable prices from the wholesale market to consumers as they occur (Palensky and Dietrich 2011; Watson et al. 2013). Other *time-of-use tariffs* distinguish predefined time clusters, such as ‘on-peak’, ‘shoulder-peak’, and ‘off-peak’; they are an intermediate solution consumers can follow easier. *Critical peak pricing* is another variant that binds surcharges to high deviations from the mean load profile (Palensky and Dietrich 2011; Watson et al. 2013). Any time-dependent tariff sets an incentive to avoid consuming electricity during times of elevated prices, hence to reduce or postpone consumption then. Parallelly, price surcharges on peak consumption support electricity suppliers in financing grid stability measures and less favorable wholesale prices (Buhl et al. 2019).

A share of large consumers also takes the opportunity to procure electricity from the **wholesale electricity markets** themselves: large consumption can give rise to sufficient economies of scale to justify their own market access. This procurement strategy allows such major consumers to cut out the negotiation with electricity suppliers and their price premium. Nonetheless, entering wholesale markets requires setting up extensive operative procedures for rolling electricity procurement and causes organization costs. In addition, market uncertainty necessitates adequate in-house risk management. The market access requires an admission subject to requirements set by the market operator; it can imply collateral deposit, set up and membership fees. Although market operators approach consumer market access differently, some of them are opening up markets to companies with large consumption (e.g., EPEX SPOT SE 2019).

Other strategies allow **bypassing structured electricity markets**. In a strict sense, bilateral contracts with generators for direct electricity delivery could fall into this category (Dong and Liu 2007). Nonetheless, rational consumers would use the competition of the retail electricity market for comparison, so they would indirectly involve a market. The same holds when consumers invest in installing own sources of generation to satisfy their electricity needs: “passive consumers are therefore becoming active ‘prosumers’” (European Commission 2015, p. 2; Morstyn et al. 2018). All or part of the generated electricity can be self-consumed or stored on-site, the remainder sold and fed into the grid.

3.2.3 Self-consumption

Self-generation and *self-consumption* are when owners of electricity generating units consume produced electricity on-site instead of feeding it into the distribution or transmission grids. Hence, the generating entities supply themselves or legally connected respectively directly contracted associates of theirs. This self-consumption has advanced to be technically feasible in large and in small scale (Dehler et al. 2017). Often, self-generated electricity stems from renewable energy sources or cogeneration of heat and power, which are both electricity sources at relatively low variable costs. Particularly in Germany, solar photovoltaic (PV) energy has achieved *grid parity*: self-generating a kilowatt-hour of PV electricity is cheaper than procuring one from the public grid (Dehler et al. 2017). “Soon, it will be cheaper for households to produce their own electricity through PV and store it in a battery (sometimes called ‘battery parity’)” (Fett et al. 2019, p. 868).

Hence, self-consumption can stand the economic comparison to a physical electricity contract in cases of both residential and commercial consumption (European Commission 2015). Nevertheless, the upfront investment can impair the cost-effectiveness of self-consumption systems for individual consumers (Planète Energies 2018), although the investment necessary for renewable energy sources is bound to decline (European Commission 2015, p. 12). Another difficulty is “[e]nsuring that the generation and self-consumption phases occur simultaneously [...]. It is easier to achieve this balance in large professional facilities, such as supermarkets, farms and factories, than in households — in Europe, in any case” — because intraday generation and consumption patterns match better (Planète Energies 2018).

When an intelligent controller automatically balances the electricity generation from multiple energy sources and the loads locally, inside the distribution system the consumer is in, this self-consumption situation meets the definition of a *microgrid* (Paper 3, pp. 729, 731). The microgrid framework depicted in Figure 4 systematizes such a decentralized electricity system. Although a microgrid objective can be self-sufficient supply with minimal or without reliance on a public power grid, a microgrid can help integrate renewable energy sources and improve the efficiency and reliability of a surrounding distribution system (Paper 3, p. 736). Electricity storage devices add to the flexibility of a microgrid and, hence, of self-consumption because a generation surplus can be held on-site for later consumption. This buffered flexibility is valuable because it reduces the uncertainty of forecasting generation (Masa-Bote et al. 2014).

Furthermore, consumer-led projects for cooperative self-generation are an instance and an application of both self-consumption and microgrids. There are residential consumers who “collectively optimize their energy supply in order to increase their autonomy” (Paper 3, p. 736) by joining forces to form citizen *energy cooperatives* (Fridgen et al. 2015a). In line with the idea of setting up a *community microgrid*, the members of such a cooperative can establish governance structures (c.f. the microgrid framework’s fourth layer, Figure 4) to communally share benefits and responsibilities (Rieger et al. 2016).

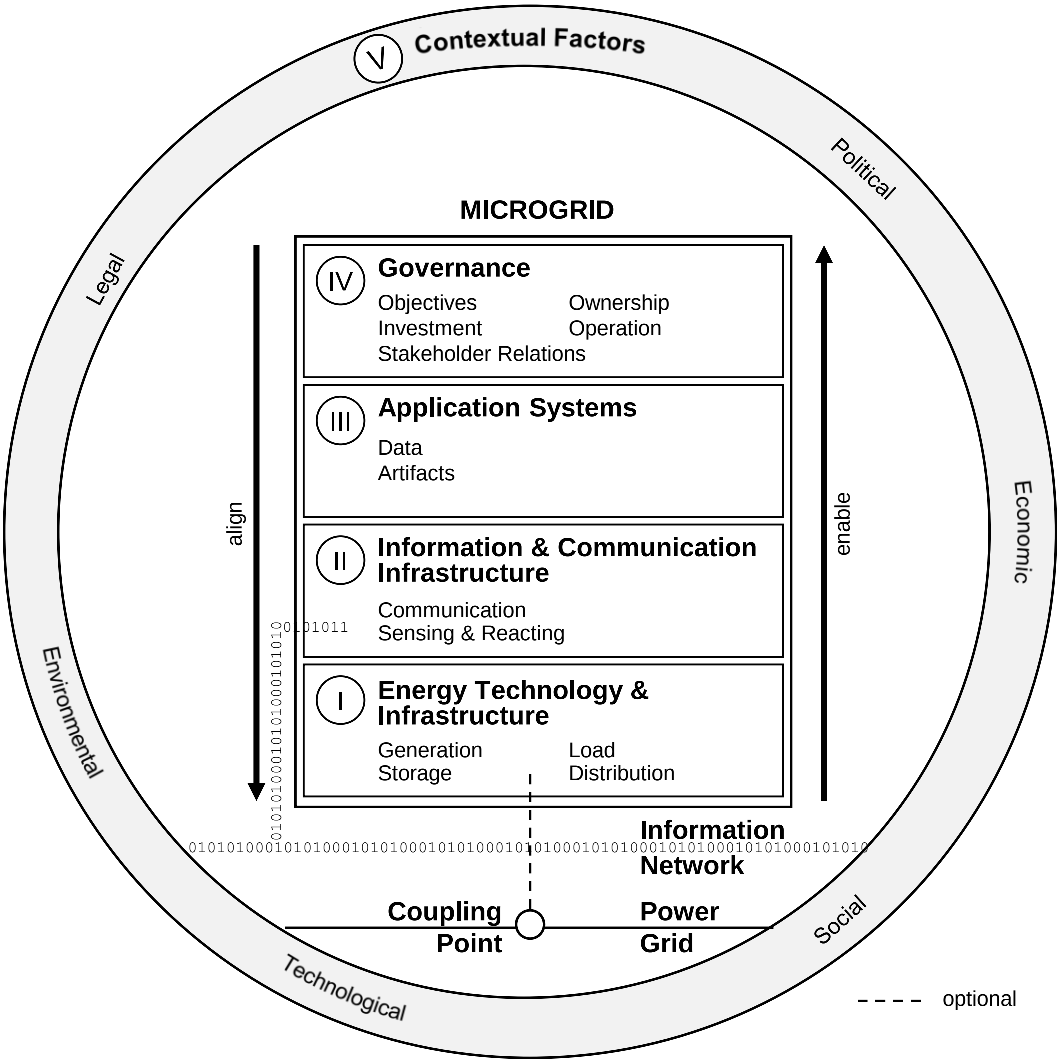

Figure 4. Microgrid Framework with Information Systems Layers
(Paper 3, Fig. 1)

3.2.4 Demand Response[13]

Flexible electricity consumers can engage in *demand side management* (DSM) activities. This umbrella term describes measures that influence the magnitude or temporal course of electricity consumption, so to adapt (peak) electricity use to the current electricity supply (Buhl et al. 2019). DSM measures therefore mainly concern the short term but also extend to the long term. On the lower end of this temporal continuum, highly reactive balancing power is provided within seconds (Palensky and Dietrich 2011). Concerning the long term, DSM encompasses programs that promote permanent energy saving or efficiency measures on the part of consumers (Feuerriegel and Neumann 2014). Figure 5 illustrates possible DSM measures and their timespan.

Demand response (DR) measures are understood as a central DSM category. They aim for a rather short-term adjustment during peak periods to adapt consumption to current generation conditions, which relieves the grid and moderates operating or procurement costs (Chen and Liu 2017). Primarily by economic means of incentive payments (incentive-based) or variable electricity prices (price-based programs, c.f. section 3.2.2 on retail electricity markets), electricity suppliers or system operators induce adequate consumption changes (Albadi and El-Saadany 2008). Moved by such market signals, participating electricity consumers decide autonomously to provide temporal flexibility (Strüker and van Dinther 2012). They adjust their consumption over minutes to days. *Load control* affects minutes to hours: technical solutions and a previous consumer consent allow electricity suppliers or system operators to regulate electricity consumption directly, including triggering, disengaging, or shifting loads (Jazayeri et al. 2005; Tang et al. 2011).

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[13] The argumentation in this section is assembled and referenced along Buhl et al. (2019), as its relevant section 3.1 was created in acting co-authorship of the thesis's author. The study resulted from work item IV.2.1 in the SynErgie research project (c.f. footnote 6).
N.B., the argumentation also resembles a recent publication that assembled work results from the SynErgie research project: Roesch et al. (2019) have therefore transferred the same line of thought, translated from the aforementioned study's first edition (Bertsch et al. 2016 / not included in references). Consequently, referencing the second edition Buhl et al. (2019), rather than Roesch et al. (2019), appears appropriate.

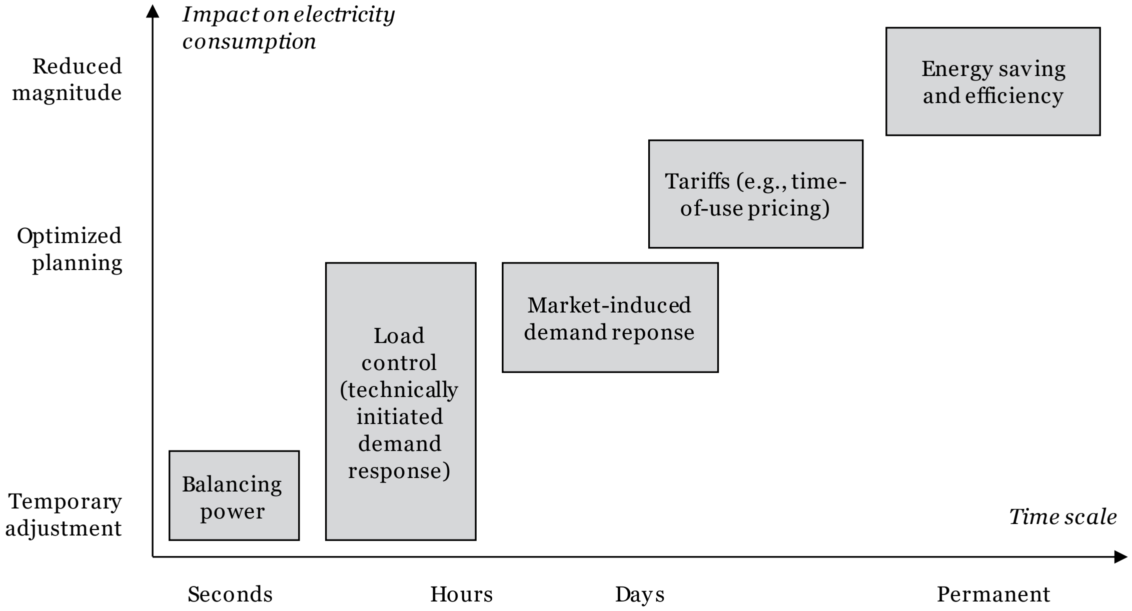

Figure 5. Measures of Demand Side Management
(Adapted from Buhl et al. 2019; Palensky and Dietrich 2011)

A bidirectional communication channel is necessary to convey the signals and data associated with DR measures: consumers' *smart meters* transmit current and recorded consumption data to the electricity supplier; suppliers send price and control signals to consumers (Strüker and van Dinther 2012). In a household, such signals "could be enabled through home energy management infrastructure (e.g., gateways/smart energy boxes" and would affect controllable *smart appliances*, such as a "washing machine, tumble dryer[], dishwasher, refrigerator, etc." (European Commission 2015, p. 5).

Electricity suppliers and consumers split the necessary investment in the *advanced metering infrastructure* (smart meters and bidirectional communications) and operational costs (maintenance, administration, billing, etc.) in different shares. In any case, sufficient incentives should reimburse consumers for their opportunity costs from granting flexibility (Albadi and El-Saadany 2008). DR is also compatible with their self-consumption (section 3.2.3) because it "can be applied to distribute a part of a consumer's energy demand to hours of onsite renewable energy generation so as to increase the self-consumption rate" (European Commission 2015, p. 5).

Striving for adjustment not only on the demand side but on the supply side as well, the concept of *transactive energy* integrates decentrally installed energy sources. It is thus “a variant and a generalized form of demand response” that utilizes the “flexibility of distributed generation and load resources to balance supply and demand” (Chen and Liu 2017, pp. 10, 14). Transactive energy applies the same economic mechanisms of market-induced DR. It strives for continuous autonomous coordination of a power system’s decentral elements (Chen and Liu 2017, p. 17). This characteristic resembles the microgrid concept (section 3.2.3), except that an intelligent controller could be virtualized.

3.3 Information Systems in (Smart) Electricity Grids

Due to extensive liberalization, European electricity markets have evolved from supply monopolies to competitive retail and wholesale market structures with complex regulation, manifold market instruments, and cross-border interconnection — all of which necessitates information processing. The electricity industry — the German electricity system in particular — is challenged to automate processes, to integrate renewable energy sources and to progress toward *smart grids* (Brandt 2016; Ketter et al. 2018). In today’s environment of increasingly distributed, intermittent energy sources, the concepts of DR, transactive energy, microgrids, and a smart grid all address similar challenges with slightly distinct approaches.

“The contemporary concept of smart grids refers to electricity networks, distribution grids in particular, which [...] integrate information systems allowing for autonomous or semi-autonomous planning, monitoring, and coordination” (Paper 3, p. 730; Schwaegerl and Tao 2014). Electrical engineering recognized the information aspect in (smart) electricity grid operation at an early stage (c.f. the *Smart Grid Architecture Model* — Brandt 2016). Interviewed experts have related the microgrid and smart grid disciplines (Appendix 6 to Paper 3, no. 3) and characterized microgrids as “miniature smart grids.” The IS layers ‘Information & Communication Infrastructure’ and ‘Application Systems’ are positioned centrally in the microgrid framework (Figure 4). They therefore give a representative impression of the role information systems take in electricity grids.

The emergence of smart grids already influences the electricity market roles, particularly considering the need for accelerated and digitalized information exchange (Brandt 2016). System operators (Paper 3, p. 734), electricity suppliers, and other market actors alike hence rely on automatization and decision support algorithms to fulfill their roles in the electricity market. Notably, this applies to the exchange and processing of information on demand flexibility (as in DR programs, for instance), self-consumption, and grid feed-in from microgrids (Paper 3). Information systems open up these previously unknown opportunities and reduce transaction costs (Watson et al. 2013, pp. 2 f.).

An example of the enabling role of digitalization is the emerging *peer-to-peer electricity trade*: “information systems have driven the development of a ‘sharing economy’ also in the electricity sector and can enable previously passive consumers to directly trade solar electricity in local communities” (Wörner et al. 2019, p. 1). By participating in adequate digital processes, such *prosumers* can market distributed, self-generated electricity more profitably, at the same time coordinating it more effectively and circumventing electricity suppliers (Morstyn et al. 2018). Such peer-to-peer electricity trade has debuted in microgrids — namely, in the “Brooklyn Microgrid” and “in [Walenstadt,] Switzerland” (Wörner et al. 2019, pp. 4, 15).

The use of cloud services is an enabler of digitalization in the energy sector that also merits being singled out. Electricity generation, consumption, and trading entail decentral, significant amounts of data, as well as information exchange and decisions in real time (Ketter et al. 2018). These result in technical requirements for which cloud services with their rapid scalability und location-independent addressability are well suited. Cloud computing technology generally has made its way into practice across industries, speeding up processes, and improving analytical efficiency. Corresponding research strives for cloud computing concepts that assist in the energy transition becoming a reality. Bera et al. (2015) and Markovic et al. (2013) summarize challenges for such concepts for smart electricity grids and point out research directions.

4 Flexibility in Cloud Computing Markets

4.1 Service Character of Cloud Computing

Cloud computing means obtaining data processing power, data storage, development environments, or ready-built applications from a remote provider on-demand via internet connections. The *cloud* metaphor has been coined to denote the nebular appearance of the provisioning hardware resources and their physical location to the customer, who cannot visually follow the service production after having handed over data via internet connections.

A frequently cited cloud computing definition is from the *National Institute of Standards and Technology* (NIST): “Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction” (Mell and Grance 2011, p. 2).

To structure cloud services, one typically distinguishes (Mell and Grance 2011):

- *Infrastructure as a Service* (IaaS)
- *Platform as a Service* (PaaS)
- *Software as a Service* (SaaS)

A model of layers is the logic connecting these categories, each one building on the previous. IaaS depicts technological resources, predominantly processing power and data storage. PaaS describes servers running accessible standard operating systems, pre-established databases, or development environments that automatically route the programmed algorithms through IaaS. SaaS means ready-built applications provisioned on a PaaS observable or hidden to the customer (Mell and Grance 2011).

Such offerings are commonly labeled ‘(cloud computing) services’ because, as an economic activity of theirs, providers offer functions of value to the customers. Likewise, the providers sell scalable functionality as virtual goods instead of separable items.[14] Because one can only consume cloud services at the moment of provisioning, they form

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[14] ‘Inseparability’ is a service characteristic, according to Stoshikj et al. (2016, p. 213).

a part of nonstorable intangibles (section 2.1.2). One trades them like nonphysical goods in bilateral contracts (Dong and Liu 2007; section 4.2) or on cloud exchanges (section 4.3.1).

Customers outsource their IT resource needs to cloud providers; they ‘buy’ instead of ‘make’ the required technical functionality (Matros et al. 2009). They end up sharing the physical hardware producing the cloud computing services (*resource pooling*). Because cloud providers furnish such services to many customers, they are typically able to offer at lower prices than the costs of making incurred to typical customers. Thus, the providers rely on a classic *economies-of-scale* effect (Matros et al. 2009). Larger providers benefit from more significant scale effects, which further strengthens their cost advantages and market power (Bestavros and Krieger 2014).

The cost advantages customers can achieve by relying on cloud services today take a large part from decreased costs of own data storage hardware, which revises earlier findings (Berendes et al. 2013). Over recent years, an eminent trend of decreasing costs has applied to hard disks and solid-state drives. The decisive factor has been an increasing supply, which has aligned with rapid data growth (Coughlin 2018). Volumes have been growing exponentially, due to demand from data-intensive Big Data applications such as Artificial Intelligence, amongst others. Data storage services in cloud data centers can fulfill this demand.

4.2 Provider-Customer Interaction

Analyzing the market for cloud services, one needs to distinguish two levels: First, the central portion of the market is the total of all providers competing for contracts in **individual customer dialogue**. Predominantly, they present their offerings on their online platforms and websites. There, customers can either enter into commercial negotiations or order ready-made cloud services according to an offering and their demand.

Typically, such offerings are heterogeneous, with only main features corresponding to cloud service categories being similar. This traditional model is equivalent to financial over-the-counter contracting (Công Bùi 2017, p. 2), which does not necessitate standardization. Concluded contracts base on either “Pay as you go” or “Fixed End” pricing models (Vaske 2015). The former case means that an hourly price is charged only for periods of use. A fixed-end contract, on the other hand, specifies a period for which cloud services are made available regardless of the final use (Vaske 2015).

Second, there is a relatively growing share of **marketplaces** on which multiple providers offer easily comparable products (Keller and König 2014). Those platforms are neutral to a multitude of providers, given that they fulfill minimum criteria, and open an additional sales channel to them. Following the *platform-economics* logic (Slavova and Constantinides 2017), the marketplaces take an intermediary role between providers and customers, reducing those groups' search and transaction costs. Comparative platforms that enable customers to select from multiple providers' offerings fall into a low development stage. In a higher development stage, platforms standardize offerings and thus enable commoditized exchange trade of cloud services (section 4.3.1). Auction mechanisms can facilitate this trade and award a customer's tender to the provider with the lowest price offer, often accompanied by automated contract conclusion or 'brokered' service initiation (Bassem and Bestavros 2016). Then, "the contract between provider and consumer is put in force at the time the usage is starting and the price at that specific moment" (Muhss et al. 2011, p. 4).

However, "[w]hile the operational costs incurred by providers are dynamic – they vary over time depending on factors such as energy cost, cooling strategies, and aggregate demand – the pricing models extended to customers are typically fixed – they are static over time and independent of aggregate demand" (Ishakian et al. 2012, p. 374). Customers' temporal demand flexibility could therefore help providers economize their service production costs while customers could generate cost savings. Dynamic pricing mechanisms (section 4.3.3) are a precondition to employing temporal demand flexibility in the cloud market, giving customers cost-saving incentives. Customers would also expect guarantees that their jobs will be executed (Ishakian et al. 2012, p. 375).

A spot market with dynamic lowest-price quotations would result from a sufficient *standardization* and trading volume (c.f. section 4.3.2) on such exchange-based platforms; transparency to the customers would be its benefit. Besides, market participants on both sides could profit from saving time and costs compared to drawn-out market studies or negotiations. In the future, customers could then hedge their price risk through derivative instruments on cloud resources — namely forwards, futures, or options. A true cloud spot market with a multitude of providers does not currently exist, as the following study of cloud market offerings will show.

4.3 Cloud Market Offerings

4.3.1 Cloud Exchanges

The trading of cloud services on exchange-like markets is a novel approach, which has developed within the recent ten years. To date, there are few such markets, and they do not include every conceivable cloud service category. “Recent attempts, such as the Deutsche Börse Cloud Exchange, the Cloud Commodities Exchange Group, and the Massachusetts Open Cloud Exchange, have opened the IaaS markets to smaller providers, thus increasing the market dynamics” (Paper 4, p. 2).

Deutsche Börse Cloud Exchange AG was the first platform for trading standardized IaaS resources, such as computing and data storage capacities. Market participants were able to register gradually from early 2014 (beta launch) through Januar 2016. Trade was only open between May 2015 (official launch) and March 2016 when the joint venture’s shareholders decided to discontinue operations (Herrmann 2016).

Organizations participating in the market had the opportunity to offer excess capacity or to request resources. The resources were sufficiently standardized (section 4.3.2) to facilitate direct selection and commissioning over the platform. Due to a manual selection procedure instead of automated allocation, however, it was also possible to consider other criteria from a vendor’s description. For the cloud service delivery, both sides then connected to the platform as an intermediary: Deutsche Börse Cloud Exchange handled access through a central *application programming interface* (API) or middleware, which claimed compatibility with every technological variant of the market-participating providers and customers. As an intermediary, Deutsche Börse Cloud Exchange also verified the quality of the providers’ offerings in a quality and security testing procedure. Furthermore, it took care of the service level monitoring and payment fulfillment (Vaske 2015).

Based on Watzl et al. (2011) and Watzl (2014), **CCEX Cloud Commodities Exchange GmbH** followed with the aim to standardize cloud computing resources in a way to make them exchange-tradeable globally, similarly to traditional commodities. Watzl (2014) designed a framework of standards for cloud exchanges that CCEX as an independent entity intended to license to existing exchanges worldwide (Công Bùi 2017). As of 2019, the standard development and funding of the initiative are in course, but available information and the market appearance are limited to the previous stand (Winkler 2019).

Meanwhile, the North American derivatives exchange group Chicago Mercantile Exchange announced setting up an on-demand marketplace for cloud resources, **UCX Universal Compute Xchange** (Công Bùi 2017). As of 2019, this platform has been set up, and registration is possible even though website information like company news is not current (UCX 2017). UCX mainly features IaaS offerings ready for a “single procurement across multiple providers” (Stage2Data 2019). UCX (2017) describes its role as “a consultative intermediary between buyers and sellers of cloud storage/compute resource[s].” At “no cost to buyers for transaction or execution,” it “enables organizations to specify the type, amount, location, storage capacity, and contract term required, and then choose from multiple [cloud providers’] bids to purchase highly secure certified compute resources” (UCX 2017).

All initiatives mentioned above have been limited to the establishment of spot markets. Derivative instruments equipped for price hedging were discussed to be subject to a later implementation (Công Bùi 2017; UCX 2017). Available information suggests that cloud marketplaces first need greater liquidity and dissemination to justify the introduction of a derivatives trade, thus to shape “a true financial exchange where buyers and sellers can trade cloud and compute resources, and futures” like it is common for other commodities (UCX 2017).

The public-funded project **Massachusetts Open Cloud** bases on Desnoyers et al.’s (2015) ‘Open Cloud Exchange’ marketplace model. Similar to the approaches laid out above, combining offerings of multiple providers is this model’s main feature. However, those providers would conclude contracts and charge independently. Still, this model should enable customers to select and switch providers and offerings more quickly as compared to a single-provider cloud (Bestavros and Krieger 2014, p. 73). It would therefore fall in the low-development category of a comparative platform. So far, the Massachusetts Open Cloud project has taken a focus on academic research on technical realization before debuting a public cloud marketplace (Xu and Baron 2017).

As apparent from these observable cases, the attempt to introduce cloud exchanges to the market has not proven successful yet. It is unclear whether there will be continued attempts in the future and if they prove successful at later phases of the developing cloud computing market. Trading cloud computing capacity in a standardized, multi-provider auction has not become a paradigm yet.

Analysts have considered the concept of vendor-neutral cloud exchanges too early for the current phase of the cloud computing market (Herrmann 2016). Deutsche Börse Cloud Exchange was open to companies, not accepting private individual registrants. One of the reasons the market purposedly was bound to close down was that the real-time trade was of no use to companies for whom long-term contract conditions were more beneficial in terms of price safety or contracts tailored to individual needs. Other companies that had already entered long-term contracts could not take part in real-time trade while the market was open (Herrmann 2016). Consequently, the market would most appeal to cloud providers with a need for real-time adjustment of their available capacity, for instance, SaaS and PaaS providers relying on sufficient IaaS resources. Other IaaS providers would offer excess capacity. In contrast, adequate demand was questionable; the supply side and the demand side purposedly were in inbalance. Other problems were Deutsche Börse Cloud Exchange’s centralized API/middleware and a claimed fee of 15 percent (Công Bùi 2017).

4.3.2 Product Standardization

Standardization is key to commoditization (Muhss et al. 2011, p. 1). Traditional commodities — mined metals, agricultural products such as coffee and soybeans, and fossil energy resources such as oil and coal — had to complete this development of “increasing homogeneity” (Reimann et al. 2010, p. 188) to become exchange-tradeable. This requirement also applies to cloud offerings: “In order to establish a broader market for cloud computing, offers must be made comparable” (Berndt and Watzl 2013, p. 356). From preconditions for arbitrary products to become exchange-tradeable, four are observable and applicable to cloud services (an extension to Muhss et al. 2011):

a. Homogenous functionality in terms of consistent variants and characteristics,
b. Sufficient supply in terms of available resources,
c. Uniform contracts including universal service level agreements, and
d. Harmonized technical access.

Homogenizing the functionality and the characteristics of cloud services spans a broad range: relatively simple, definite units of measurement form a standard for data storage (notwithstanding ancillary functional requirements like redundancy). At the same time, PaaS and SaaS are subject to complex, heterogeneous requirements (Repschlaeger et al. 2012; Walther et al. 2012). Therefore, standardization will tend to occur on the foundational cloud service layer — IaaS — but is not ruled out for PaaS and SaaS. To improve the comparability of data processing services, Deutsche Börse Cloud Exchange and individual providers such as Amazon Web Services have introduced the concept of 'virtual machines' that deliver comparable performance, no matter what hardware is provisioning their service. CCEX recognized that some corporate customers required very company-specific cloud services that one would hardly be able to standardize. Therefore, CCEX has focused on areas of offerings "that are relatively easy to standardize, such as object storage for images and documents or [...] a large number of standard computing operations for [scientific] data analyses" (Công Bùi 2017, p. 3).

Sufficient supply to meet demand is a criterion according to market principles. The volume and frequency of completed trades determine the *market liquidity* (Chordia et al. 2001). Veritable market prices result from sufficient liquidity, which can be a challenge for emerging cloud exchanges: Deutsche Börse Cloud Exchange faced the issue of gaining sufficient liquidity in its marketplace (section 4.3.1).

Cloud exchanges can make templates for **uniform contracts** available to customers and potentially oblige providers to use them. Service level agreements with clauses on "availability, response times and utilization" (Muhss et al. 2011, p. 2), among others, are commonly used in information systems outsourcing (Ishakian et al. 2012, p. 390). Furthermore, exchange operators can assure the quality of service delivery of listed providers: Deutsche Börse Cloud Exchange took efforts to verify the quality of providers' offerings on the exchange in a quality and security testing procedure.

Protocols for **harmonized technical access**, taking the role of the delivery model for cloud services, have been solidly developed in reference models and the TCP/IP stack — for example, "FTP, HTTP or SMTP protocols and [...] access [...], describe [...] and publish services" (Muhss et al. 2011, p. 1). Deutsche Börse Cloud Exchange realized the access via a central interface compatible with any customer's technology. Such documented APIs can harmonize the technical access to any cloud services and even "enable the dynamic exchange of commoditized SaaS services" (Paper 4, p. 2; Lewis 2013; Loutas et al. 2011).

Emerging cloud exchanges took different **approaches to product standardization**. Deutsche Börse Cloud Exchange intended a standardization not only of product variants but also of the quality of service delivery. Strikingly, Desnoyers et al. (2015) have not included product standardization in the Open Cloud Exchange model. Instead, this model allows “competing services and solutions that are differentiated [...] by the features they offer, [...] by their applicability to particular applications, their offerings’ reliability, price, or security, and other characteristics” (Bestavros and Krieger 2014, p. 73). Nonetheless, the authors see technical preconditions for a provider-neutral, multisided marketplace that are in part subsumable under ‘harmonized technical access’ (Bestavros and Krieger 2014, 75 f.):

- A services directory that “enables the identification of instances of comput[ing], storage, and other services to fulfill a customer request”
- A user interface that lists “information such as reputation, ranking, price”
- Automation “minimizing the need for human intervention,” providing orchestration as well as request generation, handling, and tracking
- Scheduling software that virtualizes the shared provisioning of physical hardware and that handles “constraints to limit liability or access”
- Operations software “to control core infrastructure and services” and to update the information to market participants
- Metering and billing processes
- Technical compatibility, for instance via APIs

Even though exchange tradeability may be difficult to reach for some emerging exchanges, this does not restrict individual cloud providers from building **standardized offerings**. The leading provider Amazon Web Services pioneered a uniform product when releasing its *Elastic Compute Cloud* (EC2) in 2006. Its idea is to supply data processing in virtual computing units. No matter what actual hardware is behind them, host systems in data centers deliver multiple *virtual machines*, each with comparable performance. Virtualization software simulates equipping the virtual machines with a processing unit (acting as computing power) and memory (as a data buffer) that are comparable to a physical server’s specifications (Paper 4). The specifications allow virtual machines to run a Linux or Microsoft Windows operating system. Consequently, they allow usage that matches a standalone server, except that customers access virtual machines remotely through an API instead of physically on their premises.

4.3.3 Dynamic Pricing

The overall revenue in the worldwide cloud market has increased considerably in recent years, reflecting a substantially growing demand for cloud services. “Through 2022, [the research and advisory firm] Gartner projects the market size and growth of the cloud services industry at nearly three time[s] the growth of overall IT services;” in particular, IaaS resources are in exponentially growing demand (Costello 2019).

Besides the overall revenue development in the cloud market, the increasing market dynamics encompass *dynamic pricing* (Paper 4, p. 2 f.). Marketing/e-commerce research has introduced dynamic pricing as the situational adjustment of offer prices to changing conditions (Gönsch et al. 2009); it has since been widely applied in practice. By dynamically pricing cloud services, providers can incentivize customers “to express workload scheduling flexibilities that may benefit them as well as providers” (Ishakian et al. 2012, p. 374). Amazon Web Services (AWS) thus offer *spot instances* that reflect their EC2 capacity utilization in dynamic pricing. “Spot Instance prices are set by Amazon EC2 and adjust gradually based on long-term trends in supply and demand for Spot Instance capacity […] for each region and instance type” (Amazon Web Services 2019).

Although it is not a multisided market forming prices and AWS restrict transparency of their pricing algorithm, reverse engineering has identified price-influencing factors (Ben-Yehuda et al. 2013) and auction mechanisms used similarly as in exchange trading (Cheng et al. 2016). Essentially resembling such an exchange auction, AWS’ algorithm yields prices for spot instances that observably have been changing several times an hour. These fluctuating cloud service prices, which could resemble volatile spot prices known in wholesale electricity markets, enable efforts to profit from elastic demand and to consume at lower costs.

Paper 4 has based its option model and stochastic process on the distribution of EC2 spot instance prices obtained from the Spot Price Archive (Javadi et al. 2011). This repository has made a data set with prices from the years 2009 through 2016 available.[15] Table 1, with descriptive statistics on two years of EC2’s cloud spot instance operation, illustrates its pricing dynamics.

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[15] Unfortunately, the repository has not included any EC2 spot prices from 2017 on. The following data analysis is, therefore, restricted to available 2015–2016 data from the Spot Price Archive.

	Jan–Jun 2015	Jul–Dec 2015	Jan–Jun 2016	Jul–Dec 2016	Overall
Hourly spot prices [US¢]					
Observations [count]	4,343	4,416	4,368	4,392	17,519
Arithmetic mean	3.48	5.26	4.40	3.97	4.28
Volatility	0.60	1.19	0.31	0.35	0.96
Minimum	3.20	3.20	3.92	3.38	3.20
First quartile	3.21	4.69	4.18	3.57	3.52
Median	3.21	5.07	4.35	4.01	4.26
Third quartile	3.22	5.55	4.59	4.24	4.69
Maximum	8.35	40.00	7.85	5.09	40.00
Hour-to-hour returns [%]					
Geometric mean	0.01	0.00	0.00	-0.01	0.00
Volatility [pp]	3.34	14.13	2.10	1.40	7.42
Minimum	-61.56	-83.66	-19.72	-11.32	-83.66
First quartile	0.00	-2.16	-1.01	-0.48	-0.69
Median	0.00	0.00	0.00	0.00	0.00
Third quartile	0.00	2.08	0.94	0.29	0.57
Maximum	89.94	490.22	24.82	11.51	490.22
Volatility over longer periods [pp]				**6 months**	1.40
			12 months		1.80
		18 months			8.33
	24 months				7.42

Table 1. Descriptive statistics for a two-year series of EC2 spot prices (Own computation based on data from the Spot Price Archive)

The historical data analyzed in Table 1 relates to the EC2 spot instance “m1.xlarge”, hosted in AWS’ North Virginia data center in their “us-east-1” region (Amazon Web Services 2019). “This type of cloud service encompasses a Linux operating system, 4 virtual cores, 15 gigabytes of RAM, 350 gigabytes of hard-disk space, and high network performance" (Paper 4, p. 4).[16] With the m1.xlarge instance, AWS restrains from optimizing any of these components at the expense of the others; hence, customers use this instance for general purposes (Amazon Web Services 2019).

The data set spans from 1 January 2015 through 30 December 2016, comprising prices and according price changes, so-called returns[17] (Paper 4, p. 5). The obtained historical price and return series includes every hour of every day (24 per day, except for the first day; 17,519 over the entire period). Such hourly time increments allow for best comparison, as cloud customers and providers typically plan Iaas and PaaS service usage on an hourly basis (Muhss et al. 2011, p. 3). Similarly, the minimum unit, in which Amazon Web Services (2019) and Microsoft Azure (2019) charge costs, is by the hour.[18] Table 1 presents descriptive statistics on this data set. Observed prices per computing hour reached values as low as 3.20 US cents and as high as 40.00 US cents.

Current and previously self-obtained information for this thesis allows for sporadic reference on the spot price magnitude of the m1.xlarge instance[19] in North Virginia: In November and December 2019, the price has been stable at 3.50 US cents per hour (Amazon Web Services 2019). This price resembles the arithmetic mean of hourly spot prices between January and June 2015 (Table 1) and equals the arithmetic mean of hourly spot prices between January and February 2018. In contrast, spot prices between June and August 2017 were elevated and averaged 4.62 US cents per hour.

In Paper 4's simulation, the volatility of hour-to-hour returns allowed temporal demand flexibility in cloud computing to generate relative cost savings of 1.5 percent on average, thus considerably "exploiting about 40 percent of the existing savings potential" (Paper 4, p. 12).

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[16] Accessed in 2017, this information was obtained from a previous version of Amazon Web Services (2019)'s website "Amazon EC2 Spot Instances Pricing."

[17] Paper 4 expresses the spot price change relatively, as the ratio of the new spot price S (in t+1) divided by the previous (hour t's) spot price, subtracting 1 to gain a decimal fraction: "$R(t) = \frac{S(t+1)}{S(t)} - 1$."

[18] Because Amazon Web Services (2019) update the price display to customers "every 5 minutes," they can alter EC2 spot prices in differing increments of below (or above) one hour. Assuming an hourly planning basis facilitates comparison.

[19] Note that today, Amazon Web Services (2019) label the m1.xlarge instance "General Purpose - Previous Generation." This obsolescence could imply a less frequent or even frozen spot price quotation.

5 Conclusion

5.1 Contribution, Limitations, and Outlook

This work has studied temporal demand flexibility in procuring exchange-traded goods. It has thus selected two markets that could make beneficial use of short-term elastic demand: the first is the already established, liberalized European electricity market; the second is the rapidly growing international cloud computing market. If one regards services as intangible goods, both electricity and cloud computing are nonstorable goods, which require immediate consumption on completion of the production. Whereas cloud services are, by definition, fulfilled on-demand, instantly using electricity is preferable to transforming and storing it in another energy form. Energy and efficiency losses during a *cycle transformation* give the reason.

Therefore, the insight that temporal demand flexibility bears value (even) under uncertain price development is common to both of the studied environments. When market prices vary, it is possible to fulfill time-independent requirements to produce or consume a given product or service at lower prices. This thesis has contributed approaches to recognizing and evaluating the particular value of temporal demand flexibility in the electricity (Paper 1) and cloud computing markets (Paper 4). Information systems for supporting customers' and suppliers' decisions could integrate the developed real option models and analytical algorithms. Real-time price signals and adequate incentives can then induce changes in consumption behavior necessary to seize demand flexibility.

Both markets are currently evolving and quote volatile prices in exchange-like auctions. The involvement of information systems and technology, which offers the merit of reducing transaction costs, is facilitating regular trade. Cloud computing services are virtual goods with rather simple fulfillment via internet connections, but also in the electricity market, information systems enable higher productivity and new operating models such as microgrids. Current developments make it more likely for these two markets to be interrelated or connected in the future. Consequently, this thesis has provided an outlook on market structures that may become even more relevant in the future.

In cloud computing, provider-neutral exchange structures have not succeeded in becoming a standard yet. In light of all kinds of commodities, exchange trading of cloud services is still an exception. This drawback limits the practical value of Paper 4's approach to evaluate demand flexibility to the IaaS market, for AWS EC2 spot instances in particular. Nonetheless, a trend towards standardization makes cloud computing a candidate for commoditization and prospective exchange trading.

In the electricity market, Paper 1's approach supports electricity suppliers and — potentially — companies with large electricity consumption in evaluating demand flexibility. Its limitation is the necessary access to the wholesale market with (near) real-time prices. Other commercial and individual consumers can shape their demand flexibility in different ways. Firstly, electricity consumers can install own (renewable) energy sources to produce electricity: the opportunity to self-consume improves their flexibility in scheduling and sourcing the residual demand. With this prerequisite or independently, they can participate in a microgrid, which balances decentralized electricity consumption and distribution. Paper 3 has structured design options for microgrids. Its research directions, raised in an interdisciplinary literature review and expert interviews, now encourage the business and information systems engineering discipline to provide integrated perspectives that connect established technological solutions and business models for microgrids.

Secondly, SMEs can optimize their electricity costs by auctioning their load profiles on electronic platforms. Through an electronic reverse auction, a client company is likely to reduce its electricity costs: i. if it has stable consumption (or ii. an increased consumption share during off-peak hours) iii. in a total voltage between 1 and 75 kilovolts, and obviously, iv. if more bidders compete for the supply contract (Paper 2). Beyond these four factors, Paper 2's mixed methods research approach has found the date of contract conclusion and the companies' sector to significantly influence the net electricity price as an electronic reverse auction's outcome.

The microeconomic perspective this thesis takes in studying individual supplier-consumer relationships is a general limitation:

- If many market participants make use of temporal demand flexibility, their behavior could either conflict, or influence and potentially smooth prices. In such situations on cloud or electricity markets, market uncertainty or the value of demand flexibility could shrink.

- If many electricity consumers participate in microgrids, operating and financing public electricity systems could become more challenging. Their operators could struggle to balance microgrids in grid-connected mode when necessary.
- If many companies procure their electricity from electronic reverse auctions, price-influencing factors may change.

Information systems take an ever-growing role in shaping and evaluating demand-side flexibility in electricity and cloud computing markets. Due to their nonstorability, procuring goods from the corresponding spot markets means consuming instantly. In such cases, sharing temporal demand flexibility can benefit both suppliers and customers. It also means additional decision options and complexity. This thesis has constructively contributed to understanding and embracing new possibilities opened up by IS, such as electronic spot markets and exchange trade, electronic reverse auctions, automated load shifting decisions, and microgrids.

5.2 Acknowledgment of Previous and Related Work

On all research projects and papers, the thesis's author worked with colleagues at the University of Bayreuth, the Project Group Business and Information Systems Engineering of the Fraunhofer Institute for Applied Information Technology (FIT), and the Research Center Finance and Information Management (FIM). The research also built on previous and related work conducted within these organizations.

Paper 1 continued the work of Fridgen et al. (2014a) and (2015b), who introduced a stochastic process as a prerequisite for evaluating temporal demand flexibility with a real options model. Feedback from presenting and discussing both papers at conferences permitted to revise and extend the research paper for submission to a Jourqual category A journal. The discussion of ROA requirements by Ullrich (2013) contributed to Paper 1's methodological foundation. Diepold et al. (2009) had introduced the methodological idea and laid commendable foundations for real options application in multiple subsequent contexts at the FIM Research Center.

Paper 2 referenced Paper 1 (Fridgen et al. 2016b) when establishing the proposition that "electricity consumed during peak periods is more expensive than electricity consumed during off-peak periods" (Paper 2, Table 1). Apart from that, Paper 2 has commenced a new research stream on electronic reverse auctions for electricity procurement, which integrates into the Green IS field (Seidel et al. 2017) and which was in part conducted in the SynErgie research project (c.f. acknowledgment in footnote 6, p. 17).

Paper 3 carried on the microgrid research stream that included the following work: first, Fridgen et al. (2015a) considered trade-offs between economic, ecologic, and social objectives in energy cooperatives. Second, Rieger et al. (2016) simulated DR cooperation in a residential microgrid and its effects on the energy system. Third, Fridgen et al. (2018) studied options for electricity pricing in residential microgrids. On this foundation, Paper 3 structured microgrid knowledge and future research directions.

Paper 4 transferred Paper 1's approach (Fridgen et al. 2016b) to the cloud computing market. Again, Ullrich's (2013) work contributed to the methodological foundation of the real options model. Klaus et al. (2014) had already applied ROA to evaluate service providers' flexibility. The cloud computing market, in particular, had previously been studied by Matros et al. (2009) and Berendes et al. (2013), who advised on the decision between procuring a computing service from a cloud provider and self-producing it. Eymann et al. (2006), Buhl et al. (2009), and Keller and König (2014) identified general selection and risk management approaches when procuring service-oriented computing from grids (the cloud forerunner) and the cloud market. Finally, Fridgen et al. (2017) — later followed by Thimmel et al. (2019) — designed an approach for smoothing data centers' electricity consumption by spatially distributing the cloud services production.

Consequently, this thesis aligns well with the preceding work outlined above. It has continued successful research streams relating to microgrids and demand flexibility in electricity markets, also integrating existing knowledge on elastic consumption in data centers and the real options methodology. Additionally, the thesis has contributed to new streams on electronic reverse auctions for electricity procurement and temporal demand flexibility in cloud computing markets.

6 References

Albadi MH, El-Saadany EF (2008) A summary of demand response in electricity markets. Electric Power Systems Research 78(11):1989–1996. doi:10.1016/j.epsr.2008.04.002.

Alzaghoul E, Bahsoon R (2014) Evaluating Technical Debt in Cloud-Based Architectures Using Real Options. In: 23rd Australian Software Engineering Conference (ASWEC), pp 1–10. doi:10.1109/ASWEC.2014.27.

Amazon Web Services (2019) Amazon EC2 Spot Instances Pricing. https://aws.amazon.com/ec2/spot/pricing/.

Bassem C, Bestavros A (2016) Scheduling of Data-Intensive Workloads in a Brokered Virtualized Environment. http://hdl.handle.net/2144/21783.

Benaroch M, Kauffman RJ (1999) A Case for Using Real Options Pricing Analysis to Evaluate Information Technology Project Investments. Information Systems Research 10(1):70–86. doi:10.1287/isre.10.1.70.

Ben-Yehuda OA, Ben-Yehuda M, Schuster A, Tsafrir D (2013) Deconstructing Amazon EC2 Spot Instance Pricing. ACM Transactions on Economics and Computation 1(3):1–20. doi:10.1145/2509413.2509416.

Bera S, Misra S, Rodrigues JJPC (2015) Cloud Computing Applications for Smart Grid: A Survey. IEEE Transactions on Parallel and Distributed Systems 26(5):1477–1494. doi:10.1109/TPDS.2014.2321378.

Berendes CI, Ertel M, Röder T, Sachs T, Süptitz T, Eymann T (2013) Cloud Computing lohnt sich (noch) nicht. In: Alt R (ed) Proceedings of the 13th International Conference on Wirtschaftsinformatik (WI 2013), pp 1733–1747.

Berndt P, Watzl JR (2013) Unitizing Performance of IaaS Cloud Deployments. In: IEEE 9th World Congress on Services. IEEE, pp 356–362. doi:10.1109/SERVICES.2013.25.

Bestavros A, Krieger O (2014) Toward an Open Cloud Marketplace: Vision and First Steps. IEEE Internet Computing 18(1):72–77. doi:10.1109/MIC.2014.17.

Bhattacharjee S, Gopal RD, Marsden JR, Sankaranarayanan R (2011) Digital goods and markets. ACM Transactions on Management Information Systems 2(2):1–14. doi:10.1145/1985347.1985349.

Biegel B, Hansen LH, Stoustrup J, Andersen P, Harbo S (2014) Value of flexible consumption in the electricity markets. Energy 66:354–362. doi:10.1016/j.energy.2013.12.041.

Bird JO (2017) Electrical and electronic principles and technology. Routledge, Abingdon, Oxon.

Black F, Scholes M (1973) The Pricing of Options and Corporate Liabilities. Journal of Political Economy 81(3):637–654. doi:10.1086/260062.

Borenstein S, Bushnell JB, Wolak FA (2002) Measuring Market Inefficiencies in California's Restructured Wholesale Electricity Market. American Economic Review 92(5):1376–1405. doi:10.1257/000282802762024557.

Brandt T (2016) IT Solutions for the Smart Grid. Springer Fachmedien, Wiesbaden. doi:10.1007/978-3-658-12415-1.

Buhl HU, Fridgen G, Hackenbroch W (2009) An economic analysis of service-oriented infrastructures for risk/return management. In: Proceedings of the 17th European Conference on Information Systems (ECIS 2009).

Buhl HU, Fridgen G, Körner M-F, Michaelis A, Rägo V, Schöpf M, Schott P, Sitzmann A, Bertsch J, Sachs T, Schweter H (2019) Ausgangsbedingungen für die Vermarktung von Nachfrageflexibilität: Status-Quo-Analyse und Metastudie. Arbeitspaket IV.2.1 des Projektes „Synchronisierte und energieadaptive Produktionstechnik zur flexiblen Ausrichtung von Industrieprozessen auf eine fluktuierende Energieversorgung“ (SynErgie), gefördert durch das Bundesministerium für Bildung und Forschung unter Kennzeichen 03SFK3Q0. Bayreuther Arbeitspapiere zur Wirtschaftsinformatik. Universität Bayreuth, Bayreuth. doi:10.15495/EPub_UBT_00004455.

Buhl HU, Heinrich B, Henneberger M, Krammer A (2008) Service Science. WIRTSCHAFTSINFORMATIK 50(1):60–65. doi:10.1007/PL00022212x.

Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y (2009) Progress in electrical energy storage system: A critical review. Progress in Natural Science 19(3):291–312. doi:10.1016/j.pnsc.2008.07.014.

Chen S, Liu C-C (2017) From demand response to transactive energy: state of the art. Journal of Modern Power Systems and Clean Energy 5(1):10–19. doi:10.1007/s40565-016-0256-x.

Cheng HK, Li Z, Naranjo A (2016) Research Note—Cloud Computing Spot Pricing Dynamics: Latency and Limits to Arbitrage. Information Systems Research 27(1):145–165. doi:10.1287/isre.2015.0608.

Chordia T, Roll R, Subrahmanyam A (2001) Market Liquidity and Trading Activity. The Journal of Finance 56(2):501–530. doi:10.1111/0022-1082.00335.

Công Bùi F (2017) Cloud Commodities Exchange will hoch hinaus: Im Gespräch: Karl-Michael Molzer. Börsen-Zeitung(212):2. https://www.boersen-zeitung.de/index.php?li=1&artid=2017212009.

Copeland TE, Antikarov V (2003) Real Options: A Practitioners Guide. Cengage Learning, New York, NY.

Costello K (2019) Gartner Forecasts Worldwide Public Cloud Revenue to Grow 17.5 Percent in 2019: Gartner Projects Cloud Services Industry to Grow Exponentially Through 2022. https://www.gartner.com/en/newsroom/press-releases/2019-04-02-gartner-forecasts-worldwide-public-cloud-revenue-to-g.

Coughlin TM (2018) Fundamentals of Flash Memory and Other Solid-State Memory Technologies. In: Coughlin TM (ed) Digital Storage in Consumer Electronics. Springer International Publishing, Cham, pp 61–86. doi:10.1007/978-3-319-69907-3_4.

Cox JC, Ross SA, Rubinstein M (1979) Option pricing: A simplified approach. Journal of Financial Economics 7(3):229–263. doi:10.1016/0304-405X(79)90015-1.

Crasselt N, Lohmann C (2016) Considering real options in short-term decision making. Journal of Management Control 27(4):351–369. doi:10.1007/s00187-016-0234-5.

Dehler J, Keles D, Telsnig T, Fleischer B, Baumann M, Fraboulet D, Faure-Schuyer A, Fichtner W (2017) Self-Consumption of Electricity from Renewable Sources. In: Welsch M, Pye S, Keles D, Faure-Schuyer A, Dobbins A, Shivakumar A, Deane P, Howells M (eds) Europe's Energy Transition – Insights for Policy Making. Elsevier, pp 225–236. doi:10.1016/B978-0-12-809806-6.00027-4.

Deng S-J, Oren SS (2003) Incorporating operational characteristics and start-up costs in option-based valuation of power capacity. Probability in the Engineering and Informational Sciences 17(2):155–181. doi:10.1017/S0269964803172014.

Desnoyers P, Hennessey J, Holden B, Krieger O, Rudolph L, Young A (2015) Using Open Stack for an Open Cloud Exchange(OCX). In: 2015 IEEE Intl. Conference on Cloud Engineering. IEEE, pp 48–53. doi:10.1109/IC2E.2015.40.

Diepold D, Ullrich C, Wehrmann A, Zimmermann S (2009) A real options approach for valuating intertemporal interdependencies within a value-based IT portfolio management – a risk-return perspective. In: Proceedings of the 17th European Conference on Information Systems (ECIS 2009), pp 1600–1612.

Dong L, Liu H (2007) Equilibrium Forward Contracts on Nonstorable Commodities in the Presence of Market Power. Operations Research 55(1):128–145. doi:10.1287/opre.1060.0351.

Dorsch C, Häckel B (2012) Matching Economic Efficiency and Environmental Sustainability: The Potential of Exchanging Excess Capacity in Cloud Service Environments. In: Proceedings of the 33rd Intl. Conference on Information Systems (ICIS 2012).

Druckman D, Mitchell C (1995) Flexibility in Negotiation and Mediation. The Annals of the American Academy of Political and Social Science 542(Nov.):10–23. https://www.jstor.org/stable/1048206.

EEX (2019a) Kontraktspezifikationen. https://www.eex.com/blob/101072/96bd4b367848b36819656a7be6fa20f9/20191017-eex-kontraktspezifikationen-0069a-d-final-data.pdf.

EEX (2019b) Power Futures. https://www.eex.com/en/products/power-derivatives-market/power-futures/.

ENTSO-E (2019) The Harmonised Electricity Market Role Model. https://docstore.entsoe.eu/Documents/EDI/Library/HRM/Harmonised_Role_Model_2019-01.pdf.

EPEX SPOT SE (2018) Trading on EPEX SPOT 2018. http://static.epexspot.com/document/38579/Epex_TradingBrochure_180129_Web.pdf.

EPEX SPOT SE (2019) Become a member. https://www.epexspot.com/en/becomea member.

European Commission (2015) Best practices on Renewable Energy Self-consumption. Commission Staff Working Document. https://ec.europa.eu/energy/sites/ener/files/documents/1_EN_autre_document_travail_service_part1_v6.pdf.

European Commission (2017) Electricity Balancing Guideline: Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing: GL-EB. In: Official Journal of the European Union, pp 6–53.

Eymann T, Reinicke M, Streitberger W (2006) Ökonomische Bewertung der Dienstauswahl in Service-Netzen. In: Barth T, Schüll A (eds) Grid Computing. Vieweg, Wiesbaden, pp 33–63. doi:10.1007/978-3-8348-9101-3_3.

Federal Ministry for Economic Affairs and Energy, Federal Environment Agency (2019) Development of Renewable Energy Sources in Germany in the year 2018. https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/development-of-renewable-energy-sources-in-germany-2018.pdf.

Fett D, Keles D, Kaschub T, Fichtner W (2019) Impacts of self-generation and self-consumption on German household electricity prices. Journal of Business Economics 89(7):867–891. doi:10.1007/s11573-019-00936-3.

Feuerriegel S, Neumann D (2014) Measuring the financial impact of demand response for electricity retailers. Energy Policy 65:359–368. doi:10.1016/j.enpol.2013.10.012.

Fridgen G, Drasch BJ, Schöpf M, Trick R (2016a) Towards a descriptive Framework of Demand Side Flexibility. Erasmus Energy Forum 2016. https://eref.uni-bayreuth.de/id/eprint/32485.

Fridgen G, Gründler A, Rusic M (2015a) Energy Cooperatives as an Application of Microgrids: Multi-Criteria Investment Decision Support. In: Proceedings of the 36th Intl. Conference on Information Systems (ICIS 2015).

Fridgen G, Häfner L, König C, Sachs T (2014a) Toward Real Options Analysis of IS-Enabled Flexibility in Electricity Demand. In: Proceedings of the 35th Intl. Conference on Information Systems (ICIS 2014).

Fridgen G, Häfner L, König C, Sachs T (2015b) The Value of IS-Enabled Flexibility in Electricity Demand – a Real Options Approach. In: Thomas O, Teuteberg F (eds) Proceedings of the 12th International Conference on Wirtschaftsinformatik (WI 2015), pp 993–1007.

Fridgen G, Häfner L, König C, Sachs T (2016b) Providing Utility to Utilities: The Value of Information Systems Enabled Flexibility in Electricity Consumption. Journal of the Association for Information Systems 17(8):537–563. doi:10.17705/1jais.00434.

Fridgen G, Kahlen M, Ketter W, Rieger A, Thimmel M (2018) One rate does not fit all: An empirical analysis of electricity tariffs for residential microgrids. Applied Energy 210:800–814.

Fridgen G, Keller R, Thimmel M, Wederhake LP (2017) Shifting load through space–The economics of spatial demand side management using distributed data centers. Energy Policy 109:400–413. doi:10.1016/j.enpol.2017.07.018.

Fridgen G, Mette P, Thimmel M (2014b) The Value of Information Exchange in Electric Vehicle Charging. In: Proceedings of the 35th Intl. Conference on Information Systems (ICIS 2014).

Frondel M, Ritter N, Schmidt CM, Vance C (2010) Economic impacts from the promotion of renewable energy technologies: The German experience. Energy Policy 38(8):4048–4056. doi:10.1016/j.enpol.2010.03.029.

Fuentes-Bracamontes R (2016) Is unbundling electricity services the way forward for the power sector? The Electricity Journal 29(9):16–20. doi:10.1016/j.tej.2016.10.006.

Gönsch J, Klein R, Steinhardt C (2009) Dynamic Pricing – State-of-The-Art. Zeitschrift für Betriebswirtschaft(Ergänzungsheft 3):1–40. https://ssrn.com/abstract=2179225.

Gooday G (2016) Domesticating electricity: Technology, uncertainty and gender, 1880-1914. Science and culture in the nineteenth century. Routledge, Abingdon, Oxon.

Grasenick K, Low J (2004) Shaken, not stirred: Defining and connecting indicators for the measurement and valuation of intangibles. Journal of Intellectual Capital 5(2):268–281. doi:10.1108/14691930410533696.

Helm D (2014) The European framework for energy and climate policies. Energy Policy 64:29–35. doi:10.1016/j.enpol.2013.05.063.

Herrmann W (2016) Deutsche Börse Cloud Exchange gibt auf: Cloud-Marktplatz stellt den Betrieb ein. Computerwoche 2016. https://www.computerwoche.de/a/print/deutsche-boerse-cloud-exchange-gibt-auf,3223201.

Hirth L, Ziegenhagen I (2015) Balancing power and variable renewables: Three links. Renewable and Sustainable Energy Reviews 50:1035–1051. doi:10.1016/j.rser.2015.04.180.

Höckendorf H, Sachs T, Fridgen G (2019) Electronic Markets for Electricity Procurement by Small and Medium-Sized Enterprises: Determining Price-Impacting Factors and their Influence on the Outcome of Electronic Reverse Auctions. Working Paper, University of Bayreuth.

Ishakian V, Sweha R, Bestavros A, Appavoo J (2012) CloudPack. In: Narasimhan P, Triantafillou P (eds) Middleware 2012. Springer, Berlin, Heidelberg, pp 374–393. doi:10.1007/978-3-642-35170-9_19.

Jamasb T, Pollitt M (2005) Electricity Market Reform in the European Union: Review of Progress toward Liberalization & Integration. Working Papers(0503). http://ideas.repec.org/p/mee/wpaper/0503.html.

Jansson JO (2013) The Economics of Services: Microfoundations, Development and Policy. Edward Elgar Publishing, Cheltenham.

Javadi B, Thulasiramy RK, Buyya R (2011) Statistical Modeling of Spot Instance Prices in Public Cloud Environments. In: IEEE 4th Intl. Conference on Utility and Cloud Computing (UCC), pp 219–228. doi:10.1109/UCC.2011.37.

Jazayeri P, Schellenberg A, Rosehart WD, Doudna J, Widergren S, Lawrence D, Mickey J, Jones S (2005) A Survey of Load Control Programs for Price and System Stability. IEEE Transactions on Power Systems 20(3):1504–1509. doi:10.1109/TPWRS.2005.852147.

Jede A, Teuteberg F (2016) Valuing the Advantage of Early Termination: Adopting Real Options Theory for SaaS. In: Proceedings of the 49th Hawaii Intl. Conference on System Sciences (HICSS 2016), pp 4880–4889. doi:10.1109/HICSS.2016.605.

Keller R, Häfner L, Sachs T, Fridgen G (2019) Scheduling Flexible Demand in Cloud Computing Spot Markets. Business & Information Systems Engineering 26(4):477. doi:10.1007/s12599-019-00592-5.

Keller R, König C (2014) A Reference Model to Support Risk Identification in Cloud Networks. In: Proceedings of the 35th Intl. Conference on Information Systems (ICIS 2014).

Ketter W, Collins J, Saar-Tsechansky M, Marom O (2018) Information Systems for a Smart Electricity Grid. ACM Transactions on Management Information Systems 9(3):1–22. doi:10.1145/3230712.

Klaus C, Krause F, Ullrich C (2014) Determining the Business Value of Volume Flexibility for Service Providers – A Real Options Approach. In: Proceedings of the 22nd European Conference on Information Systems (ECIS 2014).

Komarnicki P, Lombardi P, Styczynski Z (2017) Electric Energy Storage Systems. Springer, Berlin, Heidelberg. doi:10.1007/978-3-662-53275-1.

Kwoka J, Sabodash V (2011) Price Spikes in Energy Markets: “Business by Usual Methods” or Strategic Withholding? Review of Industrial Organization 38(3):285–310. doi:10.1007/s11151-011-9294-8.

Lewis GA (2013) Role of Standards in Cloud-Computing Interoperability. In: Proceedings of the 46th Hawaii Intl. Conference on System Sciences (HICSS 2013), pp 1652–1661. doi:10.1109/HICSS.2013.470.

Lomas L (2019) Non-stock items. https://docs.msupply.org.nz/items:non_stock_items.

Loutas N, Kamateri E, Bosi F, Tarabanis K (2011) Cloud Computing Interoperability: The State of Play. In: IEEE 3rd Intl. Conference on Cloud Computing Technology and Science, pp 752–757. doi:10.1109/CloudCom.2011.116.

Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D (2012) From electricity smart grids to smart energy systems – A market operation based approach and understanding. Energy 42(1):96–102. doi:10.1016/j.energy.2012.04.003.

Markovic DS, Zivkovic D, Branovic I, Popovic R, Cvetkovic D (2013) Smart power grid and cloud computing. Renewable and Sustainable Energy Reviews 24:566–577. doi:10.1016/j.rser.2013.03.068.

Martinez-Cesena EA, Azzopardi B, Mutale J (2013) Assessment of domestic photovoltaic systems based on real options theory. Progress in Photovoltaics: Research and Applications 21(2):250–262. doi:10.1002/pip.2208.

Masa-Bote D, Castillo-Cagigal M, Matallanas E, Caamaño-Martín E, Gutiérrez A, Monasterio-Huelín F, Jiménez-Leube J (2014) Improving photovoltaics grid integration through short time forecasting and self-consumption. Applied Energy 125:103–113. doi:10.1016/j.apenergy.2014.03.045.

Matros R, Stute P, Heereman von Zuydtwyck N, Eymann T (2009) Make-or-Buy im Cloud-Computing: Ein entscheidungsorientiertes Modell für den Bezug von Amazon Web Services. Bayreuther Arbeitspapiere zur Wirtschaftsinformatik. Universität Bayreuth, Bayreuth.

Mell PM, Grance T (2011) The NIST definition of cloud computing. National Institute of Standards and Technology, Gaithersburg, MD. doi:10.6028/NIST.SP.800-145.

Microsoft Azure (2019) Pricing calculator: Configure and estimate the costs for Azure products. https://azure.microsoft.com/en-us/pricing/calculator/.

Moreno B, López AJ, García-Álvarez MT (2012) The electricity prices in the European Union. The role of renewable energies and regulatory electric market reforms. Energy 48(1):307–313. doi:10.1016/j.energy.2012.06.059.

Morstyn T, Farrell N, Darby SJ, McCulloch MD (2018) Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants. Nature Energy 3(2):94–101. doi:10.1038/s41560-017-0075-y.

Muhss F, Neumann R, Schmietendorf A (2011) The Commoditization of IT Services with Cloud Computing. The World Congress in Computer Science, Computer Engineering and Applied Computing (WorldComp). http://worldcomp-proceedings.com/proc/p2011/SWW3474.pdf.

Naldi M, Mastroeni L (2016) Economic decision criteria for the migration to cloud storage. European Journal of Information Systems 25(1):16–28. doi:10.1057/ejis.2014.34.

Nicolosi M, Fürsch M (2009) The Impact of an increasing share of RES-E on the Conventional Power Market — The Example of Germany. Zeitschrift für Energiewirtschaft 33(3):246–254. doi:10.1007/s12398-009-0030-0.

Nishimura KG (1989) Customer Markets and Price Sensitivity. Economica 56(222):187–198. doi:10.2307/2554038.

Ocker F, Braun S, Will C (2016) Design of European balancing power markets. In: 2016 13th Intl. Conference on the European Energy Market (EEM). IEEE, pp 1–6. doi:10.1109/EEM.2016.7521193.

Oren SS (2001) Integrating real and financial options in demand-side electricity contracts. Decision Support Systems 30(3):279–288. doi:10.1016/S0167-9236(00)00105-6.

Palensky P, Dietrich D (2011) Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads. IEEE Transactions on Industrial Informatics 7(3):381–388. doi:10.1109/TII.2011.2158841.

Planète Energies (2018) Electricity Self-Consumption: A Popular Model. https://www.planete-energies.com/en/medias/close/electricity-self-consumption-popular-model.

Reimann M, Schilke O, Thomas JS (2010) Toward an understanding of industry commoditization: Its nature and role in evolving marketing competition. International Journal of Research in Marketing 27(2):188–197. doi:10.1016/j.ijresmar.2009.10.001.

Repschlaeger J, Zarnekow R, Wind S, Turowski K (2012) Cloud Requirement Framework: Requirements and Evaluation Criteria to adopt Cloud Solutions. In: Proceedings of the 20th European Conference on Information Systems (ECIS 2012).

Rieger A, Thummert R, Fridgen G, Kahlen M, Ketter W (2016) Estimating the benefits of cooperation in a residential microgrid: A data-driven approach. Applied Energy 180:130–141.

Roesch M, Bauer D, Haupt L, Keller R, Bauernhansl T, Fridgen G, Reinhart G, Sauer A (2019) Harnessing the Full Potential of Industrial Demand-Side Flexibility: An End-to-End Approach Connecting Machines with Markets through Service-Oriented IT Platforms. Applied Sciences 9(18):3796. doi:10.3390/app9183796.

Ronn EI (ed) (2003) Real Options and Energy Management: Using Options Methodology to Enhance Capital Budgeting Decisions. Risk Books, London.

Ross E (2017) Cross-trained workforce planning models: The effects of temporal demand flexibility. Lancaster University Management School, Lancaster. doi:10.17635/lancaster/thesis/22.

Sachs T, Gründler A, Rusic M, Fridgen G (2019) Framing Microgrid Design from a Business and Information Systems Engineering Perspective. Business & Information Systems Engineering 61(6):729–744. doi:10.1007/s12599-018-00573-0.

Schneider S (2012) Power spot price models with negative prices. Journal of Energy Markets 4(4):77–102.

Schönsleben P (2019) Tangible services and intangible products in industrial product service systems. Procedia CIRP 83:28–31. doi:10.1016/j.procir.2019.02.144.

Schwaegerl C, Tao L (2014) The Microgrids Concept. In: Hatziargyriou ND (ed) Microgrids. John Wiley & Sons, Chichester, pp 1–24.

Schweppe FC, Caramanis MC, Tabors RD, Bohn RE (1988) Spot Pricing of Electricity. Springer US, Boston, MA. doi:10.1007/978-1-4613-1683-1.

Seidel S, Bharati P, Fridgen G, Watson RT, Albizri A, Kruse LC, Guzman I, Toland J, Karsten H, Lee H, Melville N, Rush D, Butler T, Watts S, Boudreau M-C, Chandra Kruse L (2017) The Sustainability Imperative in Information Systems Research. Communications of the Association for Information Systems 40(3):40–52. doi:10.17705/1CAIS.04003.

Sezgen O, Goldman CA, Krishnarao P (2007) Option value of electricity demand response. Energy 32(2):108–119. doi:10.1016/j.energy.2006.03.024.

Skytte K (2015) Energy Policy in the Nordic Electricity Market: A power system with high penetration of wind energy. Presented at Tsinghua University. https://backend.orbit.dtu.dk/ws/portalfiles/portal/118440654/Skytte_Nordic_power_system_Tsinghua_Beijing_181115.pdf.

Slavova M, Constantinides P (2017) Digital Infrastructures as Platforms: the Case of Smart Electricity Grids. ECIS 2017 Proceedings:1217–1231. https://aisel.aisnet.org/ecis2017_rp/79/.

Stage2Data (2019) Stage2Data Announces Strategic Partnership with Universal Compute Xchange (UCXmarket). https://finance.yahoo.com/news/stage2data-announces-strategic-partnership-universal-170000594.html.

Stoshikj M, Kryvinska N, Strauss C (2016) Service Systems and Service Innovation: Two Pillars of Service Science. Procedia Computer Science 83:212–220. doi:10.1016/j.procs.2016.04.118.

Stratmann K (2020) Negativer Strompreis: Die Energie-Industrie muss Strom immer häufiger verschenken. Handelsblatt. https://app.handelsblatt.com/unternehmen/energie/negativer-strompreis-die-energie-industrie-muss-strom-immer-haeufiger-verschenken/25382850.html.

Strbac G (2008) Demand side management: Benefits and challenges. Energy Policy 36(12):4419–4426. doi:10.1016/j.enpol.2008.09.030.

Strüker J, van Dinther C (2012) Demand Response in Smart Grids: Research Opportunities for the IS Discipline. In: Proceedings of the 18th Americas Conference on Information Systems (AMCIS 2012), pp 1–10.

Tang Y, Zhang S, Liu Y (2011) Incentive Payment Design for Electricity Demand Response. IEEE 2011 International Conference on Management and Service Science:1–5. doi:10.1109/ICMSS.2011.5999374.

Thimmel M, Fridgen G, Keller R, Roevekamp P (2019) Compensating balancing demand by spatial load migration – The case of geographically distributed data centers. Energy Policy 132:1130–1142. doi:10.1016/j.enpol.2019.06.063.

Tian Y (1993) A modified lattice approach to option pricing. Journal of Futures Markets 13(5):563–577. doi:10.1002/fut.3990130509.

UCX (2017) About UCX. https://ucxchange.com/about/.

Ullrich C (2013) Valuation of IT Investments Using Real Options Theory. Business & Information Systems Engineering 5(5):331–341. doi:10.1007/s12599-013-0286-0.

Umutlu G, Dorsman A, Telatar E (2011) The Electricity Market, Day-Ahead Market and Futures Market. In: Dorsman A, Westerman W, Karan MB, Arslan Ö (eds) Financial Aspects in Energy. Springer, Berlin, Heidelberg, pp 109–128. doi:10.1007/978-3-642-19709-3_7.

Vaske H (2015) Die Deutsche Börse Cloud Exchange geht an den Start. Computerwoche 2015. https://www.computerwoche.de/a/print/die-deutsche-boerse-cloud-exchange-geht-an-den-start,3099403.

Walther S, Plank A, Eymann T, Singh N, Phadke G (2012) Success Factors and Value Propositions of Software as a Service Providers – A Literature Review and Classification. In: Proceedings of the 18th Americas Conference on Information Systems (AMCIS 2012), pp 1–14.

Watson RT, Boudreau M-C, Chen AJ (2010) Information Systems and Environmentally Sustainable Development: Energy Informatics and New Directions for the IS Community. MIS Quarterly 34(1):23. doi:10.2307/20721413.

Watson RT, Lawrence TM, Boudreau M-C, Johnsen KJ (2013) Design Of A Demand Response System: Economics And Information Systems Alignment. In: Proceedings of the 21st European Conference on Information Systems (ECIS 2013).

Watzl JR (2014) A framework for exchange-based trading of cloud computing commodities. Dissertation, Ludwig-Maximilians-Universität, München. http://edoc.ub.uni-muenchen.de/16870/.

Watzl JR, Gentschen Felde N, Kranzlmüller D (2011) Analyzing the Applicability of Airline Booking Systems for Cloud Computing Offerings. In: Lin SC, Yen E (eds) Data Driven e-Science. Springer US, New York, NY, pp 331–344. doi:10.1007/978-1-4419-8014-4_26.

Winkler T (2019) Rohstoff des 21. Jahrhunderts: Aigen-Schlägler Mathematiker will Speicherplatz und Rechenleistung über Börse vermarkten. BezirksRundschau Oberösterreich. https://www.meinbezirk.at/oberoesterreich/c-wirtschaft/aigen-schlaegler-mathematiker-will-speicherplatz-und-rechenleistung-ueber-boerse-vermarkten_a3723357.

Wörner A, Ableitner L, Meeuw A, Wortmann F, Tiefenbeck V (2019) Peer-to-Peer Energy Trading in the Real World: Market Design and Evaluation of the User Value Proposition. In: Proceedings of the 40th Intl. Conference on Information Systems (ICIS 2019), pp 1–17.

Wu DJ, Kleindorfer PR, Zhang JE (2002) Optimal bidding and contracting strategies for capital-intensive goods. European Journal of Operational Research 137(3):657–676. doi:10.1016/S0377-2217(01)00093-5.

Xu LH, Baron RB (2017) MOC Marketplace Concept at the MOC – GIJI. https://massopen.cloud/blog/moc-marketplace/.

Yam C-Y, Baldwin A, Shiu S, Ioannidis C (2011) Migration to Cloud as Real Option: Investment Decision under Uncertainty. In: IEEE 10th Intl. Conference on Trust, Security and Privacy in Computing and Communications (TrustCom), pp 940–949. doi:10.1109/TrustCom.2011.130.

Zhou S (2017) An Introduction to Retail Electricity Choice in the United States. https://www.osti.gov/biblio/1398875.

7 Appendix

7.1 Research Papers Relevant to This Thesis[20] [21]

Paper 1

Fridgen, Gilbert; Häfner, Lukas; König, Christian; Sachs, Thomas (2016):

Providing Utility to Utilities: The Value of Information Systems Enabled Flexibility in Electricity Consumption

In: *Journal of the Association for Information Systems*, (17:8), pp. 537–563.
DOI: 10.17705/1jais.00434.
(VHB Jourqual 3: Category A, SCI Impact Factor 2018: 3.103, SJR 2018: 1.818, CiteScore 2018: 6.51 / 95% percentile)

Paper 2

Höckendorf, Henry; Sachs, Thomas; Fridgen, Gilbert (2019):

Electronic Markets for Electricity Procurement by Small and Medium-Sized Enterprises: Determining Price-Impacting Factors and their Influence on the Outcome of Electronic Reverse Auctions.

Paper 3

Sachs, Thomas; Gründler, Anna; Rusic, Milos; Fridgen, Gilbert (2019):

Framing Microgrid Design from a Business and Information Systems Engineering Perspective: A Framework and Agenda for Research

In: *Business & Information Systems Engineering*, pp. 1–16.
DOI: 10.1007/s12599-018-00573-0.
(VHB Jourqual 3: Category B, SCI Impact Factor 2018: 3.600, SJR 2018: 0.807, CiteScore 2018: 4.63 / 87% percentile)

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[20] Papers 1–4 can be found in the supplement. Kindly note that the text formatting and the reference style may differ from published papers, to allow for a consistent layout. There is a separate reference section, as well as a separate numbering of figures, tables, and footnotes for each paper.

[21] (Continued on next page.)

Paper 4

Keller, Robert; Häfner, Lukas; Sachs, Thomas; Fridgen, Gilbert (2019):

Scheduling Flexible Demand in Cloud Computing Spot Markets: A Real Options Approach.

In: *Business & Information Systems Engineering*, pp. 1–15.
DOI: 10.1007/s12599-019-00592-5.
(VHB Jourqual 3: Category B, SCI Impact Factor 2018: 3.600, SJR 2018: 0.807, CiteScore 2018: 4.63 / 87% percentile)

7.2 Declaration of Co-authorship and Individual Contribution

The following pages outline the individual contribution of all co-authors to the research papers included in this thesis. Signed copies declaring the authors' contributions to each paper have been submitted with this thesis. For this section, their content has been partially translated from German originals into English.

Paper 1 — Providing Utility to Utilities: The Value of Information Systems Enabled Flexibility in Electricity Consumption

The thesis's author co-authored this research paper with Gilbert Fridgen, Lukas Häfner, and Christian König. The co-authors have opted for alphabetical name order and have contributed to the paper as described below.

Gilbert Fridgen (co-author)

- The share of Prof. Dr. Gilbert Fridgen essentially consists of the idea and proposition to solve the problem using real options theory.
- He provided coaching for the novice PhD students, his experience and feedback in the paper process.

Lukas Häfner (co-author)

- Lukas Häfner's share is mainly characterized by its quantitative focus.
- He substantially elaborated the model, including its formal representation and description.
- In addition, he contributed a fundamental revision of the literature review.

Christian König (co-author)

- The share of Dr. Christian König essentially consists of his initial coaching in the paper process and his initial feedback on methodology and presentation.
- He also contributed experience to ensure relevance and readability for the target audience.

Thomas Sachs (co-author)

- Thomas Sachs's share consists of the elaboration of the real options methodology, under consideration of multiple market forms, as well as those corresponding and further paper sections.
- He contributed to developing the hour-ahead model and implemented the simulation for the model's evaluation.
- On this basis, he realized the sensitivity analysis conceptually and programmatically.

Paper 2 – Electronic Markets for Electricity Procurement by Small and Medium-Sized Enterprises: Determining Price-Impacting Factors and their Influence on the Outcome of Electronic Reverse Auctions

The thesis's author co-authored this research paper with Henry Höckendorf and Gilbert Fridgen. The co-authors have contributed to the paper as described below.

Henry Höckendorf (co-author)

- Research idea and realization, motivation for the Green IS field
- Design of the mixed methods research approach and literature review, hypothesis derivation
- Qualitative study: preparation, realization and analysis of six expert interviews
- Quantitative study: real-world data acquisition, linear regression and statistical testing

Thomas Sachs (co-author)

- Supervision during master thesis, guidance and continuous collaboration
- Co-design of the mixed methods approach, methodological revision for consistency and conciseness
- Comprehensive revision and streamlining of content and structure for journal submission
- Sporadic complementation, for instance to the discussion of findings

Gilbert Fridgen (subordinate co-author)

- Supervision and scientific guidance
- Participation in research topic and method development
- Contribution of experience and feedback

Paper 3 — Framing Microgrid Design from a Business and Information Systems Engineering Perspective: A Framework and Agenda for Research

The thesis's author co-authored this research paper with Anna Gründler, Milos Rusic, and Gilbert Fridgen. The co-authors have contributed to the paper as described below — the name order representing the extent of authorship.

Thomas Sachs (leading co-author)

- Participation in method and model development (the framework's structure and elements), provision of feedback in the context of the master thesis project
- Elaboration of objectives (section 1) and section 5 on evaluation results
- Supplementation of the literature base
- Joint elaboration of the text version for the initial BISE journal submission
- Comprehensive development of the essay for publication, including revision of all sections during the four-round review process

Anna Gründler (subordinate co-author)

- SOTA research and structuring, conception of the model and its elements (section 4)
- Interview organization, realization and analysis to evaluate and identify research gaps (section 6)
- Joint elaboration of the text version for the initial BISE journal submission
- Participation in the development of the essay for publication, in particular section 5 on evaluation results

Milos Rusic (subordinate co-author)

- SOTA research and structuring, conception of the model and its elements (section 4)
- Interview organization, realization and analysis to evaluate and identify gaps in research (section 6)
- Joint elaboration of the text version for the initial BISE journal submission

Gilbert Fridgen (subordinate co-author)

- Supervision and scientific mentorship
- Participation in method and model development (the framework's structure and elements)
- Contribution of experience and feedback, e.g., to the elaboration of the text version for the initial BISE journal submission

Paper 4 — Scheduling Flexible Demand in Cloud Computing Spot Markets: A Real Options Approach

The thesis's author co-authored this research paper with Robert Keller, Lukas Häfner, and Gilbert Fridgen. The co-authors have contributed to the paper as described below. Regardless of the name order, the first three co-authors have equally contributed to the paper.

Robert Keller (co-author)

- Lead: Knowledge and motivation specific to cloud computing markets
- Lead: Hypotheses formulation and statistical testing
- Average: Analysis of related work on forecasting cloud spot markets
- Average: Presentation of the research results
- Low: Real option modelling and formal analysis
- Low: Data processing, evaluation design and implementation

Lukas Häfner (co-author)

- Lead: Real option modelling and formal analysis
- Average: Data processing, evaluation design and implementation
- Average: Hypotheses formulation and statistical testing
- Average: Analysis of related work on forecasting cloud spot markets
- Average: Presentation of the research results
- Low: Knowledge and motivation specific to cloud computing markets

Thomas Sachs (co-author)

- Lead: Data processing, evaluation design and implementation
- Lead: Presentation of the research results
- Average: Knowledge and motivation specific to cloud computing markets
- Average: Real option modelling and formal analysis
- Low: Analysis of related work on forecasting cloud spot markets
- Low: Hypotheses formulation and statistical testing

Gilbert Fridgen (subordinate co-author)

- Inferior authorship
- Supervision and guidance

7.3 Paper 1 —
Providing Utility to Utilities: The Value of Information Systems Enabled Flexibility in Electricity Consumption

Authors: Fridgen, Gilbert; Häfner, Lukas; König, Christian; Sachs, Thomas

Published in: *Journal of the Association for Information Systems* (2016)

Abstract: As the transition to renewable energy sources progresses, the integration of such sources makes electricity production increasingly fluctuate. To contribute to power grid stability, electric utilities must balance volatile supply by shifting demand. This measure of demand response depends on flexibility, which arises as the integration of information systems in the power grid grows. The option to shift electric loads to times of lower demand or higher supply bears an economic value. Following a design science research approach, we illustrate how to quantify this value to support decisions on short-term consumer compensation. We adapt real options theory to the design—a strategy that IS researchers have used widely to determine value under uncertainty. As a prerequisite, we develop a stochastic process, which realistically replicates intraday electricity spot price development. With this process, we design an artifact suitable for valuation, which we illustrate in a plug-in electric vehicle scenario. Following the artifact's evaluation based on historical spot price data from the electricity exchange EPEX SPOT, we found that real options analysis works well for quantifying the value of information systems enabled flexibility in electricity consumption.

7.4 Paper 2 — Electronic Markets for Electricity Procurement by SMEs: Determining Price-Impacting Factors and their Influence on the Outcome of Electronic Reverse Auctions

Authors: Höckendorf, Henry; Sachs, Thomas; Fridgen, Gilbert

Extended Abstract[22]

In the liberalized European electricity market, small and medium-sized enterprises (SMEs) have been obliged to measure and provide load profiles of their electricity consumption to their electricity suppliers. Smart meters determine these load profiles over time (Callaway and Hiskens 2011; Li et al. 2013). This information allows the electricity suppliers to estimate wholesale prices and to determine the fit of a client company's load profile with their energy portfolio (Erlinghagen et al. 2015).

In line with their omnipresent development, business-to-business e-commerce platforms have arisen on which electricity suppliers can compete to supply SMEs based on their load profiles. We refer to such platforms specialized in electricity procurement as electronic electricity markets (EEMs). These EEMs use information systems and challenge the concept of traditional electricity markets due to their tendering approach: by conducting electronic reverse auctions (e-RA: Beall 2003; Cullen and Webster 2007), they allow for transparency to client companies and electricity prices based on their consumption behavior. In turn, suppliers gain improved access to potential clients, which includes the immediate availability of relevant consumption information. The result — gained market efficiency — should reduce electricity prices.

Previous research has estimated profit-optimal strategies for electricity suppliers in tendering processes and forecasted electricity market prices. However, research has lacked an analysis of factors that influence the electricity price for client companies in online tendering. With this paper, we hence aim to answer the following research questions:

(1) What factors impact the electricity price for SMEs on EEMs?
(2) What influence do the identified factors exert on the net electricity price?

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[22] At the time of this thesis' publication, this research paper is under review for publication in a scientific journal. Therefore, an extended abstract covering the paper's content is provided.

The paper contributes to close the gap in e-RA research pointed out by Aloini et al. (2012): the lack of empirical investigation regarding the influence of auction variables on the price outcome. We use a mixed methods research approach, which Venkatesh et al. (2013) discussed and introduced into the IS field. Thus combining quantitative and qualitative research methods in a single study, we consult existing literature on electronic markets and e-RA to derive hypotheses that we test through expert interviews.

In detail, we conduct a literature review transferring existing theories from related research areas, in order to put forward hypotheses about price-impacting factors (Step A following Recker 2013). Following, we iterate expert interviews to either maintain or amend the hypotheses (Step B following Kaplan and Maxwell 2005, Myers and Newman 2007). Testing the influence of ten factors on the net electricity price, we review appropriate hypotheses through a multiple linear regression with real-world data on terminated electricity e-RA (Step C). Finally, we discuss our results.

We find that the number of bidders, the month of contract conclusion, the consumption duration, the peak/off-peak ratio, the sector, and the voltage measurement have a significant influence on the e-RA outcome on EEM. This presented set of factors is likely to influence the net electricity price, partially reinforcing the results that e-RA and e-market literature for EEMs indicated. The findings apply to the German, Austrian, and Swiss electricity market. Since the EU is unifying regulations and laws regarding the electricity market as part of the planned Internal Energy Market (European Commission 2019; Helm 2014), this paper's results might henceforth apply to additional electricity markets in the EU (Böckers and Heimeshoff 2014).[23]

We intend our findings to support further EEM optimization minimizing the electricity price for client companies. Eventually, client companies might be able to optimize the identified factors and thereby reduce their electricity costs. Calling attention to e-RA trading of electricity encourages the empowerment of electricity market structures in the European Union and fosters the efficiency of supplier-client relationships in times of the energy transition.

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[23] See the next page for references used in the extended abstract.

References

Aloini, D., Dulmin, R., & Mininno, V. (2012). E-reverse auction design: Critical variables in a B2B context. Business Process Management Journal, 18(2), 219–249. doi:10.1108/14637151211225180

Beall, S. (2003). The role of reverse auctions in strategic sourcing. Focus study. Tempe: W.P. Carey School of Business, Arizona State University; CAPS Research.

Böckers, V., & Heimeshoff, U. (2014). The extent of European power markets. Energy Economics, 46, 102–111. doi:10.1016/j.eneco.2014.09.004

Callaway, D. S., & Hiskens, I. A. (2011). Achieving Controllability of Electric Loads. Proceedings of the IEEE, 99(1), 184–199. doi:10.1109/JPROC.2010.2081652

Cullen, A. J., & Webster, M. (2007). A model of B2B e-commerce, based on connectivity and purpose. International Journal of Operations & Production Management, 27(2), 205–225. doi:10.1108/01443570710720621

Erlinghagen, S., Lichtensteiger, B., & Markard, J. (2015). Smart meter communication standards in Europe – a comparison. Renewable and Sustainable Energy Reviews, 43, 1249–1262. doi:10.1016/j.rser.2014.11.065

European Commission. (2019). Quarterly Report on European Electricity Markets (Market Observatory for Energy No. 1, first quarter of 2019). Bruxelles. Retrieved from https://ec.europa.eu/energy/sites/ener/files/quarterly_report_on_european_electricity_markets_q1_2019_final.pdf

Helm, D. (2014). The European framework for energy and climate policies. Energy Policy, 64, 29–35. doi:10.1016/j.enpol.2013.05.063

Kaplan, B., & Maxwell, J. A. (2005). Qualitative Research Methods for Evaluating Computer Information Systems. In J. G. Anderson & C. E. Aydin (Eds.), Health informatics series. Evaluating the organizational impact of healthcare information systems (2nd ed., pp. 30–55). New York, NY: Springer.

Li, Z., Yang, F., Mohagheghi, S., Wang, Z., Tournier, J. C., & Wang, Y. (2013). Toward smart distribution management by integrating advanced metering infrastructure. Electric Power Systems Research, 105, 51–56. doi:10.1016/j.epsr.2013.07.008

Myers, M. D., & Newman, M. (2007). The qualitative interview in IS research: Examining the craft. Information and Organization, 17(1), 2–26. doi:10.1016/j.infoandorg.2006.11.001

Recker, J. (2013). Scientific research in information systems: A beginner's guide. Progress in IS. Berlin, New York: Springer.

Venkatesh, V., Brown, S., & Bala, H. (2013). Bridging the Qualitative–Quantitative Divide: Guidelines for Conducting Mixed Methods Research in Information Systems. Management Information Systems Quarterly, 37(1), 21–54.

7.5 Paper 3 —
Framing Microgrid Design from a Business and Information Systems Engineering Perspective: A Framework and Agenda for Research

Authors: Sachs, Thomas; Gründler, Anna; Rusic, Milos; Fridgen, Gilbert

Published in: *Business & Information Systems Engineering* (2019)

Abstract: Microgrids are decentralized distribution networks that integrate distributed energy resources and balance energy generation and loads locally. The introduction of microgrids can help overcome the challenges of global energy systems. Despite this potential, the information systems domain has seen limited research on microgrids. This paper synthesizes research on elements of microgrids for electric energy. Interviewed experts maintain that technological microgrid solutions have been solidly developed; nevertheless, the lack of economic and business consideration is stalling their deployment. The authors argue that business and information systems engineering research can provide integrated perspectives that connect technology and markets. Consequently, the authors derive a framework from an extensive interdisciplinary literature review that structures the academic state of the art on microgrid design and could guide associated information systems research. The framework comprises four layers: energy technology and infrastructure, information and communication infrastructure, application systems, and governance. The authors evaluate the framework in interviews with 15 experts from industry and three from academia. Their feedback allows to iteratively refine the framework and point out research directions on microgrids in business and information systems engineering.

7.6 Paper 4 —
Scheduling Flexible Demand in Cloud Computing Spot Markets: A Real Options Approach

Authors: Keller, Robert; Häfner, Lukas; Sachs, Thomas; Fridgen, Gilbert

Published in: *Business & Information Systems Engineering* (2019)

Abstract: The rapid standardization and specialization of cloud computing services have led to the development of cloud spot markets on which cloud service providers and customers can trade in near real-time. Frequent changes in demand and supply give rise to spot prices that vary throughout the day. Cloud customers often have temporal flexibility to execute their jobs before a specific deadline. In this paper, the authors apply real options analysis (ROA), which is an established valuation method designed to capture the flexibility of action under uncertainty. They adapt and compare multiple discrete-time approaches that enable cloud customers to quantify and exploit the monetary value of their short-term temporal flexibility. The paper contributes to the field by guaranteeing cloud job execution of variable-time requests in a single cloud spot market, whereas existing multi-market strategies may not fulfill requests when outbid. In a broad simulation of scenarios for the use of Amazon EC2 spot instances, the developed approaches exploit the existing savings potential up to 40 percent – a considerable extent. Moreover, the results demonstrate that ROA, which explicitly considers time-of-day-specific spot price patterns, outperforms traditional option pricing models and expectation optimization.