Technology-Driven Decentralization in Public Administration and Electric Power Systems

Dissertation

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Abstract

Blockchain is no longer a hype technology. Powerful applications exist in many contexts, but in others, progress is slow. To investigate reasons for the differences in uptake, this thesis explores two antithetical contexts: public administration and electric power systems. While blockchain applications in public administration are gaining traction, many blockchain projects in electric power systems have been abandoned. This thesis argues that applications of blockchain are successful where the anticipated benefits are specific and where organizational, technical, and regulatory challenges appear manageable. Moreover, blockchain is successful where decentralized organizational structures dominate. The thesis includes seven papers that investigate various aspects of technology-driven decentralization and blockchain adoption in the two above-mentioned contexts. Their abstracts are available in the appendix and their full texts in the supplemental material. The first two papers examine compliance with the requirements of the EU's General Data Protection Regulation, a particularly pertinent challenge for blockchain projects. The third paper reflects on the importance of experimentation when working with innovative and unfamiliar technologies. The fourth paper investigates a successful implementation of blockchain in public administration; namely, a federal infrastructure to coordinate German asylum procedures. Papers five, six, and seven focus on technology-driven decentralization in electric power systems. They explore essential foundations for understanding the lack of successful blockchain projects in the areas of peer-to-peer trading and microgrid operation. The fifth paper suggests that these application areas have unclear overall profitability, even when the use of energy storage helps to draw on several revenue streams. The sixth and seventh paper further challenge the need for residential peer-to-peer trading and decentralized microgrid operation by establishing the financial and stability benefits of local grid managers and identifying electricity tariffs that can encourage desirable and sustainable operation by such managers.

Table of contents

List of abbreviations

A-E-A	Affordance-Experimentation-Actualization
BAMF	Germany's Federal Office for Migration and Refugees (Bundesamt für Migration und Flüchtlinge)
DID	Decentralized Identifier
EBSI	European Blockchain Services Infrastructure
EU	European Union
FLORA	Federal Blockchain Infrastructure Asylum
GDPR	General Data Protection Regulation
MiCA	Markets in Crypto-assets
RES	Renewable Energy Sources
VC	Verifiable Credential
W3C	World Wide Web Consortium

List of tables

1. Introduction

Secure digital technologies play an increasingly important role in modern economies and societies. One such technology that has received substantial attention in recent years is blockchain technology. In simple terms, a blockchain is an append-only, cryptographically secured, and distributed database. Its copies are stored and updated by so-called nodes in a blockchain network rather than a single database manager. Blockchains can store various data, including software code, so-called smart contracts, that nodes can read and execute. In general, blockchains are suitable for contexts that require the sharing and persistent tracking of information across organizational boundaries, but where concerns about trust and data sovereignty make centralized IT systems unfeasible or undesirable (Paper 1; Paper 2; Sedlmeir et al., 2020)[1]. Blockchain technology is interesting for various industries, such as financial services and logistics, but also for the public sector (Andoni et al., 2019; Roth, Stohr, et al., 2021; Ziolkowski et al., 2020).

This thesis examines the use of blockchain in two such public sector contexts, namely, public administration and electric power systems. It explores the benefits typically expected and the challenges encountered in these two contexts, and ways to prepare blockchain for effective use. Moreover, it analyzes in detail four commonly discussed application areas – two from each of the two contexts: (1) decentralized digital identities, (2) coordination of cross-authority processes, (3) peer-to-peer trading, and (4) traceability of electricity. It concludes with a discussion of the positive effects that decentralized organizing structures appear to have on blockchain's success in public sector contexts.

The seven publications in this thesis examine various aspects of the use of blockchain in public administration and electric power systems. The first two papers explore approaches to address a common regulatory challenge for blockchain projects: compliance with the requirements of the European Union's (EU) General Data Protection Regulation (GDPR) (Paper 1: "How to Develop a GDPR-Compliant Blockchain Solution for Cross-Organizational Workflow Management: Evidence from the German Asylum Procedure" and Paper 2: "Building a Blockchain Application that Complies with the EU General Data Protection Regulation"). The third paper investigates experimentation as an essential strategy for authorities and companies to familiarize themselves with new technologies and prepare them for effective use (Paper 3: "Affordance-Experimentation-Actualization Theory in Artificial Intelligence Research - A Predictive Maintenance Story"). The fourth paper investigates the

[1] To improve readability, the seven papers of this dissertation are cited as 'Paper [x]'.

functional requirements for the use of blockchain to coordinate cross-authority procedures in federally organized contexts (Paper 4: “The Evolution of an Architectural Paradigm - Using Blockchain to Build a Cross-Organizational Enterprise Service Bus”). The fifth, sixth, and seventh paper focus on technology-driven decentralization in electric power systems and offer important foundations for understanding why blockchain is hard to implement for peer-to-peer trading and microgrid operation, two of the most discussed application areas in electric power systems. The fifth paper paints an ambiguous picture for the overall profitability of these application areas, even when projects can leverage energy storage to draw on the full available revenue potential (Paper 5: “Business Models and Profitability of Energy Storage”). The sixth and seventh paper discuss the specific revenue shortcomings and grid stability risks associated with residential peer-to-peer trading and decentralized microgrid operation (Paper 6: “Estimating the benefits of cooperation in a residential microgrid: A data-driven approach” and Paper 7: “One rate does not fit all: An empirical analysis of electricity tariffs for residential microgrids”).

The thesis is structured as follows. It first addresses the technical foundations of blockchain technology, before discussing the benefits and challenges of the technology’s use in public administration and electric power systems. It then examines general approaches to prepare blockchain for effective use in these contexts. The next two chapters examine the most frequently discussed application areas in each of the two contexts. The penultimate chapter summarizes an important success factor identified from these application areas, namely, the prevalence of decentralized organizing structures. The thesis' conclusion summarizes, discusses the contributions, limitations, and outlook of its seven publications, and acknowledgers previous and related work.

2. Blockchain

2.1. Technical foundations

Blockchain technology is often considered a highly innovative technology, particularly for cross-organizational contexts (Höß et al., 2021; Jensen et al., 2019; Ølnes et al., 2017). It allows a network of participants to jointly manage a transactional and tamper-resistant database (Arnold et al., 2019; Carvalho et al., 2021; Schweizer et al., 2017). Blockchains offer a high level of resistance to manipulations, in that they store transactions in a cryptographically secured chain of blocks and keep distributed copies of the chain (Andoni et al., 2019; Sedlmeir et al., 2020; Upadhyay, 2020). In the past few years, blockchain technology has gained considerable traction due to its various possible applications in the private and public sectors (Benbunan-Fich et al., 2020; Mattke et al., 2019; Ziolkowski et al., 2020).

Blockchain technology typically has four technological properties (Roth, Stohr, et al., 2021): *secure and redundant data storage*, *selective transparency*, *reliable information sharing and process automation*, and *adaptability* to different cooperation settings in distributed networks. *Secure and redundant data storage* is often defined as the most prominent property of blockchain technology (Ahl et al., 2020; Chapron, 2017; Kranz et al., 2019). It results from the cryptographical grouping of transactions, such as payments or process information, into blocks, and the construction of a cryptographic chain of blocks with copies stored on several participating nodes (Lockl et al., 2020; Pedersen et al., 2019; Sedlmeir, Ross, et al., 2021). The storage of multiple copies on different nodes minimizes vulnerability to failure and attacks, while the continuous chain of blocks creates a highly tamper-resistant data structure wherein manipulations are easily identified (Hughes et al., 2019; Sedlmeir, Ross, et al., 2021; Sousa et al., 2019).

Secondly, blockchain enables *selective transparency*, meaning that participants can be given limited rights to input and access data (Noor et al., 2018; Perrons & Cosby, 2020; Roth, Stohr, et al., 2021). *Selective transparency* reduces complexity by establishing the necessary transparency without disclosing information that either should not or may not be accessed (Hawlitschek et al., 2018; Mattke et al., 2019; Roth, Stohr, et al., 2021). Especially in settings where competitors cooperate, this selective disclosure is vital for instilling trust and preventing abuse (Filippi, 2016; Iansiti & Lakhani, 2017; Risius & Spohrer, 2017).

Thirdly, blockchain enables *reliable information sharing and process automation* (Rossi et al., 2019; Sousa et al., 2019; Ziolkowski et al., 2020). This encompasses properties of both *secure and redundant data storage* and *selective transparency* (Roth, Stohr, et al., 2021).

While the first guarantees the authenticity of information (Perrons & Cosby, 2020; Roth, Stohr, et al., 2021; Sedlmeir et al., 2020), the second allows the reliable dissemination of important information to affected participants (Amend et al., 2021; Iansiti & Lakhani, 2017; Roth, Stohr, et al., 2021). Smart contracts additionally allow for process automation by providing automated triggers for process steps and extensive monitoring capabilities (Drummer & Neumann, 2020; Kranz et al., 2019; Mendling et al., 2018).

Fourthly, many blockchain frameworks are *adaptable* (Andersen & Bogusz, 2019; Roth, Stohr, et al., 2021; Siegfried et al., 2020). Specifically, they enable the creation of sub-networks with different participants and rules for information processing to reflect changing requirements over time and local particularities (Andersen & Bogusz, 2019; Rieger, Stohr, et al., 2021; Roth, Stohr, et al., 2021). Particularly in cross-organizational contexts, various cooperation scenarios require a technology that has a high degree of *adaptability* (Kshetri, 2018; Roth, Stohr, et al., 2021; Ziolkowski et al., 2020).

2.2. Benefits

Although the expected benefits of using blockchain are diverse, they generally fit into three categories: efficiency, effectiveness, and security (Hughes et al., 2019; Roth, Stohr, et al., 2021; Roth, Utz, et al., 2021). Applications that pursue efficiency gains use blockchain to improve the output of a defined set of processes (Atlam et al., 2018; Renwick & Gleasure, 2021; Roth, Utz, et al., 2021). Effectiveness benefits result from optimizing the structure of processes to achieve the desired output (Lowitzsch et al., 2020; Perrons & Cosby, 2020; Roth, Utz, et al., 2021). Security encompasses the protection of processes from failure and threats to ensure reliable output (Roth, Stohr, et al., 2021; Roth, Utz, et al., 2021; Warkentin & Orgeron, 2020).

Efficiency gains are often realized via the digitization of paper-based processes that have resisted the adoption of digital solutions with centralized designs. Using blockchain to tamper-resistantly store and exchange data can reduce error rates, cut costs, and improve data quality (Ahl et al., 2020; Andoni et al., 2019; Roth, Stohr, et al., 2021). Additional process logic can ensure automated and seamless exchange of relevant data between involved parties while preventing those without authorization from accessing this data (Paper 4; Rieger, Stohr, et al., 2021; Roth, Stohr, et al., 2021).

Steps to realize effectiveness benefits range from the introduction of new payment procedures to the reorganization of established structures (Hughes et al., 2019; Kranz et al., 2019; Upadhyay, 2020). Particularly in contexts where a central organization is neither desired nor feasible, blockchain can enable decentralized cooperation because it does not require independent third parties to establish trusted connections between different parties involved (Beck et al., 2018; Di Silvestre et al., 2019; Rossi et al., 2019). Since transactions can be redundantly stored on the blockchain, with copies on a specified set of participating nodes, manipulations can easily be identified and the privacy of critical data can be retained (Hughes et al., 2019; Perrons & Cosby, 2020; Sedlmeir et al., 2020).

Expected security benefits commonly relate to blockchain's redundancy, tamper-resistance, and selective transparency (Rieger, Stohr, et al., 2021; Roth, Stohr, et al., 2021; Roth, Utz, et al., 2021). These features establish auditability of data and can facilitate trust between cooperating organizations (Perrons & Cosby, 2020; Roth, Stohr, et al., 2021; Ziolkowski et al., 2020). However, safety considerations are often secondary, with blockchain applications primarily focused on improving efficiency, effectiveness, or both (Andoni et al., 2019; Perrons & Cosby, 2020; Roth, Utz, et al., 2021).

While the benefits generally fit into the three categories, their emphasis and specificity differ across contexts. For many applications in public administration, the expected benefits are very specific, and more than one benefit type is addressed (Amend et al., 2021; Roth, Stohr, et al., 2021; Treiblmaier et al., 2021). For instance, blockchain is expected to enable a reorganization of digital authentication procedures toward a citizen-centric model (Rieger, Roth, et al., 2021; Sedlmeir, Smethurst, et al., 2021; van Bokkem et al., 2019). Moreover, blockchain could enable the timely and secure distribution of process information between competent authorities in federally structured environments (Ølnes et al., 2017; Rieger, Stohr, et al., 2021; Ziolkowski et al., 2020). As a result, blockchain could replace many paper-based and error-prone processes (Amend et al., 2021; Rieger, Stohr, et al., 2021; Sedlmeir, Smethurst, et al., 2021).

In electric power systems, expected benefits are often generic (Bogensperger et al., 2018; Richard et al., 2019; Roth, Utz, et al., 2021). In many ways, the benefits do not diverge from the technological properties of blockchain and are more akin to generic hopes. Moreover, many applications, such as peer-to-peer trading, emphasize radical effectiveness at the cost of substantial changes in established procedures and market roles (Andoni et al., 2019; Roth, Utz, et al., 2021; Sousa et al., 2019).

2.3. Challenges

Challenges stemming from the use of blockchain are very diverse but can also be grouped into three categories: organizational, technical, and regulatory (Amend et al., 2021; Rossi et al., 2019; Roth, Utz, et al., 2021). Organizational challenges commonly result from changes to organizational structures, roles, processes, and the development of new capabilities (Beck et al., 2018; Roth, Utz, et al., 2021; Sousa et al., 2019). Technical challenges commonly involve integrating blockchain with legacy systems and meeting functional requirements (Andoni et al., 2019; Perrons & Cosby, 2020; Roth, Utz, et al., 2021). Regulatory challenges typically result from the General Data Protection Regulation, the change or replacement of legally required market roles, or the modification of processes that are essential for system stability (Di Silvestre et al., 2019; Richard et al., 2019; Roth, Utz, et al., 2021).

Organizational

In public administration, structures, roles, and processes often vary according to local procedures and cooperation settings (Auer, 2005; Keating, 2017; Roth, Stohr, et al., 2021). Consequently, blockchain systems must be able to account for local differences in structures, roles, and processes without undermining organization-specific responsibilities (Biela et al., 2012; Erk & Koning, 2010; Roth, Stohr, et al., 2021). Moreover, they must be easy to implement and maintain so that they can be adapted to the changing specifications and requirements of participating organizations (Andersen & Bogusz, 2019; Kshetri, 2018; Roth, Stohr, et al., 2021). The implementation and maintenance of blockchain systems often require new capabilities that have to be acquired externally, creating undesired dependencies on third parties (Amend et al., 2021; Upadhyay, 2020; Ziolkowski et al., 2020).

In electric power systems, decentralization and disintermediation often conflict with established roles and processes (Andoni et al., 2019; Di Silvestre et al., 2019; Roth, Utz, et al., 2021). Many of these roles are associated with critical and mediating functions, and their responsibilities are defined by law, which makes them hard to change and replace (Andoni et al., 2019; Di Silvestre et al., 2019; Roth, Utz, et al., 2021). Moreover, blockchain systems are often complex and insufficiently profitable. That is, decentralization and disintermediation may not be profitable, while the increased granularity caused by the involvement of additional actors would only add to system complexity (Andoni et al., 2019; Li et al., 2019; Roth, Utz, et al., 2021). In addition, many of the small actors in electric power systems do not have the resources to develop know-how about blockchain technology in their own companies and may have to engage external experts to manage their data (Andoni et al., 2019; Bogensperger et al., 2018; Roth, Utz, et al., 2021).

Technical

Technical challenges for both public administration and electric power systems result, primarily, from difficulties in integrating blockchain with legacy systems and meeting the functional requirements for successful application (Andoni et al., 2019; Sousa et al., 2019; Ziolkowski et al., 2020). In particular, blockchain systems require powerful application programming interfaces to guarantee seamless interaction between the blockchain and legacy systems. Without such interfaces, transferring data from legacy systems to the blockchain and vice versa becomes very cumbersome and costly (Rossi et al., 2019; Roth, Stohr, et al., 2021; Treiblmaier & Sillaber, 2020).

An additional lack of interoperability and technical standards makes successful large-scale implementations cumbersome (Ahl et al., 2020; Roth, Utz, et al., 2021; Treiblmaier et al., 2021). This applies to both public administration and electric power systems. Since a universal blockchain framework is unlikely, interoperability between common blockchain frameworks is essential to ensure the unobstructed flow of information and cross-organizational cooperation (Paper 2; Roth, Stohr, et al., 2021; Ziolkowski et al., 2020). Although defining global standards may provide the foundation for interoperability, such standards are difficult to define and generalize across contexts (Rieger, Roth, et al., 2021; Sedlmeir, Smethurst, et al., 2021; Treiblmaier et al., 2021). Moreover, interoperability is a constant challenge, and changes to frameworks, and standards have to be coordinated with many parties to prevent unintentional forking (Andersen & Bogusz, 2019; Andoni et al., 2019; Rieger, Stohr, et al., 2021).

For electric power systems, the scalability trilemma of decentralization, scalability, and security is another particularly salient technical challenge. Common blockchain frameworks typically try to combine all three characteristics but compromise at least one of the dimensions (Andoni et al., 2019; Mengelkamp et al., 2018; Roth, Utz, et al., 2021).

Regulatory

Regulatory challenges result not exclusively, but to a large extent, from the requirements of data privacy laws, such as the General Data Protection Regulation (Paper 1; Paper 2; Di Silvestre et al., 2019). The GDPR aims to order and harmonize the processing of personal data in the European Union. It includes provisions concerning the rights of natural persons (data subjects) and the obligations of data processors (data controllers). It applies when data is evidently personal but also when combining it with other data allows the identification of a natural person (Paper 2; Klar, 2020; Rieger, Stohr, et al., 2021).

The establishment of clear responsibilities for compliance, the securing of lawful bases for data processing, and the observance of the rights to erasure and rectification are all essential for blockchain projects to meet the requirements of the GDPR (Paper 1; Paper 2; Berberich & Steiner, 2016). Defining responsibilities is often difficult, particularly in blockchain networks in which participants are anonymous and data is processed and stored by all participants (Paper 2; Sedlmeir et al., 2020; Treiblmaier et al., 2021). In particular, legal opinions differ as to which participants in blockchain networks qualify as stand-alone controllers and which as joint controllers. The distinction is important because joint controllers have to create an arrangement that identifies each joint controller (Paper 2; Klar, 2020; Renwick & Gleasure, 2021).

Securing lawful bases for processing is another crucial challenge (Paper 2; Amend et al., 2021; Berberich & Steiner, 2016). Overall, the GDPR specifies six sources of lawful bases, ranging from the data subject's consent over legal obligations to requirements to discharge public administration (Paper 2; Hoofnagle et al., 2019; Klar, 2020). Establishing lawful bases is often difficult in blockchain networks because such a basis has to be defined for each action of data processing by each network participant. Processing includes, for instance structuring, storage, and dissemination (Amend et al., 2021; Renwick & Gleasure, 2021; Rieger, Stohr, et al., 2021). Moreover, the establishment of lawful bases is not a one-time exercise since such bases may cease to exist or apply, for instance when a data subject withdraws consent or when a data processor no longer has a legal obligation to process the data. In such cases, data controllers are no longer permitted to store the respective personal data and they must erase it (Paper 2; Amend et al., 2021; Klar, 2020).

The third challenge is compliance with the rights to erasure and rectification. Erasure may become necessary for several reasons, such as simple errors in entering data or legal time limits (Hoofnagle et al., 2019; Klar, 2020; Rieger, Stohr, et al., 2021). Yet, this conflicts, fundamentally, with blockchain's tamper-resistant design. Moreover, data subjects can demand that data controllers rectify false personal data (Paper 1; Paper 2; Rieger, Stohr, et al., 2021). Observing the right to rectification is challenging because it requires the modification of each copy of the blockchain (Paper 2; Renwick & Gleasure, 2021; Sedlmeir et al., 2020). While this may be possible in blockchain networks where participants can be identified and held to account for not modifying their copy of the blockchain, it is close to impossible in those networks where participants are anonymous (Paper 2; Klar, 2020; Rieger, Stohr, et al., 2021).

While all three challenges can be addressed, it is important to observe a few basic rules. Foremost, the storage of personal data on a blockchain should be avoided, where possible. If a use case requires that data on the blockchain is attributable to a natural person, pseudonymization solutions should be employed (Paper 1; Paper 2; Berberich & Steiner, 2016). Pseudonymization means that personal data can be attributed to a specific data subject only with the use of separately held, additional information (Paper 2; Berberich & Steiner, 2016; Rieger, Stohr, et al., 2021). Specifically, the data on the blockchain should be highly pseudonymized, for instance, via the inclusion of several levels of pseudonymization (Paper 2; Amend et al., 2021; Rieger, Stohr, et al., 2021). Secondly, it should be easy to anonymize, such as through easy erasure of the additional data (Paper 2; Amend et al., 2021; Rieger, Stohr, et al., 2021). Thirdly, it should be exceptionally difficult to inadvertently attribute to a natural person without the use of the additional data (Paper 2; Klar, 2020; Rieger, Stohr, et al., 2021). Moreover, blockchain systems with anonymous participants should be avoided (Paper 1; Paper 2; Berberich & Steiner, 2016).

Although often prominent, GDPR compliance is not the only substantial regulatory challenge. In electric power systems, for instance, the legal definition of market roles complicates the elimination of existing and the establishment of new roles for decentralized markets based on blockchain technology (Bundesnetzagentur, 2019; Richard et al., 2019; Roth, Utz, et al., 2021). Moreover, the replacement of certain roles is undesirable. System operators, for instance, are responsible for the reliable transmission and distribution of electricity (Andoni et al., 2019; Di Silvestre et al., 2019; Roth, Utz, et al., 2021). The regulation of electric energy systems, thus, attaches various responsibilities to the operators' role, such as grid management, system service procurement, and reporting obligations. Small actors often cannot meet these obligations (Andoni et al., 2019; Bogensperger et al., 2018; Roth, Utz, et al., 2021). Accordingly, fundamental changes to regulation will only occur if, at some point, replacing or creating new market roles improves the security of supply (Bogensperger et al., 2018; Richard et al., 2019; Roth, Utz, et al., 2021).

Similar regulations are imposed on clearing and settlement processes using smart contracts and cryptographic tokens (Arnold et al., 2019; Barbereau et al., 2022; Roth, Utz, et al., 2021). Tokens, in particular, can perform a variety of functions depending on their purpose and are, therefore, often only vaguely defined by law (Arnold et al., 2019; Oliveira et al., 2018; Roth, Utz, et al., 2021). This makes the effective regulation of tokens cumbersome, which is why many blockchain projects that use tokens either face high regulatory resistance or refrain from further use (Bogensperger et al., 2018; Richard et al., 2019; Roth, Utz, et al., 2021). The proposed regulation on Markets in Crypto-assets (MiCA) may, however, pave the way to a legal framework for different forms of crypto-assets and crypto-asset services (Roth, Utz, et al., 2021; Sandner, 2020).

2.4. Preparation for effective use

While applications of blockchain in the private sector address many of these challenges successfully, best practices and reference designs may not be easily transferable to public sector contexts (Benbunan-Fich et al., 2020; Roth, Stohr, et al., 2021; Treiblmaier et al., 2021). In effect, many of these applications may require that authorities and companies establish their own approaches and experiment with different blockchain designs.

One potential approach that can help structure and manage this experimentation process is Affordance-Experimentation-Actualization (A-E-A) theory. A-E-A theory is based on the concept of affordances, which conceptualize how animals and humans perceive their environment and how this perception influences their behavior (Gibson, 1977). The affordances of a digital technology are the possibilities for action that it offers to a goal-oriented actor (Paper 3; (Markus & Silver, 2008; Strong et al., 2014). In essence, A-E-A theory provides a tool that guides the identification and actualization of such possibilities for action (Krancher et al., 2018; Strong et al., 2014; Volkoff & Strong, 2013).

Actualization typically requires that a technology is ready for effective use and that the involved actors understand the action possibilities that arise from using the technology as well as the associated potential outcomes (Paper 3; Du et al., 2019; Ostern et al., 2020). When these conditions are not met, A-E-A theory suggests an experimentation phase where actors learn about benefits, remedy challenges, and establish potential applications.

Such an experimentation phase can have three elements: conceptual exploration, constraint mitigation, and conceptual adaptation (Paper 3; Du et al., 2019). Conceptual exploration helps to ensure a basic conceptual understanding of the technology and its properties. It can take different forms, such as participating in workshops, watching tutorials, or reading academic and industry material on the technology (Paper 3; Fridgen, Lockl, et al., 2018).

Conceptual adaptation helps to explore a technology independently of successful applications in other contexts (Paper 3; Du et al., 2019; Fridgen, Lockl, et al., 2018). It resolves misconceptions about the technology, such as the misconception that blockchain is highly energy-intensive by default (Du et al., 2019; Mora et al., 2018; Stoll et al., 2019), and exclusive association with particular applications and contexts, such as blockchain being useful only for financial services and supply chains (Jensen et al., 2019; Roth, Stohr, et al., 2021; Treiblmaier & Sillaber, 2020). In effect, conceptual adaption emphasizes the establishment of own approaches and designs that best fit the particular purpose and context.

Constraint mitigation helps to identify and mitigate challenges that can arise when a technology is introduced in a specific organizational context (Paper 3; Du et al., 2019; Fridgen, Lockl, et al., 2018). Implementing blockchain technology might, for example, entail governance and interoperability challenges (Andoni et al., 2019; Treiblmaier & Sillaber, 2020; Zavolokina et al., 2020).

Conceptual adaptation and constrain mitigation can take various forms, ranging from innovation workshops with external consultants, to the development of prototypes, and joint projects with universities, partners, and specialized IT service providers and start-ups (Paper 3; Du et al., 2019; Fridgen, Lockl, et al., 2018).

3. Applications in public administration

Public services are increasingly supported by digital technologies (Benbunan-Fich et al., 2020; Guggenmos et al., 2019; Roth, Stohr, et al., 2021). The expected benefits of digital innovation are often apparent and typically involve increased efficiency and improved service delivery (Benitez et al., 2018; Roth, Stohr, et al., 2021; Warkentin & Orgeron, 2020). Yet, it is difficult to establish universal success factors for digital innovation in public administration (Avgerou & Bonina, 2020; Rose et al., 2015; Scott et al., 2016) because these contexts are subject to complex decision-making and accountability procedures (Perrons & Cosby, 2020; Roth, Stohr, et al., 2021; Ziolkowski et al., 2020).

Moreover, digital innovation in public administration is often limited by complex legacy systems (Paper 1; Paper 4; Guggenmos et al., 2019). Particularly in federally structured contexts, data is stored in fragmented databases and IT systems differ substantially between authorities. Yet, constitutional and organizational concerns regularly inhibit attempts to centralize and integrate (Goh & Arenas, 2020; Guggenmos et al., 2019; Warkentin & Orgeron, 2020). Thus, authorities typically need to create solutions that can connect diverse data repositories and foster cross-organizational information exchange.

Blockchain technology is often an option in such contexts, especially in those that are federally organized (Paper 4; Ølnes et al., 2017; Seebacher & Schüritz, 2017). Germany's federal government, for instance, has singled out blockchain as a strategically important technology for the delivery of public services in federal contexts (Paper 1; Paper 2; Paper 4). Another prominent example is the EU's European Blockchain Services Infrastructure (EBSI) for cross-border public services (CEF Digital, 2021; Roth, Stohr, et al., 2021).

Table 1 summarizes the three most commonly explored application areas in public administration (CEF Digital, 2021; Roth, Stohr, et al., 2021; Sedlmeir, Smethurst, et al., 2021).

These include *decentralized digital identities* where blockchain supports the digitalization and exchange of documents that confirm identity attributes, such as names, citizenship, or the permission to drive. *Coordination of cross-authority processes* applications use blockchain to exchange process information and provide workflow management functions. *Document traceability* applications rely on blockchain to store hash values and meta-data of important documents, such as contract documents, to later confirm origin, validity, and integrity.

This thesis will focus on the first two application areas as they often take centre stage in discussing blockchain applications in public administration (Paper 4; Rieger, Roth, et al., 2021; Sullivan & Burger, 2019).

Table 1: Commonly discussed application areas of blockchain in public administration.

Application	Definition
Decentralized digital identities	Digitalization and exchange of (official) documents that confirm identity attributes.
Coordination of cross-authority processes	Exchanging of process information between authorities and (partial) automation of process monitoring and management.
Document traceability	Creating registries that confirm the origin, validity, and integrity of digital (contract) documents.

3.1. Decentralized digital identities

Decentralized digital identities is an application explored both in private and public sector contexts (Rieger, Roth, et al., 2021; Sedlmeir, Smethurst, et al., 2021; Sullivan & Burger, 2019). Figuratively speaking, *decentralized digital identity* applications offer digitalized versions of physical identification systems that build on paper- or plastic based identity documents. They enable holders to manage digital identity documents in a digital wallet. Similar to physical identification systems, various issuers can provide such digital identity documents and confirm identity attributes (Chadwick et al., 2019; Stokkink & Pouwelse, 2018; van Bokkem et al., 2019). For instance, a competent authority can issue a digital ID card and confirm the related attributes, such as name, age, and citizenship. Upon request, holders can present identity attributes to third parties, so-called verifiers. In some *decentralized digital identity* systems, holders can limit the disclosure to certain parts of a digital document (Rieger, Roth, et al., 2021; Sedlmeir, Smethurst, et al., 2021; van Bokkem et al., 2019). For instance, they can choose to not disclose the age attribute on their digital ID card when a verifier only requires their name.

Decentralized digital identity applications typically reference two World Wide Web Consortium standards: the Verifiable Credentials (VC) standard and the Decentralized Identifiers (DID) standard (Chadwick & Burnett, 2021; Rieger, Roth, et al., 2021; Sedlmeir, Smethurst, et al., 2021). The VC standard specifies basic syntactic requirements and mechanisms for cryptographically secure and machine-verifiable digital identity documents. The DID standard provides specifications for digital identifiers that enable authentication and encrypted peer-to-peer exchange of verifiable credentials (Chadwick & Burnett, 2021; Höß et al., 2022; Sedlmeir, Smethurst, et al., 2021).

The European Union as well as local and national governments in Canada, Germany, and Spain, proactively explore the use of VCs and DIDs. (Reed & Preuschkat, 2021; Rieger, Roth, et al., 2021; Sedlmeir, Smethurst, et al., 2021). The spectrum ranges from official identity documents to diplomas to vaccination certificates (CEF Digital, 2021; Rieger, Roth, et al., 2021; Sedlmeir, Smethurst, et al., 2021). These governments understand their role as providers and verifiers of basic VCs, such as digital ID cards. Moreover, they actively define data models and requirements for public sector VCs (CEF Digital, 2021; Preuschkat & Reed, 2021; Sedlmeir, Smethurst, et al., 2021).

While not strictly required, blockchains commonly provides three functions in *decentralized digital identity* applications (Hardman, 2021; Reed & Preuschkat, 2021; Sedlmeir, Smethurst, et al., 2021). Firstly, they serve as decentralized Public Key Infrastructures (dPKIs) that anchor issuer identifiers. This typically involves the storage of issuer DIDs. These DIDs resolve to so-called DID Documents that specify essential information about the DID, such as the issuer’s name and public key material that authenticates the issuer, and methods to verify information provided by the issuer (Hardman, 2021; Moe et al., 2019; Rieger, Roth, et al., 2021; Windley, 2019). Secondly, blockchains store VC schemas and definitions. VC schemas standardize a particular type of VC, such as a diploma, and provide a data model for this VC type. In turn, VC definitions offer additional details on the characteristics of VCs from a particular issuer, such as the population of specific attributes of the VC type’s data model and certain cryptographic material used to sign VCs (Chadwick & Burnett, 2021; Hardman, 2021; Stokkink & Pouwelse, 2018). Thirdly, blockchain solutions typically provide revocation registration features. That is, issuers can store information on the validity of VCs on the blockchain, enabling easy verification. Such information is typically accumulated through cryptographic mechanisms to preserve privacy (Grüner et al., 2019; Hardman, 2021; Rieger, Roth, et al., 2021).

Decentralized digital identity applications are commonly associated with benefits of all three types. They are expected to increase effectiveness by reducing dependency on federated identity providers, such as Alphabet, Apple, and Facebook (Preuschkat & Reed, 2021; Rieger, Roth, et al., 2021; Sedlmeir, Smethurst, et al., 2021). Moreover, they are believed to minimize identity-related costs, such as those for onboarding new users and for verifying the validity of identity documents (Lee et al., 2019; Stokkink & Pouwelse, 2018; van Bokkem et al., 2019). Furthermore, proponents argue that such applications can improve security by avoiding unsafe identity data silos, reducing the risk of identity theft, and preventing surveillance by governments and large companies (Chadwick et al., 2019; Rieger, Roth, et al., 2021; Sedlmeir, Smethurst, et al., 2021). However, these benefits are often difficult to quantify, and it remains to be seen whether they will materialize as expected.

At the same time, *decentralized digital identity* applications face many of the typical organizational, technical, and regulatory challenges of blockchain applications. These range from defining governance aspects to standardization and compliance with privacy requirements (Preuschkat & Reed, 2021; Rieger, Roth, et al., 2021; Sedlmeir, Smethurst, et al., 2021). Organizational challenges exist particularly in network governance, shared standards, and usability (Hardman, 2021; Sedlmeir, Smethurst, et al., 2021). Technical challenges result from limited scalability and delegation of credentials (Grüner et al., 2019; Hardman, 2021; Rieger, Roth, et al., 2021). The delegation of credentials is challenging because a holder will not necessarily want to be registered as an issuer to delegate a VC to another person or party (Hardman, 2021). Regulatory challenges are mainly related to privacy concerns, such as the inadvertent attribution of a VC to a natural person, resulting from the analysis of revocation registries on the blockchain (Grüner et al., 2019; Hardman, 2021; Rieger, Roth, et al., 2021).

However, various interdisciplinary groups and start-ups work on promising solutions to the most pressing organizational, technical, and regulatory challenges (Rieger, Roth, et al., 2021; Sedlmeir, Smethurst, et al., 2021; Weigl et al., 2022). Moreover, active governmental support, such as Germany's innovation competition 'Showcase Secure Digital Identities' and the proposed European Digital Identity, underlines the significant prospects of *decentralized digital identity* applications (Federal Ministry for Economic Affairs and Energy, 2020; Sedlmeir, Smethurst, et al., 2021; Weigl et al., 2022).

3.2. Coordination of cross-authority processes

Another commonly discussed application area of blockchain in public administration is the *coordination of cross-authority processes*. Such processes typically involve a large number of authorities with different competencies where the delegation of process governance to a central authority is not possible or desirable (Benbunan-Fich et al., 2020; Rieger, Stohr, et al., 2021; Roth, Stohr, et al., 2021). These constellations are especially common in federal systems where power is equally distributed across various authorities (Fossum & Jachtenfuchs, 2017; Grant & Tan, 2013; Roth, Stohr, et al., 2021).

A prominent example of *coordination of cross-authority processes* is Germany's Federal Blockchain Infrastructure Asylum (FLORA) (Paper 1; Paper 2; Paper 4). The German asylum procedure involves close collaboration between various authorities at the municipal, state, and federal levels. The Federal Office for Migration and Refugees (BAMF) plays a pivotal role in handling and issuing decisions regarding asylum applications. However, federal separation of competencies prevents the delegation of process governance to a central authority in the procedure, such as the BAMF (Paper 4; Rieger, Stohr, et al., 2021; Roth, Stohr, et al., 2021). The BAMF has thus developed a decentralized, blockchain-based system for the coordination of asylum procedures (Paper 4; Rieger, Stohr, et al., 2021; Roth, Stohr, et al., 2021).

This blockchain system logs and propagates status messages and process data on certain sub-processes of the German asylum procedure. Each sub-process has a distinct set of status messages with related dependencies and rules, which are implemented as a status machine. The BAMF expects that its blockchain system will provide the competent authorities with an efficient, secure, and GDPR-compliant means to exchange process information, supporting cross-organizational process coordination (Paper 1; Paper 4; Rieger, Stohr, et al., 2021).

A closely related example is EBSI's Asylum Process Management Use Case, which focuses on Dublin transfers (CEF Digital, 2021; Roth, Stohr, et al., 2021). The Dublin regulation (Regulation (EU) No 604/2013, 2013) defines the member state of the European Union that is responsible for examining an asylum application submitted within the European Union. Moreover, it establishes the rules and processes for requesting another member state to take charge or take back an asylum application as well as transferring asylum applicants. EBIS's Asylum Process Management Use Case explores the use of EBSI to support these processes by persistently logging and securely propagating process updates and the required process data (CEF Digital, 2021; Roth, Stohr, et al., 2021).

Overall, blockchain systems for the *coordination of cross-authority processes* are expected to improve efficiency and security (Iansiti & Lakhani, 2017; Risius & Spohrer, 2017; Roth, Stohr, et al., 2021). Specifically, these blockchain systems can enable secure and timely distribution of new process information to all competent authorities. This distribution can minimize transmission errors and ensures that all competent authorities have the same level of information (Paper 1; Paper 4; Roth, Stohr, et al., 2021). Moreover, once process information has been written to the blockchain, it can trigger subsequent steps of the process at other authorities. Such triggers can reduce overall process times and, in particular, downtimes between steps (Paper 1; Paper 4; Roth, Stohr, et al., 2021). Smart contracts also allow automated process control and, prospectively, (partial) automation of selected process steps. They can help avoid errors and improve process quality (Paper 1; Paper 4; Rieger, Stohr, et al., 2021). At the same time, sensitive and personal data can remain in the competent authorities' legacy systems (Paper 1; Paper 4; Guggenmos et al., 2019). A blockchain system can, thus, increase information availability while preserving data sovereignty, the once-only principle, and data protection, as well as enabling the immediate exchange of information (Amend et al., 2021; Roth, Stohr, et al., 2021; Ziolkowski et al., 2020). Overall, the expected benefits are very specific. However, reference projects such as FLORA and EBSI have yet to quantify these benefits and broadly prepare blockchain for effective use (c.f. Chapter 2.4).

Challenges exist especially on the organizational and regulatory side (Amend et al., 2021; Rieger, Stohr, et al., 2021; Roth, Stohr, et al., 2021). Organizationally, the implementation of a blockchain system for the coordination of cross-authority processes requires integration of the competent authorities (Paper 4; Amend et al., 2021; Roth, Stohr, et al., 2021). To minimize the attendant complexity, these authorities need to agree on a technical and organizational governance framework that enables the joint development, deployment, and use of blockchain while safeguarding the technical and organizational separation of competencies (Paper 4; Rieger, Stohr, et al., 2021; Roth, Stohr, et al., 2021). However, the establishment of such governance frameworks may be considerably easier than in other contexts because authorities typically trust one another and are familiar with creating administrative agreements that govern their cooperation and coordination (Paper 2; Rieger, Stohr, et al., 2021; Ziolkowski et al., 2020)

On the regulatory side, compliance with data privacy requirements is an especially pertinent challenge because most data exchanged during cross-authority procedures is personal (Paper 1; Paper 2; Rieger, Stohr, et al., 2021). As discussed in Section 2.3, these challenges are not easy to address but manageable. For instance, the BAMF's blockchain system provides a readily available reference for meeting these requirements via organizational and technical means. In particular, the right to erasure can be addressed through a design that only stores pseudonymized process data on the blockchain and uses specialized software components – so-called privacy services – to store and exchange ID mappings that allow the pseudonymized data on the blockchain to be attributed to asylum applications. Erasure of this mapping anonymizes the process data on the blockchain (compliance by anonymization) (Paper 1; Paper 2; Rieger, Stohr, et al., 2021). Responsibilities for GDPR compliance can be outlined in administrative agreements (Berberich & Steiner, 2016; Klar, 2020; Renwick & Gleasure, 2021).

On the technical side, challenges particularly include interoperability with legacy systems (Paper 4; Amend et al., 2021; Treiblmaier & Sillaber, 2020). Yet, blockchain is often more fit for purpose than centralized solutions such as conventional workflow management systems (Paper 1; Paper 2; Paper 4). Firstly, the use of centralized systems inherently contradicts decentral organizing principles and would require the redistribution of competencies and, therewith, associated legislative action. Secondly, it would lead to unbalanced data guardianship and, thus, unwanted responsibilities. Thirdly, centralization complicates the efficient mapping of local specifics and differences. Blockchain solutions can circumvent these challenges and act as cross-organizational enterprise service buses (Paper 1; Paper 4; Roth, Utz, et al., 2021).

Overall, blockchain solutions for the coordination of cross-authority procedures are among the most promising applications in public administration. The expected benefits are highly specific and the encountered challenges often appear manageable.

4. Applications in electric power systems

To date, electric power systems comprise numerous centrally organized actors that produce, transmit and distribute electrical energy across long distances from the place of production to the place of consumption (Dong et al., 2018; Lin et al., 2019; van Leeuwen et al., 2020). Much of the electricity produced still relies on non-renewable fossil fuels, which is no longer in line with global sustainability goals (Andoni et al., 2019; Mengelkamp et al., 2018; Perrons & Cosby, 2020). As a result, renewable energy sources (RES), albeit often volatile and intermittent, are increasingly introduced to electric power systems to drive sustainability (Andoni et al., 2019; Ante et al., 2021). In parallel, corresponding concepts that enable the integration of RES into the energy value chain are gaining traction (Paper 5; Noor et al., 2018; Sousa et al., 2019). These concepts include, for instance, reliable proofs of the origin of the consumed 'green' electricity (Bogensperger et al., 2018; Perrons & Cosby, 2020; Roth, Utz, et al., 2021). Since centralized concepts often cannot provide such proof in a cost-effective manner, innovative technologies are required to help develop such solutions (Andoni et al., 2019; Mengelkamp et al., 2018; Roth, Utz, et al., 2021).

Blockchain is one such technology. Due to its decentralized nature, it has quickly been identified as a potential agent of change in electric power systems (Ahl et al., 2020; Li et al., 2019; Roth, Utz, et al., 2021). As a result, numerous projects have been initiated that explored potential innovative additions to or replacements of existing processes (Andoni et al., 2019; Bogensperger et al., 2018; Roth, Utz, et al., 2021). Table 2 presents the seven most commonly explored applications (Roth, Utz, et al., 2021).

Table 2: Commonly explored applications of blockchain in electric power systems (Roth, Utz, et al., 2021).

Application	**Definition**
Peer-to-peer trading – retail	Organization of local electricity markets for small actors, such as residential pro- and consumers, without the involvement of traditional retailers or grid operators.
Peer-to-peer trading – wholesale	Organization of large commercial markets for electricity without the use of centralized trading houses or electricity exchanges.
Peer-to-peer trading – system services	Organization of peer-to-peer markets for system services that are usually managed by grid operators.
Microgrid operation	Operation of a small network of (decentralized) electricity users with local (renewable) sources of supply, usually attached to a centralized public grid but able to function independently.
E-Roaming	Exchanging financial and non-financial data between different charging infrastructure operators and e-mobility service providers, giving users of electric vehicles access to charging stations of different providers.
Labeling of electricity	Providing electricity consumers with verifiable information on shares of power sources, including storage, in the grid at the time of consumption.
Trading of certificates	Sale and exchange of certificates that provide proof of origin or emission from specific generation and storage facilities.

These seven applications include three varieties of *peer-to-peer trading* (retail, wholesale, and system services), wherein blockchain sustains trading systems without centralized market operators (Li et al., 2019; Morstyn et al., 2018; Roth, Stohr, et al., 2021; Roth, Utz, et al., 2021).

Microgrid operation intends to use blockchain and smart contracts to schedule and manage production and consumption assets in microgrids (Mengelkamp et al., 2018; Noor et al., 2018; Roth, Utz, et al., 2021). *E-roaming* relies on blockchain to exchange electric vehicle charging data and settle transactions between charging point operators and mobility service providers (Höß et al., 2022; Roth, Utz, et al., 2021; Zhang et al., 2018). The application addresses limited access to charging points by enabling the free and secure exchange of data regardless of charging network membership. Smart contracts and crypto tokens may further automate and unify processes across national borders. These efficiency gains are expected to entail considerable cuts in transaction fees for mobility providers and costs for consumers (IRENA, 2019; Roth, Utz, et al., 2021; Zhang et al., 2018). Yet, none of the sources provide a precise estimate of these gains.

Labeling of electricity uses blockchain to track the share of power sources in the grid at the time of consumption. The application is expected to reduce the risk of 'greenwashing', accelerate data exchange about fed-in and consumed electricity, and reduce manual processes. While these benefits are expected to minimize costs, estimates remain vague (Andoni et al., 2019; Bogensperger et al., 2018; Roth, Utz, et al., 2021). The same is true for *trading of certificates.* In such applications, blockchain is used to create and exchange certificates that provide proofs of origin or emissions based on labeling data. Since every certificate is issued uniquely, its secure and redundant storage on the blockchain creates a transparent and unequivocal ownership history. Developing an industry-wide platform to trade these certificates may, however, turn out to be cumbersome without established technical standards (Luke et al., 2019; Peter et al., 2019; Roth, Utz, et al., 2021).

This thesis will focus on *peer-to-peer trading* as well as *labeling of electricity* and *trading of certificates* because these are the most commonly discussed respectively most promising applications of blockchain in electric power systems.

4.1. Peer-to-peer trading

The use of blockchain for *peer-to-peer trading* commonly has the following objectives: (1) to increase the involvement of small actors (*peer-to-peer trading - retail*), (2) to create more flexible energy markets (*peer-to-peer trading - wholesale*), and (3) to increase resilience of energy systems (*peer-to-peer trading - system services*). Proponents expect secure bilateral communication using blockchain to be essential for reaching these objectives. Moreover, proponents predict substantial cost savings and increased profits from transactions automated through smart contracts. Additional replacement of expensive intermediaries may even further reduce costs and increase profits (Ahl et al., 2020; Andoni et al., 2019; Lüth et al., 2018).

Peer-to-peer - retail trading applications are considered a promising and disruptive approach towards more localized electrical power systems (Li et al., 2019; Lüth et al., 2018; Roth, Utz, et al., 2021). With these applications, proponents hope to empower prosumers who already contribute to environmentally friendly energy generation with, for instance, their rooftop solar panels (Paper 6; Paper 7; Roth, Utz, et al., 2021). In particular, proponents aim to use blockchain to reduce the costs of processing small transactions. Reduced processing costs, in turn, would enable small electricity producers to turn a profit from selling their surplus renewable energy to other prosumers or consumers in the network (Jiang et al., 2020; Noor et al., 2018; Roth, Utz, et al., 2021). Immutable and transparent storage of transactions may also reduce the need for intermediaries (Hua et al., 2020; Lüth et al., 2018; Roth, Utz, et al., 2021) and open the electricity market to smaller actors, which in turn may increase competition, enhance grid efficiency, and further decrease electricity prices (Ante et al., 2021). Consumers would benefit from green electricity at reasonable prices produced by their neighbors (Ableitner et al., 2020; Andoni et al., 2019). Whereas current energy markets would require time-consuming manual paperwork for peer-to-peer transaction, blockchain-based smart contracts are expected to significantly limit the efforts involved. Smart contracts could also automate trading between various actors by using real-time data about energy fed into the grid and reacting to respective price signals (Ahl et al., 2020; Roth, Utz, et al., 2021; Thomas et al., 2019).

In *peer-to-peer - wholesale trading* applications, smart contracts are expected to further automate exchange trading. These automation opportunities include, for instance, certain escrow services such as liability fees, guarantees, and warranties (Bogensperger et al., 2018; Richard et al., 2019; Roth, Utz, et al., 2021). Smart contracts are also considered suitable for the efficient and automated execution of clearing processes after successful trading. Due to their tamper-resistant storage on the blockchain, both the number of warranties required and the general clearing costs could be reduced (Höß et al., 2022; Richard et al., 2019; Roth, Utz, et al., 2021). For some, this may reduce access barriers to exchange trading so that even small actors, such as microgrid operators, can trade self-generated electricity on electricity exchanges (Mengelkamp et al., 2018; Morstyn et al., 2018; Roth, Utz, et al., 2021).

In addition to exchange trading, over-the-counter (OTC) electricity trading is sometimes identified as a promising area of application for blockchain technology (Bogensperger et al., 2018; Bundesnetzagentur, 2019; Di Silvestre et al., 2019). In OTC trading, transactions are usually settled using standard contracts, which can be individually adapted. Although OTC trading now often involves brokerage firms to save investment in in-house staff and IT infrastructure, there are still many instances where trading is done via email, instant messaging, or phone calls. This not only leads to many misunderstandings but also a lack of transparency and control. Blockchain could establish this transparency and improve the traceability of transactions in OTC trading. Since all communication can be stored securely on the blockchain, it is much easier to verify the transaction in case of misunderstandings or suspected fraud (Bogensperger et al., 2018; Di Silvestre et al., 2019; Richard et al., 2019).

To participate in system service markets, actors must meet specific requirements which are verified with time-consuming control services including registration, verification, and approval. Blockchain technology could automate many of these services, enabling the rapid integration of new actors into *peer-to-peer – system services* markets (Bogensperger et al., 2018; Bundesnetzagentur, 2019; Roth, Utz, et al., 2021). Smart contracts could further help automate system service activation and settlement in these markets (Bogensperger et al., 2018; Roth, Utz, et al., 2021; Thomas et al., 2019). Moreover, they may optimize billing processes within balancing groups. These are often characterized by cumbersome manual paperwork and require time. With blockchain technology, it would be possible to standardize the billing processes by transparently and immutably documenting group deviations, and consolidating, balancing, and offsetting these against the provided control power. Such tamper-resistant documentation speeds up the billing process and also simplifies tracking or intervening in transactions for distribution system operators (DSO) or transmission service operators (TSO), if necessary (Bogensperger et al., 2018; Bundesnetzagentur, 2019; Richard et al., 2019).

What all three peer-to-peer trading applications have in common is that they propose substantial re-organization of established structures and processes (Andoni et al., 2019; Perrons & Cosby, 2020; Roth, Utz, et al., 2021). These changes entail substantial challenges at the organizational and regulatory levels and are difficult to implement outside of research projects (Andoni et al., 2019; Bogensperger et al., 2018; Roth, Utz, et al., 2021). Decentralization and disintermediation of trading processes, for instance, conflict with established roles and regulations, which are often associated with critical and mediating functions, and their responsibilities are defined by law. This makes them hard to replace or even change (Andoni et al., 2019; Bogensperger et al., 2018; Roth, Utz, et al., 2021).

Moreover, *retail peer-to-peer trading* applications are often combined with *microgrid operation* applications, which adds to regulatory challenges (Ante et al., 2021; Roth, Utz, et al., 2021; Tsao & Thanh, 2021). Outside of Europe, where regulatory frameworks for microgrids are often less restrictive, such as in the US, Thailand, and various African countries, such challenges are less pronounced (Andoni et al., 2019; Noor et al., 2018; van Leeuwen et al., 2020).

Less restrictive regulatory frameworks, however, are only of use if microgrid transactions cannot already be processed efficiently and securely using conventional energy management software (Paper 6; García Vera et al., 2019; Zia et al., 2018). Such software typically involves predictable management effort and costs (Roth, Utz, et al., 2021). In contrast, blockchain systems are often difficult to implement and not profitable for small transactions. Besides, frequently required near-real-time transactions are currently hard to implement with blockchain technology. Hence, decentralized energy markets and microgrid management based on blockchain are difficult to establish (Bundesnetzagentur, 2019; IRENA, 2019; Richard et al., 2019).

Yet, various research groups and start-ups still work on solutions to the most pressing organizational, technical, and regulatory challenges (Bogensperger et al., 2018; IRENA, 2019; Roth, Utz, et al., 2021). Peer-to-peer approaches may, thus, be worthwhile in countries outside of Europe, where regulatory frameworks are sometimes less restrictive. There, blockchain may even provide a solution to the problem of supplying scattered communities with sufficient electricity (Andoni et al., 2019; Noor et al., 2018; van Leeuwen et al., 2020).

4.2. Traceability of green electricity

Using blockchain technology to label green electricity might be a tamper-resistant and transparent method for tracing the origin of consumed electricity (Bogensperger et al., 2018; Luke et al., 2019; Roth, Utz, et al., 2021). Once a RES generation facility is registered, energy purchase agreements can be negotiated with consumers. The details of these agreements can be transferred into a smart contract, while details of the quantities of generated and consumed electricity can be immutably and transparently stored on the blockchain (Richard et al., 2019; Roth, Utz, et al., 2021; SAP, 2018). The resulting proofs of origin indicate how much green electricity has been produced and fed into the grid at the time of consumption. Thus, blockchain-based labeling may mitigate concerns regarding the sources of consumed electricity. That is, a precise proof of fed-in and consumed electricity is expected to reduce the risk of 'greenwashing', accelerate data exchange, and reduce manual processes (Bogensperger et al., 2018; Roth, Utz, et al., 2021; Smart Service Welt II, 2020).

While these efficiency gains are expected to reduce costs substantially, there are no specific estimates as to this reduction. Specific challenges are, in turn, easier to identify

(Bogensperger et al., 2018; Richard et al., 2019; Roth, Utz, et al., 2021). They include technical challenges, such as limited usability, and regulatory challenges, such as compliance with data privacy regulation. Few customers have the required digital literacy to access and interpret data on a blockchain. Instead, they must trust the data display provided by energy suppliers or other third parties. Another complex challenge is compliance with data privacy regulations, such as the GDPR. As discussed in Section 2.3, data privacy regulation requires that data can be erased if is either directly or indirectly attributable to a person, which is difficult to implement with blockchain. As such, labeling systems have to prevent the easy identification of a person from the data stored on the blockchain (Andoni et al., 2019; Richard et al., 2019; Roth, Utz, et al., 2021).

Trading of certificates applications use labeling data to establish on the blockchain certificates that provide an immutable record of origin or emission for specific generation and storage facilities (Bundesnetzagentur, 2019; Richard et al., 2019; Roth, Utz, et al., 2021). This enables operators of solar and wind facilities to provide certified proof of how much green electricity they produce and feed into the grid. As a result, green and regional power concepts become more credible and markets for the trading of these certificates more viable (Bogensperger et al., 2018; Richard et al., 2019; Roth, Utz, et al., 2021). Smart contracts may be used for the tokenization of green electricity certificates and could also enable the exchange of certificates at a peer-to-peer level. Such green electricity certificates represent the net surplus of green electricity generated by the producer (Ernst & Young, 2019; Luke et al., 2019). Since every certificate is issued uniquely, its secure and redundant storage on the blockchain creates a transparent and unequivocal ownership history (Bogensperger et al., 2018; Bundesnetzagentur, 2019; Richard et al., 2019).

However, quantifying these expected benefits is difficult. Moreover, developing a blockchain platform for certificate trading is highly complex, especially without established technical standards (Andoni et al., 2019; Richard et al., 2019; Roth, Utz, et al., 2021). In addition, it must be ensured that the data on the blockchain is authentic. That is, generation facilities must be authenticated and all involved metering devices calibrated (Peter et al., 2019; Roth, Utz, et al., 2021; Smart Service Welt II, 2020).

Many of these challenges may, however, become manageable with increasing digitalization. Since neither application affects established market roles, regulatory hurdles also appear to be manageable. Although GDPR compliance remains a fundamental challenge, it may be addressable using innovative solutions that combine blockchain technology with zeroknowledge proofs and/or verifiable credentials (Höß et al., 2021; Roth, Utz, et al., 2021; Sedlmeir, Smethurst, et al., 2021).

5. Decentralized organizing structures

An interesting insight from the investigated applications in federally organized public administration and electric power systems is that decentralized organizing structures seem to be an essential factor in successful adoption of blockchain (Goh & Arenas, 2020; Leidner & Kayworth, 2006; Roth, Stohr, et al., 2021). That is, many applications of blockchain appear to be successful not because they replace intermediaries but because these are not intended (Rieger, Stohr, et al., 2021; Roth, Stohr, et al., 2021).

In particular, many fundamental organizing principles of federally organized contexts, such as the *empowerment* of individual actors (Egeberg, 2001; Grant & Tan, 2013; Roth, Stohr, et al., 2021), *separation of competencies* (Borriello & Crespy, 2015; Mckay, 2005; Roth, Stohr, et al., 2021), *cooperation and coordination* (Paper 4; Ebinger & Richter, 2016; Roth, Stohr, et al., 2021), and *organizational flexibility* (Erk & Koning, 2010; Fossum & Jachtenfuchs, 2017; Roth, Stohr, et al., 2021), are also reflected in the basic technological properties of blockchain.

This is evident both in the BAMF's FLORA project and EBSI (CEF Digital, 2021; Rieger, Stohr, et al., 2021; Roth, Stohr, et al., 2021). FLORA and EBSI seem to be successful not despite the complexities that beset federal organizing structures but because blockchain supports organizing principles of federalism such as *separation of competencies* and *organizational flexibility* (Roth, Stohr, et al., 2021). In effect, *redundant and secure data storage* (Jensen et al., 2019; Roth, Stohr, et al., 2021; Sedlmeir et al., 2020), *selective transparency* (Paper 4; Perrons & Cosby, 2020; Roth, Stohr, et al., 2021), *reliable information sharing and process automation* (Roth, Stohr, et al., 2021; Sedlmeir et al., 2020; Sousa et al., 2019), and *adaptability* to different procedures and cooperation settings (Paper 4; Roth, Stohr, et al., 2021; Ziolkowski et al., 2020) make blockchain a promising technology to address the fundamental organizational requirements of federally structured environments. Similar observations can also be made for *decentralized digital identity* applications, such as those being explored in Canada, Germany, and Spain, all countries with a (quasi-)federal mode of government (Sedlmeir, Smethurst, et al., 2021; Weigl et al., 2022).

The importance of a fit between organizing principles and technological properties is also demonstrated by applications in electric power systems. Electric power systems are often centrally organized and security of supply considerations have led to strict technical standards, clear responsibilities, hierarchical structures, and narrowly defined roles (Andoni et al., 2019;

Bogensperger et al., 2018; Roth, Utz, et al., 2021). However, such standards, structures and roles leave little room for flexibility, changing cooperation and coordination settings, or empowerment (Andoni et al., 2019; Bogensperger et al., 2018; Roth, Utz, et al., 2021). Thus, it is not surprising that blockchain as a technology, which emphasizes decentralization, flexibility, and the empowerment of market actors gains little traction in electric power systems. This applies in particular to applications that aim to change the core structure of electric power systems, such as peer-to-peer trading (Andoni et al., 2019; Bogensperger et al., 2018; Richard et al., 2019). Other applications, such as the labeling of green energy (Richard et al., 2019; Roth, Utz, et al., 2021; SAP, 2018), which address innovative additions to the existing system, are much more likely to succeed, even if their implementation with blockchain is not always necessary.

6. Conclusion

Blockchain proves to be a versatile and powerful technology for public sector applications. It can be a part of a larger system – as is the case for *decentralized digital identities* – or its foundation – as is the case for the *coordination of cross-authority processes*. It appears to be successful in public sector contexts where benefits can be clearly identified and where organizational, technical, and regulatory challenges are manageable. Moreover, blockchain's success appears to depend on how well its technical properties match the organizing principles of the application context (Leidner & Kayworth, 2006; Roth, Stohr, et al., 2021). Thus, blockchain technology is prominent in federally structured governments but less successful in contexts without decentralized organizing structures, such as electric power systems.

6.1. Contributions, limitations, and outlook

Paper 1 applies a technical perspective to reconcile blockchain with the requirements of the GDPR. Specifically, it investigates how blockchain systems can be designed to meet the requirements of the rights to erasure and rectification. Based on insights from the BAMF's FLORA project, the paper offers two design principles. Firstly, it recommends avoiding storing personal data on a blockchain. Secondly, it emphasizes the importance of using pseudonymization when a use case requires that the data on the blockchain can be attributed to a natural person. While these two design principles may be less pertinent in contexts other than cross-authority processes, they present an important reference point for the design of blockchain systems that are GDPR-compliant.

Paper 2 extends Paper 1 and takes a broader, management perspective to reconciling blockchain with the requirements of GDPR. It identifies the three most demanding of these requirements and discusses three conceivable combinations of technical and organizational means by which the three requirements may be addressed. It then describes and discusses the BAMF's use of one of these three combinations, namely a pseudonymization approach. Paper 2 then concludes with a refinement of the two design principles of Paper 1. Specifically, it emphasizes the importance of choosing designs with access control. Moreover, it provides specific recommendations for creating pseudonymization solutions for the coordination of cross-organizational processes. Naturally, the discussed combinations of technical and organizational means are examples only, and each blockchain project needs to identify a combination that best fits its particular context. However, the examples are good reference points for understanding the basic challenges and alternative means by which they might be addressed.

Paper 3 investigates the importance of experimenting with innovative technologies, such as blockchain or artificial intelligence, that lack established use cases. It contributes to A-E-A theory by finding corroborative evidence for the existence of Du et al.'s (2019) experimentation phase of which it also provides further detail. Specifically, it adds a third element to the experimentation phase: conceptual adaption. While this element may not be relevant for all innovative digital technologies and projects, it offers an important option for organizations particularly unfamiliar with a technology.

Paper 4 explores the functional requirements of process coordination in federally structured governments. It discusses the importance of digital solutions with decentralized designs to reflect the separation of competencies and local procedural differences. It then investigates blockchain's prospects in such contexts, based on insights from the BAMF's FLORA project. The paper finds that the BAMF's blockchain system represents a cross-organizational extension of an established architectural paradigm, the Enterprise Service Bus. Naturally, some of these insights may not be fully generalizable or transferable to other contexts. Still, the paper is an important initial step toward actionable design principles for blockchain solutions that support cross-organizational process coordination.

Paper 5 explores the range and profitability of business models for energy storage. It presents a framework to characterize such business models of which it identifies 28. Moreover, it matches these 28 identified business models with a set of commercially available technologies to demonstrate that all business models are technically feasible. It then reviews the results of previous studies to establish that many business models are still unprofitable but near a tipping point. It concludes with a recommendation of research directions to foster widespread profitability of energy storage. Naturally, the identified business models and presented profitability estimates are only a snapshot of the status quo and may change over the coming years. Nevertheless, the models and estimates provide a valuable reference for future economic analyses of energy storage.

Paper 6 investigates demand response in residential microgrids. Specifically, it uses a simulation framework to compare a cooperative approach – wherein a microgrid controller manages demand response centrally – to an approach where each residential unit in the microgrid manages demand response independently. The paper finds that cooperative actions result in substantially higher cost savings. Moreover, it highlights the importance of including a two-way, power-based component (capacity charge) in the design of microgrid tariffs to encourage the flattening of demand and supply peaks. Effective flattening is only possible in a cooperative setting. Naturally, the chosen simulation framework simplifies certain challenges involved in operating real-world demand response schemes. As a result, the identified cost savings and load curve effects may not be as pronounced in live operation. Nevertheless, the paper provides a strong case for choosing cooperative over individual approaches.

Paper 7 builds on paper 6 and examines requirements for effective microgrid tariffs. It extends the simulation framework and finds that volumetric and time-varying rates risk shortsighted load management and high peak loads. Moreover, it calculates that a combination of capacity charges and fixed monthly payments would encourage stable load and generation profiles and the equitable allocation of system costs. While these effects may, again, be less pronounced in a real-world setting, the study can serve as a practical and broad reference point for future residential microgrid tariff design.

6.2. Acknowledgment of previous and related work

I co-authored the papers in this thesis, among others, with colleagues at the Universities of Augsburg and 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 papers built on several of their previous and related works.

Paper 1, Paper 2, and Paper 4 are part of a successful stream of blockchain research at the FIT's Fraunhofer Blockchain Lab. For instance, they build on (Schweizer et al., 2017), (Fridgen, Radszuwill, et al., 2018) and (Lockl et al., 2020) and complement (Guggenberger et al., 2020), (Sedlmeir et al., 2020), (Sedlmeir, Ross, et al., 2021), and (Drasch et al., 2020). Paper

3 is part of a lively stream on managing innovative digital technologies such as artificial intelligence, and innovative digital concepts such as the Internet of Things. For instance, it complements (Oberländer et al., 2018) and (Jöhnk et al., 2021). Paper 5, Paper 6, and Paper 7 contribute to a strong research stream on digital solutions for the energy industry. For instance, they continue the work in (Fridgen et al., 2014), (Fridgen et al., 2015), and (Fridgen et al., 2016), and complement (Sachs et al., 2019), (Heffron et al., 2020), and (Keller et al., 2020).

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Appendices

Appendix A: Research papers included in this thesis

Papers 1–7 are available in the supplement. Kindly note that their formatting may differ from the published papers to allow for a consistent layout. Each paper has a separate reference section, as well as a separate numbering of figures, tables, and footnotes, if applicable.

Paper 1

Guggenmos, F., Lockl, J., Rieger, A., Wenninger, A., & Fridgen, G. (2020). How to Develop a GDPR-Compliant Blockchain Solution for Cross-Organizational Workflow Management: Evidence from the German Asylum Procedure. In *Proceedings of the 53rd Hawaii International Conference on System Sciences (HICSS),* Hawaii, USA.

DOI: 10.24251/HICSS.2020.492

VHB Jourqual 3: C, GII-GRIN-SCIE Journal Rating 2018: A+

Paper 2

Rieger, A., Lockl, J., Urbach, N., Guggenmos, F., & Fridgen, G. (2019). Building a Blockchain Application that Complies with the EU General Data Protection Regulation. *MIS Quarterly Executive*, *18*(4).

DOI: 10.17705/2msqe.00020

VHB Jourqual 3: B, SNIP 2020: 3.411, SJR 2020: 2.729, CiteScore 2020: 11.6 / 98 percentile

Paper 3

Keller, R., Stohr, A., Fridgen, G., Lockl, J., & Rieger, A. (2019). Affordance-Experimentation-Actualization Theory in Artificial Intelligence Research – A Predictive Maintenance Story. In *Proceedings of the 2019 International Conference on Information Systems (ICIS)*, München, Germany.

Handle: https://aisel.aisnet.org/icis2019/is_development/is_development/1/

VHB Jourqual 3: A, GII-GRIN-SCIE Journal Rating 2018: A

Paper 4

Amend, J., Fridgen, G., Rieger, A., Roth, T., & Stohr, A. (2021). The Evolution of an Architectural Paradigm: Using Blockchain to Build a Cross-Organizational Enterprise Service Bus. In *Proceedings of the 54th Hawaii International Conference on System Sciences (HICSS)*, Hawaii, USA.

DOI: 10.24251/HICSS.2021.522

VHB Jourqual 3: C, GII-GRIN-SCIE Journal Rating 2018: A+

Paper 5

Baumgarte, F., Glenk, G., & Rieger, A. (2020). Business Models and Profitability of Energy Storage. *iScience*, 101554.

DOI: 10.1016/j.isci.2020.101554

VHB Jourqual 3: NA, SNIP 2020: 1.156, SJR 2020: 1.805, CiteScore 2020: 3.4 / 83 percentile

Paper 6

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.

DOI: 10.1016/j.apenergy.2016.07.105

VHB Jourqual 3: NA, SNIP 2020: 2.696, SJR 2020: 3.035, CiteScore 2020: 17.6 / 99 percentile

Paper 7

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.

DOI: 10.1016/j.apenergy.2017.08.138

VHB Jourqual 3: NA, SNIP 2020: 2.696, SJR 2020: 3.035, CiteScore 2020: 17.6 / 99 percentile

Appendix B: Research papers and book chapters not included in this thesis

Over the course of my dissertation, I also co-authored the following research papers and peer-reviewed book chapters. These works are not part of this thesis.

Research papers

- Fridgen, G., Lockl, J., Radszuwill, S., Rieger, A., Schweizer, A., & Urbach, N. (2018). A Solution in Search of a Problem: A Method for the Development of Blockchain Use Cases. In *Proceedings of the 24th Americas Conference on Information Systems (AMCIS),* New Orleans, USA. https://www.fim-rc.de/paperbibliothek/veroeffentlicht/751/wi-751.pdf
- Guggenmos, F., Lockl, J., Rieger, A., & Fridgen, G. (2019). Blockchain in der öffentlichen Verwaltung. *Informatik Spektrum*, 42, 174–181. https://doi.org/10.1007/s00287-019-01177-y
- Höß, A., Schlatt, V., Rieger, A. & Fridgen, G. (2021). The Blockchain Effect: From Inter-Ecosystem to Intra-Ecosystem Competition. *29th European Conference on Information Systems (ECIS),* Marrakesh, Marocco. https://aisel.aisnet.org/ecis2021_rp/36/
- Rieger, A., Roth, T., Sedlmeir, J., & Fridgen, G. (2021). The privacy challenge in the race for digital vaccination certificates. *Med*. https://doi.org/10.1016/j.medj.2021.04.018
- Sedlmeir, J, Smethurst, R., Rieger, A, Fridgen G. (2021). Digital Identities and Verifiable Credentials. *Business & Information Systems Engineering,* (forthcoming).
- Barbereau, T., Smethurst, R., Papageorgiou, O., Rieger, Alexander & Fridgen, G. (2022). DeFi, Not So Decentralized: The Measured Distribution of Voting Rights. In *Proceedings of the 55th Hawaii International Conference on System Sciences (HICSS)*, Hawaii, USA (forthcoming).
- Höß, A., Roth, T, Sedlmeir, J., Fridgen, G. & Rieger, A. (2022). With or Without Blockchain? Towards a Decentralized, SSI-based eRoaming Architecture. In *Proceedings of the 55th Hawaii International Conference on System Sciences (HICSS)*, Hawaii, USA (forthcoming).

- Weigl, L., Barbereau, T., Rieger, A., & Fridgen, G. (2022). The Social Construction of Self-Sovereign Identity: An Extended Model of Interpretive Flexibility. In *Proceedings of the 55th Hawaii International Conference on System Sciences (HICSS)*, Hawaii, USA (forthcoming).
- Roth, T., Stohr, A., Amend, J., Fridgen, G., & Rieger, A. (2021). Blockchain as a driving force for federalism: A theory of cross-organizational task-technology fit. *International Journal of Information Management, (under review).*
- Roth, T., Utz, M., Baumgarte, F, Sedlmeir, J. & Rieger, A. (2021). Electricity Powered by Blockchain: Broken Dreams and a New Hope. *SnT Working Paper.*
- Stohr, A., Ollig, P., Keller, R., & Rieger, A. (2021). Generative mechanisms of AI adoption: A critical realist perspective on predictive maintenance. *SnT Working Paper.*

Peer-reviewed book chapters

- Arnold, L., Brennecke, M., Camus, P., Fridgen, G., Guggenberger, T., Radszuwill, S., Rieger, A., Schweizer, A., & Urbach, N. (2019). Blockchain and Initial Coin Offerings: Blockchain's Implications for Crowdfunding. In H. Treiblmaier & R. Beck (Eds.), *Business Transformation through Blockchain*. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-319-98911-2_8
- Rieger, A., Stohr, A., Wenninger, A., & Fridgen, G. (2021). Reconciling Blockchain with the GDPR: Insights from the German Asylum Procedure. In C.G. Reddick, M.P. Rodríguez-Bolívar, & H.J. Scholl (Eds.), *Blockchain and the Public Sector*. Public Administration and Information Technology, vol 36. Springer, Cham. https://doi.org/10.1007/978-3-030-55746-1_4
- Amend, J., van Dun, C., Fridgen, G., Köhler, F., Rieger, A., Stohr, A., & Wenninger, A. (2021). Using Blockchain to Coordinate Federal Processes: The Case of Germany's Federal Office for Migration and Refugees. In M. Röglinger, N. Urbach, R.A. Alias, K. Kautz, C. Saunders, & M. Wiener (Eds), *Digitalization Cases (2nd ed.)*. Springer International Publishing. https://doi.org/10.1007/978-3-030-80003-1
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Appendix C: Author contribution statements

The following pages outline the individual contribution of all co-authors to the research papers included in this thesis. My contributions are detailed in a complementary paragraph. Signed copies declaring the authors' contributions to each paper have been submitted with this thesis.

Paper 1

How to Develop a GDPR-Compliant Blockchain Solution for Cross-Organizational Workflow Management: Evidence from the German Asylum Procedure

The following authors have contributed to above scientific paper in below CRediT roles:

Guggenmos, Florian (equal co-authorship): Conceptualization, Formal analysis, Investigation, Visualization, Writing – original draft.

Lockl, Jannik (equal co-authorship): Conceptualization, Investigation, Methodology, Writing – review & editing.

Rieger, Alexander (equal co-authorship): Conceptualization, Project administration, Validation, Writing – review & editing.

Wenninger, Annette (equal co-authorship): Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft.

Fridgen, Gilbert (subordinate co-authorship): Supervision, Writing – review & editing.

Specifically, I contributed by proposing the idea for the paper and its objectives: the establishment of tentative design principles for the creation of blockchain solutions that comply with the EU's General Data Protection Regulation. I managed and coordinated the tasks required for the completion of the project, ranging from data collection and analysis to the writing of the first draft to reviewing and editing. Moreover, I was responsible for validating the results of the initial analysis for their generalizability and transferability. Lastly, I reviewed and substantially edited the original draft of the paper.

Paper 2

Building a blockchain application that complies with the EU general data protection regulation

The following authors have contributed to above scientific paper in below CRediT roles:

Rieger, Alexander (lead co-authorship): Conceptualization, Formal analysis, Investigation, Project administration, Visualization, Writing – original draft.

Guggenmos, Florian (subordinate co-authorship): Investigation, Validation, Writing – original draft.

Lockl, Jannik (subordinate co-authorship): Investigation, Methodology, Writing – review & editing.

Fridgen, Gilbert (subordinate co-authorship): Supervision, Writing – review & editing.

Urbach, Nils (subordinate co-authorship): Supervision, Writing – review & editing.

Specifically, I contributed by proposing the idea for the paper and its objectives: the establishment of recommendations for managing the requirements of the EU's General Data Protection Regulation. I analyzed the relevant literature as well as pertinent evidence from the blockchain project of Germany's Federal Office for Migration and Refugees. I also made an essential contribution to the collection of pertinent evidence. I managed and coordinated the tasks required for the completion of the project, ranging from data collection and analysis to the writing of the first draft to reviewing and editing. Finally, I designed the figures and tables.

Paper 3

Affordance-Experimentation-Actualization Theory in Artificial Intelligence Research – A Predictive Maintenance Story

The following authors have contributed to above scientific paper in below CRediT roles:

Keller, Robert (equal co-authorship): Conceptualization, Formal analysis, Project administration, Supervision, Writing – original draft

Stohr, Alexander (equal co-authorship): Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft.

Fridgen, Gilbert (subordinate co-authorship): Supervision, Writing – review & editing.

Lockl, Jannik (subordinate co-authorship): Validation, Writing – review & editing.

Rieger, Alexander (subordinate co-authorship): Validation, Writing – review & editing.

Specifically, I contributed by validating the results of the initial analysis for their generalizability and transferability. I also reviewed and edited the original draft of the paper.

Paper 4

The Evolution of an Architectural Paradigm - Using Blockchain to Build a Cross-Organizational Enterprise Service Bus

The following authors have contributed to above scientific paper in below CRediT roles:

Amend, Julia (equal co-authorship): Conceptualization, Formal analysis, Investigation, Writing – original draft.

Fridgen, Gilbert (equal co-authorship): Conceptualization, Supervision, Writing – review & editing.

Rieger, Alexander (equal co-authorship): Supervision, Validation, Writing – review & editing.

Roth, Tamara (equal co-authorship): Conceptualization, Formal analysis, Investigation, Writing – original draft.

Stohr, Alexander (equal co-authorship): Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft.

Specifically, I contributed by supervising the research project. I was also responsible for validating the results of the initial analysis for their generalizability and transferability. Lastly, I reviewed and substantially edited the original draft of the paper.

Paper 5

Business Models and Profitability of Energy Storage

The following authors have contributed to above scientific paper in below CRediT roles:

Baumgarte, Felix (equal co-authorship): Conceptualization, Data curation, Formal analysis, Visualization, Writing – original draft.

Glenk, Gunther (equal co-authorship): Conceptualization, Formal analysis, Visualization, Writing –original draft.

Rieger, Alexander (equal co-authorship): Conceptualization, Validation, Writing – review & editing.

Specifically, I contributed to the definition of the objectives of the paper: the characterization of business models for energy storage and the review of recent studies to investigate their profitability. I also participated in the development of the paper's business model framework. Together with Felix Baumgarte, I reviewed and collected the relevant literature to establish the profitability of the characterized business models. I made a substantial contribution to the analysis of the relevant literature. Moreover, I was responsible for validating the results of the initial analysis for their generalizability and transferability. Lastly, I reviewed and substantially edited the original draft of the paper.

Paper 6

Estimating the benefits of cooperation in a residential microgrid: A data-driven approach

The following authors have contributed to above scientific paper in below CRediT roles:

Rieger, Alexander (equal co-authorship): Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft.

Thummert, Robert (equal authorship): Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft.

Fridgen, Gilbert (equal co-authorship): Supervision, Writing – review & editing.

Kahlen, Micha (equal co-authorship): Supervision, Validation, Writing – review & editing.

Ketter, Wolfgang (equal co-authorship): Supervision, Validation, Writing – review & editing.

Specifically, I contributed by proposing the idea for the paper and its objectives: the simulation-based evaluation of individual and cooperative demand response. Jointly with Robert Thummert, I scrubbed the data required for the simulations, defined and implemented the simulation framework, and analyzed the results of the simulation runs. Together, we created the figures and tables and wrote the original draft of the paper.

Paper 7

One rate does not fit all: An empirical analysis of electricity tariffs for residential microgrids.

The following authors have contributed to above scientific paper in below CRediT roles:

Fridgen, Gilbert (equal co-authorship): Supervision, Writing – review & editing,

Kahlen, Micha (equal co-authorship): Supervision, Validation, Writing – review & editing.

Ketter, Wolfgang (equal co-authorship): Supervision, Writing – review & editing.

Rieger, Alexander (equal co-authorship): Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft.

Thimmel, Markus (equal co-authorship): Formal analysis, Methodology, Supervision, Writing – original draft.

Specifically, I contributed by proposing the idea for the paper and its objectives: the simulation-based evaluation of different types of electricity tariffs for residential microgrids. I scrubbed the data required for the simulations, defined and implemented the simulation framework, and analyzed the results of the simulation runs. I also created the figures and tables and wrote the original draft of the paper.

Appendix D: Paper abstracts

Paper 1

How to Develop a GDPR-Compliant Blockchain Solution for Cross-Organizational Workflow Management: Evidence from the German Asylum Procedure

Authors: Guggenmos, Florian; Lockl, Jannik; Rieger, Alexander; Wenninger, Annette; & Fridgen, Gilbert

Published in: Proceedings of the 53rd Hawaii International Conference on System Sciences.

Abstract: Blockchain technology has the potential to resolve trust concerns in cross-organizational workflows and to reduce reliance on paper-based documents as trust anchors. Although these prospects are real, so is regulatory uncertainty. In particular, the reconciliation of blockchain with Europe's General Data Protection Regulation (GDPR) is proving to be a significant challenge. We tackled this challenge with the German Federal Office for Migration and Refugees. Here, we explain how we used Action Research to guide the Federal Office in creating a GDPR-compliant blockchain solution for the German asylum procedure. Moreover, we explain the architecture of the Federal Office's solution and present two design principles for developing GDPR-compliant blockchain solutions for cross-organizational workflow management.

Paper 2

Building a blockchain application that complies with the EU general data protection regulation

Authors: Rieger, Alexander; Lockl, Jannik; Urbach, Nils; Guggenmos, Florian; & Fridgen, Gilbert

Published in: MIS Quarterly Executive

Abstract: Complying with the EU General Data Protection Regulation (GDPR) poses significant challenges for blockchain projects, including establishing clear responsibilities for compliance, securing lawful bases for processing personal data, and observing rights to rectification and erasure. We describe how Germany's Federal Office for Migration and Refugees addressed these challenges and created a GDPR-compliant blockchain solution for cross-organizational workflow coordination. Based on the lessons learned, we provide three recommendations for ensuring blockchain solutions are GDPR-compliant.

Paper 3

Affordance-Experimentation-Actualization Theory in Artificial Intelligence Research – A Predictive Maintenance Story

Authors: Keller, Robert; Stohr, Alexander; Fridgen, Gilbert; Lockl, Jannik; & Rieger, Alexander

Published in: Proceedings of the 2019 International Conference on Information Systems.

Abstract: Artificial intelligence currently counts among the most prominent digital technologies and promises to generate significant business value in the future. Despite a growing body of knowledge, research could further benefit from incorporating technological features, human actors, and organizational goals into the examination of artificial intelligence-enabled systems. This integrative perspective is crucial for effective implementation. Our study intends to fill this gap by introducing affordance-experimentation-actualization theory to artificial intelligence research. In doing so, we conduct a case study on the implementation of predictive maintenance using affordance-experimentation-actualization theory as our theoretical lens. From our study, we find further evidence for the existence of the experimentation phase during which organizations make new technologies ready for effective use. We propose extending the experimentation phase with the activity of 'conceptual exploration' in order to make affordance-experimentation-actualization theory applicable to a broader range of technologies and the domain of AI-enabled systems in particular.

Paper 4

The Evolution of an Architectural Paradigm - Using Blockchain to Build a Cross-Organizational Enterprise Service Bus

Authors: Amend, Julia; Fridgen, Gilbert; Rieger, Alexander; Roth, Tamara; & Stohr, Alexander

Published in: Proceedings of the 54th Hawaii International Conference on System Sciences.

Abstract: Cross-organizational collaboration and the exchange of process data are indispensable for many processes in federally organized governments. Conventional IT solutions, such as cross-organizational workflow management systems, address these requirements through centralized process management and architectures. However, such centralization is difficult and often undesirable in federal contexts. One alternative solution that emphasizes decentralized process management and a decentralized architecture is the blockchain solution of Germany’s Federal Office for Migration and Refugees. Here, we investigate the architecture of this solution and examine how it addresses the requirements of federal contexts. We find that the solution’s architecture resembles an improvement and cross-organizational adaption of an old architectural paradigm, the enterprise service bus.

Paper 5

Business Models and Profitability of Energy Storage

Authors: Baumgarte, Felix; Glenk, Gunther; & Rieger, Alexander

Published in: iScience

Abstract: Rapid growth of intermittent renewable power generation makes the identification of investment opportunities in energy storage and the establishment of their profitability indispensable. Here we first present a conceptual framework to characterize business models of energy storage and systematically differentiate in- vestment opportunities. We then use the framework to examine which storage technologies can perform the identified business models and review the recent literature regarding the profitability of individual combinations of business models and technologies. Our analysis shows that a set of commercially available technologies can serve all identified business models. We also find that certain combinations appear to have approached a tipping point toward profitability. Yet, this conclusion only holds for combinations examined most recently or stacking several business models. Many technologically feasible combinations have been neglected, indicating a need for further research to provide a detailed and conclusive understanding about the profitability of energy storage.

Paper 6

Estimating the benefits of cooperation in a residential microgrid: A data-driven approach

Authors: Rieger, Alexander; Thummert, Robert; Fridgen, Gilbert; Kahlen, Micha; & Ketter, Wolfgang

Published in: Applied Energy

Abstract: Private households are increasingly taking cooperative action to change their energy consumption patterns in pursuit of green, social, and economic objectives. Cooperative demand response (DR) programs can contribute to these common goals in several ways. To quantify their potential, we use detailed energy consumption and production data collected from 201 households in Austin (Texas) over the year 2014 as well as historic real-time prices from the Austin wholesale market. To simulate cooperative DR, we adapt a load-scheduling algorithm to support both real-time retail prices and a capacity-pricing component (two-part pricing schemes). Our results suggest that cooperative DR results in higher cost savings for households than individual DR. Whereas cooperative DR that is based on real-time pricing alone leads to an increase in peak demand, we show that adding a capacity-pricing component is able to counteract this effect. The capacity-pricing component successfully reduces the cooperative's peak demand and also increases the cost savings potential. Effective peak shaving is furthermore only possible in a cooperative setting. We conclude that cooperative DR programs are not only beneficial to customers but also to energy providers. The use of appropriate tariffs allows consumers and suppliers to share these benefits fairly.

Paper 7

One rate does not fit all: An empirical analysis of electricity tariffs for residential microgrids

Authors: Fridgen, Gilbert; Kahlen, Micha; Ketter, Wolfgang; Rieger, Alexander; & Thimmel, Markus

Published in: Applied Energy

Abstract: Increasingly, residential customers are deploying PV units to lower electricity bills and contribute to a more sustainable use of resources. This selective decentralization of power generation, however, creates significant challenges, because current transmission and distribution grids were designed for centralized power generation and unidirectional flows. Restructuring residential neighborhoods as residential microgrids might solve these problems to an extent, but energy retailers and system operators have yet to identify ways of fitting residential microgrids into the energy value chain. One promising way of doing so is the tailoring of residential microgrid tariffs, as this encourages grid-stabilizing behavior and fairly re-distributes the associated costs. We thus identify a set of twelve tariff candidates and estimate their probable effects on energy bills as well as load and generation profiles. Specifically, we model 100 residential microgrids and simulate how these microgrids might respond to each of the twelve tariffs. Our analyses reveal three important insights. Number one: volumetric tariffs would not only inflate electricity bills but also encourage sharp load and generation peaks, while failing to reliably allocate system costs. Number two: under tariffs with capacity charges, time-varying rates would have little impact on both electricity bills and load and generation peaks. Number three: tariffs that bill system and energy retailer costs via capacity and customer charges respectively would lower electricity bills, foster peak shaving, and facilitate stable cost allocation.