From cryptic to cryptographic: On the wide-ranging potentials and challenges of blockchain-based financial products and markets

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Vincent Schaaf (geb. Gramlich)

aus

Köln

Dekan:	Prof. Dr. Claas Christian Germelmann
Erstberichterstatter:	Prof. Dr. Nils Urbach
Zweitberichterstatter:	Prof. Dr. Jens Strüker
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“The Times 03/Jan/2009 Chancellor on brink of second bailout for banks”

Satoshi Nakamoto in Genesis Block of the Bitcoin Blockchain

Abstract

Emerging from the financial crisis of 2008, bitcoin and the underlying blockchain technology have introduced a new asset class, a new payment system, and a whole, new decentralized financial system (DeFi). Furthermore, blockchain is also reshaping the infrastructure and underlying paradigms of the traditional financial sector (TradFi). While there is a plethora of blockchain applications with transformative potential, the integration of a novel and multifaceted technology in the complex and tangled financial system poses a wide range of challenges such as scalability, privacy, volatility, missing real-world applicability, and adoption. With this dissertation I aim to explore the wide-ranging potentials of blockchain-based financial products and the challenges that need to be addressed to fully leverage blockchains prospects for the financial system.

This dissertation and its 10 essays are structured around three research goals. Through Essays 1-4, I examine the challenges and promises of DeFi (RG1), providing a comprehensive overview of the ecosystem and its potentials and challenges, particularly the integration of real-world assets (RWAs). Secondly, in Essays 5 and 6, I investigate how blockchain can permeate and reconfigure TradFi but also showcase its limitations (RG2), specifically in taxation and central banking. Third, I address fundamental blockchain challenges and solution approaches (RG3), with a particular focus on electricity consumption, formal and game-theoretic security, and the role of zero-knowledge proofs in privacy-preserving systems in Essays 7-10.

The dissertation is structured in two main parts as follows: First, I give an introduction to my dissertation where I showcase the importance of the topic, introduce necessary fundamental knowledge, and lay out the three research goals of my dissertation, the research questions of the individual essays, and their interrelation. Furthermore, I set out the employed research designs, summarize the key findings of the individual essays, and discuss the contributions and limitations of my work and possible avenues for future research. The second part of my dissertation encompasses the abstracts to my 10 essays.

Keywords: Blockchain, Decentralized finance, Distributed ledger technology, Financial infrastructure, Tokenization, Zero-knowledge proofs

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Mainz, July 2025

Vincent Schaaf

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Introduction to
From cryptic to cryptographic: On the wide-ranging potentials and challenges of blockchain-based financial products and markets

Abstract

The goal of this dissertation is to explore the multifaceted potentials of blockchain-based financial system and to support their effective realization by developing a comprehensive understanding of the associated challenges and viable solution approaches. The following introduction to my dissertation begins by outlining the relevance of blockchain-based financial products and markets and by contextualizing the topic within the broader discourse of information systems research (Section 1). I then provide the necessary conceptual and technical foundations, including an overview of blockchain technology, its associated challenges, and its applications in the financial system (Section 2). Subsequently, I introduce the three research goals that guide the structure of the work, aligning each with the corresponding research questions addressed in the individual essays (Section 3). Thereafter, I present the research designs employed in the essays (Section 4) and summarize their core findings (Section 5). Finally, I discuss the insights and contributions of the individual essays and the dissertation as a whole, reflect on limitations, and showcase avenues for future research (Section 6).

Keywords: Blockchain, Decentralized finance, Distributed ledger technology, Financial infrastructure, Tokenization, Zero-knowledge proofs

Table of contents – Introduction

1 Motivation

Since the emergence of blockchain through the origin of Bitcoin in 2008 (Nakamoto 2008), practitioners and academics have explored countless areas of application for the technology (Beck et al. 2017). These comprise, among others, interorganizational information sharing (Bossler et al. 2024; Guggenberger et al. 2020), governance (Ellinger et al. 2024), or information tracing in different industries and supply chains (Queiroz et al. 2019). However, the application area where blockchain has been the most impactful and has received the most attention and adoption remains its origin, the financial sector (Rossi et al. 2019). Here, the transformative effect of blockchain can be divided into two main areas: 1) Forming the foundation for a completely new blockchain-based, decentralized financial system (DeFi) (Gramlich et al. 2023) and 2) inducing the transformation of the existing, traditional financial system (TradFi) (Risius and Spohrer 2017). Both areas showcase tremendous potential but also a large variety of challenges (Rossi et al. 2019). Some of these challenges are shared among both while others are unique to one or the other. Leveraging shared and unique potentials and tackling application specific or common challenges is not only key in ensuring the success of the individual areas but also paves the way towards a convergence of both paradigms which could maximize the potential of blockchain and its enhancement of the financial sector (Hanneke et al. 2024; Risius and Spohrer 2017).

The emergence of DeFi signifies a pivotal shift in the financial landscape, moving from traditional, centralized financial systems to a decentralized architecture that emphasizes trust and efficiency through disintermediation (Gramlich et al. 2023). Initially emerging from the foundational concepts of Bitcoin (Nakamoto 2008), DeFi leverages blockchain technology, particularly through the deployment of smart contracts on platforms such as Ethereum, to create complex financial products and services that encapsulate the characteristics of a fully functional financial ecosystem (Buterin 2014; Schär 2021). DeFi has gained significant attention, as evidenced by the rapid growth in cryptocurrency market capitalization peaking at $3.7 trillion and the Total Value Locked (TVL) in DeFi protocols peaking at $205 billion in December 2024 (CoinMarketCap 2025; DefiLlama 2025). However, the transition to a decentralized paradigm is fraught with challenges, including pronounced volatility in cryptocurrency markets, scalability issues, and regulatory uncertainties that hinder widespread adoption (Gramlich et al. 2023). Moreover, the technology necessitates a certain level of technological literacy among users, compounded by concerns regarding energy consumption and compliance with privacy regulations (Gramlich, Guggenberger, Paetzold et al. 2024; Sedlmeir et al. 2022).

In the context of TradFi, the integration of blockchain technology offers an opportunity for significant transformation while also presenting a series of intricate challenges. TradFi encompasses established financial institutions and practices, which have traditionally relied on intermediaries to facilitate transactions, manage risk, and provide trust through regulatory frameworks (Feulner et al. 2022). However, the advent of blockchain technology invites a re-evaluation of these roles, as it offers the potential to streamline and disintermediate processes, increasing transparency, reducing transaction costs, and enhancing security and resilience (Cisar et al. 2025). The tokenization of real-world assets (RWAs) serves as a conduit for aligning the needs of both the traditional and the emerging, decentralized financial system (Hanneke et al. 2024). While it unlocks the affordances of blockchain technology for traditional financial assets and products it offers a solution to the challenge of missing adoption of DeFi and its high dependency on the cryptocurrency market. In this context, regulatory bodies are currently engaged in crafting frameworks to govern the integration of blockchain technology in TradFi effectively, e.g., the German electronic securities law (BaFin 2021) and the European "DLT Pilot Regime" (ESMA 2023), which support blockchain-based security registries and trading systems. Furthermore, academics and practitioners also investigate the utilization of blockchain in the traditional financial system beyond tokenization: These include, among other, central bank digital currencies (Bhaskar et al. 2022; Tronnier et al. 2023) or the application of blockchain technology within taxation (Hyvärinen et al. 2017). On the one hand, blockchain integration into TradFi aims to tackle some of the hurdles faced in DeFi, e.g., regulatory uncertainty or dependency on the cryptocurrency market due to missing real-world applications. On the other hand, however, other hurdles are directly transferred, e.g., scalability of blockchain (Principato et al. 2023) or security of different protocols (Álvarez et al. 2024; Gramlich, Jelito and Sedlmeir 2024), or even intensified, e.g., balancing the trade-off between privacy and identification necessary for compliance to financial regulation (Gramlich, Guggenberger, Principato et al. 2024). Tackling these challenges often evolves around the utilization of related technologies. In this context zero-knowledge proofs (ZKPs) play a particularly important role as their ability to prove the correctness of certain statements without revealing the underlying information is key in tackling both blockchain scalability and the trade-off between privacy and identification.

The goal of this dissertation is to take a holistic view to the application of blockchain technology in the financial system considering both gates of entry: Redefining the ground rules of the financial system through DeFi and improving TradFi through a proliferation of blockchain into the existing financial infrastructure. I believe that a detailed understanding of both fields and their potentials, applications, and individual and shared challenges is necessary to assess the overall impact of blockchain on the financial system and establish a common ground that can serve as fundament for the convergence of both systems. With this holistic understanding I aim to achieve the overarching research objective of this dissertation:

Exploring and leveraging the potentials of blockchain-based financial systems

The remainder of this introduction to my dissertation is structured as follows. Section 2 will establish the required fundamental knowledge on blockchain technology, its challenges and the role ZKPs in solving them, and the applications in the financial system. Subsequently, I will lay out my three research goals (RGs) and relate the 10 essays and their individual research questions (RQs) to them. Section 4 then describes the research methods I employed through the essays of my dissertation and Section 5 provides a summary of the individual essays and their key findings. Finally, I will wrap up this introduction in Section 6 by discussing the insights of my essays and their interrelation and laying out the limitations of my work and opportunities for future research.

Subsequently, the remainder of my dissertation encompasses an Appendix with the description of individual author contributions for all essays, an overview of other publications I accumulated during my doctorate, and, finally, the 10 essays of my dissertation.

2 Blockchain-based financial systems

2.1 Blockchain foundations

A blockchains is a distributed ledger where transactions are grouped in blocks that are cryptographically linked using hash functions. This structure ensures a clear ordering of transactions and prevents retroactive modifications, thereby providing chronological ordering and tamper-resistance (Butijn et al. 2021). Blockchains are sustained by a peer-to-peer (P2P) network of nodes that redundantly store the ledger and propagate transactions, ensuring that availability does not depend on a single entity (Beck et al. 2017). To maintain the integrity of the blockchain, a consensus mechanism determines the validity and ordering of transactions in each newly appended block, eliminating the need for a trusted central authority (Álvarez et al. 2024). In most blockchain systems, participants are required to pay transaction fees, typically denominated in the network's native cryptocurrency—such as Bitcoin in the Bitcoin network or Ether in Ethereum. The validator entitled to proposing a new block is rewarded with these transaction fees, often supplemented by newly minted native cryptocurrency, thereby incentivizing participation and prioritization of transactions from users willing to pay higher fees (Gramlich, Jelito and Sedlmeir 2024). Besides simple transactions of cryptocurrency, some blockchains extend their functionality by allowing users to deploy and interact program code directly on-chain (Buterin; Szabo 1994). These "smart contracts" enable complex financial logic, such as tokenization of tangible or intangible assets (Hanneke et al. 2024), forming the backbone of DeFi ecosystems, where financial products and services operate autonomously without intermediaries (see Section 2.3)(Gramlich et al. 2023).

Blockchains exhibit fundamental design choices regarding their openness for participation (Butijn et al. 2021). In terms of general participation, public blockchains allow unrestricted access, enabling anyone to view the ledger and execute transactions, whereas private blockchains restrict access to a predefined group of participants. Similarly, participation in the consensus mechanism differs across blockchain designs. In permissionless blockchains, anyone can partake in the consensus process. Permissioned blockchains, on the other hand, restrict consensus participation to a selected set of entities allowing them to rely on traditional distributed system consensus models from research dating back to the 1980s (Dwork et al. 1988). These mechanisms fall into two main categories: Crash Fault Tolerant (CFT) consensus, which maintains system availability even if some participants fail due to technical issues (Cristian 1991), and Byzantine Fault Tolerant (BFT) consensus, which ensures integrity and availability even in the presence of malicious actors (Castro and Liskov 1999). While permissionless blockchains also integrate BFT principles, they cannot adopt a one-person-one-vote strategy due to the open nature of participation, which makes it impossible to verify the uniqueness of each consensus participant. To prevent sybil attacks where one participant pretends to be multiple participants to increase his influence (Douceur 2002), permissionless blockchains must link their voting power to a scarce, digitally verifiable resource (Gramlich, Guggenberger, Paetzold et al. 2024). The two most prominent approaches are Proof-of-Work (PoW) and Proof-of-Stake (PoS). In PoW, participants (commonly known as miners) solve cryptographic puzzles by expending computational power (electricity and hardware) to earn the right to propose a new block. In contrast, PoS participants (referred to as stakers or validators) lock up native tokens as collateral to obtain voting power corresponding to their share of the total amount staked.

2.2 Blockchain challenges and the role of zero-knowledge proofs

There are two fundamental trade-offs to blockchain technology and its applications: scalability versus decentralization and transparency versus privacy. Especially in permissionless blockchains, decentralization is a key affordance that ensures high security guarantees for the system's availability and integrity (Rossi et al. 2019). However, achieving a high degree of decentralization requires that participation costs—such as hardware acquisition and operating expenses—remain sufficiently low to incentivize a broad and diverse set of network participants. Consequently, leading decentralized blockchains like Bitcoin and Ethereum have deliberately strongly limited their block size and block time, prioritizing accessibility for validators and node operators over transaction throughput (Buterin; Nakamoto 2008). The challenge, therefore, is to increase the overall system's transaction capacity without imposing additional computational or storage burdens on individual participants (Richard et al. 2023). Two key approaches have emerged to address this issue: sharding and Layer 2 scaling solutions (Principato et al. 2023). Sharding divides the blockchain into smaller shards, where each participant only processes a subset of transactions (execution sharding) or stores only a part of the ledger (data sharding), reducing overall system load (Richard et al. 2023). The alternative is outsourcing processing of specific transactions to a more centralized subsystem. These include Layer 2 blockchains (also denoted as sidechains), which operate with their own consensus mechanisms, and rollups, which rely on a central operator but frequently post cryptographic proofs to the main blockchain to ensure transaction validity or enable disputes (Principato et al. 2023).

The second major trade-off in blockchain design is transparency versus privacy. Transparency is a foundational feature of blockchain, ensuring that all past transactions, account balances, and smart contract rules are publicly accessible, thereby preventing double-spending and enabling autonomous contract enforcement (Lautenschlager et al. 2023). However, this transparency poses significant risks when dealing with personal or business-sensitive information, hampering blockchain adoption especially in organizations (Sedlmeir et al. 2022). While in some cases private blockchains can mitigate privacy concerns and maintain the desirable level of transparency, in many cases, either stronger privacy guarantees are necessary, or the public verifiability is key to the specific application (Gramlich, Guggenberger, Principato et al. 2024).

A promising solution to these challenges are ZKPs, a cryptographic technique first theorized in the 1980s (Feige et al. 1988; Goldwasser et al. 1985) but only recently gaining traction in research and real-world implementations, particularly within blockchain applications (Principato et al. 2023). ZKPs allow one party to prove the correctness of a statement or computation without revealing the underlying data (Goldreich and Oren 1994). Their verification process is succinct, meaning that verifying a ZKP is computationally far less intensive than verifying, i.e., re-executing, the original computation itself. These properties make ZKPs particularly well-suited for addressing the scalability and privacy trade-offs in blockchain systems.

In terms of scalability, ZKPs form the basis of ZK-Rollups, where a central operator processes transactions off-chain and submits only a succinct cryptographic proof of their correctness to the main blockchain (Principato et al. 2023). This drastically reduces the computational and storage burden on Layer 1 nodes, as they no longer need to validate every individual transaction, yet they can still cryptographically verify the entire rollup's integrity. This approach significantly increases blockchain throughput while maintaining most of its security guarantees even for the transaction processed on the rollup. Regarding privacy, ZKPs facilitate confidential transactions without compromising blockchain rule enforcement (Sedlmeir et al. 2022). Instead of broadcasting all transaction details publicly, users can submit a ZKP to the blockchain, demonstrating that the transaction is valid without disclosing specific sender, recipient, or amount details. This was pioneered in ZCash (Ben Sasson et al. 2014), the first privacy cryptocurrency, where users can execute private transactions while still ensuring compliance with blockchain rules, e.g., ensuring that tokens being sent were previously received and not double-spent. In summary, by enabling bilateral, off-chain data exchange with verifiable cryptographic assurances on the blockchain, ZKPs enable a scalable yet decentralized, secure system and public verifiability while maintaining data privacy.

2.3 Blockchain applications in the financial system

Since its emergence with Bitcoin, the financial system has remained the most prominent application domain for blockchain technology. Over time, blockchain's application in finance has expanded beyond cryptocurrency to a broad spectrum of financial use cases (Sunyaev et al. 2021). These can be categorized into two major groups: open, permissionless financial applications, which aim to establish an alternative financial system independent of centralized control (Gramlich et al. 2023), and blockchain applications to enhance existing financial processes and systems, often in more controlled, permissioned settings (Risius and Spohrer 2017).

The foundation of a permissionless blockchain-based financial system began with Bitcoin as a decentralized digital currency with a corresponding P2P payment system, eliminating centralized control over monetary policy and transactions (Nakamoto 2008). The introduction of smart contracts, particularly through Ethereum, enabled a new paradigm known as DeFi, which extends blockchain's functionality beyond simple transactions to encompass a full financial ecosystem operating on decentralized networks (Schueffel 2021). Within DeFi, several core applications have emerged, including tokenization, which enables the blockchain-based representation of tangible or intangible assets, allowing fractional ownership, automated transactions, and global and efficient settlement (Hanneke et al. 2024). Another major category includes money markets and lending protocols that facilitate borrowing and lending without intermediaries by using smart contracts to automate loan origination, interest rates, and collateral management (Bartoletti et al. 2021). Additionally, decentralized exchanges (DEXs), most prominently automated market makers (AMMs) leveraging liquidity pools and algorithmic pricing mechanisms to facilitate trading counterparts, have provided an alternative to centralized trading venues (Xu et al. 2022). Beyond these, there is a wide range of DeFi applications such as insurance, portfolio management, derivatives, and yield optimization, replicating existing financial products and services in a decentralized manner (Gramlich, Principato, Schellinger, Sedlmeir, Amend et al. 2022).

While cryptocurrency and DeFi have seen substantial adoption, with the total cryptocurrency market capitalization peaking at $3.7 trillion (CoinMarketCap 2025) and DeFi's total value locked (TVL) reaching $205 billion in December 2024 (DefiLlama 2025), they face significant challenges in achieving large-scale adoption and maturity as an asset class or financial system (Gramlich et al. 2023). One of the primary concerns is the high volatility of cryptocurrencies, which results in unpredictable price fluctuations and hinders their usability as stable financial instruments (Katona 2021). Moreover, since DeFi is heavily dependent on cryptocurrencies, DeFi and its products inherit their volatility, deterring adoption and hindering maturation towards a stable financial system (Carter and Jeng 2021). A key aspect here is the relative absence of RWAs in DeFi that could boast its real-world usage and decrease dependency on cryptocurrencies (Gramlich et al. 2023). In addition to economic concerns, DeFi applications still grapple with socio-technical, e.g., regulatory uncertainty or technological literacy (Chen and Bellavitis 2020), and technological challenges inherent to blockchain, e.g., scalability limitations (Amler et al. 2021).

Beyond DeFi, both practitioners and academics have explored how blockchain can enhance traditional financial processes by integrating it into existing financial systems. One key area of interest are payment systems, especially cross-border, where blockchain technology can facilitate automated, disintermediated payment settlement, reducing transaction costs and increasing settlement speed (Kim and Kim 2022). While some institutions are even adopting DeFi products such as stablecoins, i.e., tokens pegged to a FIAT currency, on permissionless blockchains for this, others are developing private, permissioned blockchain solutions tailored for institutional use (Hanneke et al. 2024). Furthermore, information system (IS) scholars have proposed a variety of potential blockchain applications in finance beyond payments and DeFi. Notable examples include Central Bank Digital Currencies (CBDCs), where scholars propose the utilization of blockchain for secure, transparent, and programmable monetary policy implementation and efficient settlement (Chiu and Davoodalhosseini 2023). However, CBDCs are also a good example for applications where blockchain affordances have been praised by scholars and a platitude of conceptual approaches have been suggested

(Allen et al. 2020). However, almost all practical existing endeavors from central banks do not consider the usage of blockchain technology (CBDC Tracker 2025), showcasing a gap between conceptual affordances and practical implementations of blockchain technology.

By leveraging blockchain in both permissionless and permissioned financial applications, the technology is shaping a diverse and evolving financial ecosystem, bridging the gap between traditional finance and decentralized alternatives. However, addressing challenges such as asset volatility, regulatory certainty, real-world applicability, and technological limitations will be critical for widespread adoption of blockchain-based financial systems.

3 Derivation of research goals, gaps, and questions

The novelty of blockchain and related innovations, e.g., smart contracts or ZKPs, paired with the sophistication and complexity of the financial markets has nurtured a highly complex field of exploration and innovation (Beck et al. 2017; Gramlich et al. 2023). As a result, many different avenues for blockchain application within the financial industry are being explored, the two main groups being the creation of a new, open and permissionless financial system totally based on blockchain (DeFi) and the integration of blockchain in the traditional financial system and infrastructure (TradFi). By shedding light on this complex field, the different avenues, and their individual and shared merits and hurdles, I set out to achieve the overarching research objective of my dissertation in:

Exploring and leveraging the potentials of blockchain-based financial systems

To fulfill this overarching research objective I partitioned my research into three RGs:

- RG1: *Understanding the challenges and leveraging the potential of DeFi*
- RG2: *Exploring the usage of blockchain in TradFi*
- RG3: *Investigating general blockchain challenges and solution approaches*

Within these RGs I identified relevant gaps in the current literature to derive specific RQs, which I sought to answer with individual essays. An overview on the 10 essays of my dissertation, their publication outlet, ranking, and status, and their assignment to the three RGs is given in Table 1. The following section will lay out the relevance and research gap for my three RGs and the derivation of the specific RQs.

Table 1: Overview of the 10 essays addressing the defined RGs

Title	Publication outlet	VHB JQ4 ranking	Publication status
RG_1: Understanding the challenges and leveraging the potential of DeFi			
Essay 1: A multivocal literature review of decentralized finance: Current knowledge and future research avenues	Electronic Markets	B	Published as Gramlich et al. (2023)
Essay 2: Enabling end-to-end digital carbon emission tracing with shielded NFTs	Energy Informatics	C	Published as Babel et al. (2022)
Essay 3: Designing the future of bond markets: Reducing transaction costs through tokenization	Electronic Markets	B	Published as Cisar et al. (2025)
Essay 4: From bricks to blocks: Designing a framework for the tokenization of real estate for DeFi	Communications of the Association for Information Systems	B	Under Review
RG_2: Exploring the usage of blockchain in TradFi			
Essay 5: A multivocal literature review on capturing value propositions for private organizations in a CBDC ecosystem	Communications of the Association for Information Systems	B	Published as Schaaf et al. (2025)
Essay 6: Tokens against tax-fraud: Utilizing blockchain technology in the principal-agent dynamics of federated tax systems	Business & Information Systems Engineering	B	Under Review
RG_3: Investigating general blockchain challenges and solution approaches			
Essay 7: Toward a holistic perspective on blockchain electricity consumption	45th Internation Conference on Information Systems	A	Published as Gramlich, Guggenberger, Paetzold et al. (2024)
Essay 8: Unsealing the secrets of blockchain consensus: A systematic comparison of the formal security of proof-of-work and proof-of-stake	39th ACM/SIGAPP Symposium on Applied Computing	n/a	Published as Álvarez et al. (2024)
Essay 9: Maximal extractable value: Current understanding, categorization, and open research questions	Electronic Markets	B	Published as Gramlich, Jelito and Sedlmeir (2024)
Essay 10: The adverse effect of privacy calculus on signaling and how zero-knowledge proofs can mitigate it	Information Systems Research	A+	Under Review

3.1 RG1: *Understanding the challenges and leveraging the potential of DeFi*

The emergence of DeFi represents a paradigm shift where blockchain technology revolutionizes the fundamental structure and functioning of the financial system (Chen and Bellavitis 2020). This potential for disruptive innovation has often been attributed to blockchain technology and has been the focus of blockchain research within the financial industry and other applications areas (Beck et al. 2017; Rossi et al. 2019). Researchers within the domain of IS and beyond have given attention to many different applications, e.g., tokenization (Hanneke et al. 2024; Sunyaev et al. 2021) or more complex financial services such as lending or trading protocols (Gudgeon et al. 2020; Xu et al. 2022), or fundamental questions within DeFi, e.g., the effects of disintermediation (Feulner et al. 2022) or centralization tendencies in DeFi protocols and DAOs (Zhou et al. 2024). Despite the attention of recent years, the research stream on DeFi, just like DeFi itself, is still in its infancy and shaped by fast paced exploration and innovation (Schär 2021). Additionally, the already formed complexity makes it hard to gain an overarching understanding of the field within a single academic article. To fill this gap, I encompass multiple articles within my dissertation to create an understanding of the challenges and the ways to leverage the potential of DeFi (RG1).

As it is common for such a nascent and quickly evolving field, the current literature on DeFi and its different aspects and applications is missing key requirements for a mature research field (Keathley-Herring et al. 2016). DeFi remains inadequately conceptualized from various perspectives, especially in terms of technical, regulatory, and organizational dimensions (Matsuo 2020). Furthermore, the existing literature lacks consensus on a unified understanding of DeFi, highlighting the need for a clear and succinct definition (Katona 2021). Establishing a common definition and a holistic aggregation of current knowledge can help individuals, organizations, and policymakers in making informed decisions while it also serves as a foundation for further technological, economical, and sociological exploration and advancing of DeFi (Schär 2021). To fill this gap, I seek out to answer the following RQ in my first essay:

RQ 1.1.: What are a common definition, the state of research, and future research avenues for DeFi?

Answering RQ 1.1. in Essay 1 showcased the large potential of DeFi and its broad application possibilities but also severe current limitations. Academic and grey, i.e., practitioner-driven, literature highlighted DeFi's limited adoption and high volatility and ascribe it, in particular, to limited integration of RWAs, i.e., financial assets that already exist in TradFi such as bonds or real-estate (Guggenberger et al. 2023). This shortcoming results in a detachment of DeFi from the financial system and its assets and in a high dependency on and correlation with the volatile cryptocurrency market (Gramlich et al. 2023). While IS researchers have already proposed concepts for onboarding RWAs into DeFi, especially focused on stocks and bonds (Guggenberger et al. 2023; Roth et al. 2019), and significantly contributed to design theory for asset tokenization, they often exhibit shortcomings that hamper practical feasibility and adoption. Some concepts fall short in appropriately representing the assets complexity and versatility, e.g., equity and debt financing in real-estate investments (Baum 2021). Others do not leverage new legislation, e.g., the German electronic securities law (BaFin 2021) or the European Market in Crypto Assets Regulation (MiCAR) (European Union 2023) that address the previously existing regulatory uncertainty around tokenized assets. Moreover, further user or investor needs, such as the protection of personal data in applications that incorporate sensitive data such as tracing of electricity consumption and related carbon emissions, are often neglected (Sedlmeir et al. 2021). To address this gap, I seek to answer the following RQ in my Essays 2-4:

RQ 1.2.: How to successfully integrate RWAs into DeFi, specifically, bonds, real estate, and carbon certificates?

Specifically, Essay 2 investigates the tokenization of carbon certificates through establishing traceability, while ensuring privacy for personal or business sensitive electricity consumption data. In Essay 3, we design a framework for the tokenization of real estate focused on enabling the full spectrum of real-estate investment products and maximizing regulatory certainty through the utilization of novel regulatory frameworks. Finally, Essay 4 proposes a solution for the tokenization of bonds and investigates its potential under the lens of transaction cost theory.

3.2 RG2: *Exploring the usage of blockchain in TradFi*

While the foundation of blockchain technology, i.e., bitcoin, was rooted in the creation of a fully open and permissionless system, the exploration of permissioned blockchain systems has gained notable traction among IS researchers and practitioners (Risius and Spohrer 2017). Permissioned blockchains, also referred to as "consortia blockchains," are designed to facilitate a more streamlined consensus mechanism that does not depend on scarce resources such as computational power in PoW or cryptocurrency in PoS (Rossi et al. 2019). Instead, these systems leverage the trustworthiness of a consortium of participants, thus allowing for controlled access to the network while still providing some of the decentralization benefits inherent to blockchain technology. Moreover, these permissioned systems are frequently conceptualized as private blockchains, offering a layer of protection for sensitive personal or business-related information by restricting access to authorized parties only (Butijn et al. 2021). However, this raises critical questions among scholars and practitioners about the appropriateness of applying blockchain technology in such closed environments, as its core affordances typically emphasize openness and public traceability (O'Leary 2023).

In the realm of permissioned blockchain IS, existing research predominantly focuses on the utilization of blockchain to enhance inter-organizational processes (Guggenberger et al. 2020). Applications such as supply chain tracing (Queiroz et al. 2019) and the settlement of financial transactions (Kim and Kim 2022) are illustrative of how permissioned blockchains can provide solutions in scenarios where blockchain can address trust issues among stakeholders but public traceability and public, permissionless control is not required. Yet, it is essential to question whether the advantages of decentralized technology can be fully realized in a permissioned context, or if these adaptations ultimately undermine the transformative potential that blockchain proponents advocate for (O'Leary 2023). Thus, to complement the insights gained into permissionless blockchain systems in RG1, I aim at exploring the usage of blockchain in the more centralized and permissioned context of TradFi (RG2).

While there has been considerable exploration of permissioned blockchains in interorganizational contexts, applications involving governmental control have received comparatively less attention. Notably, central bank digital currencies (CBDCs) have emerged as a focal point in this discussion, with existing prototypes and pilot projects often operating within centralized ledger infrastructures (Di Iorio et al. 2024). However, some scholars advocate for the exploration of blockchain technology within these frameworks, suggesting that its inherent properties could facilitate more transparent and efficient governmental financial systems (Zhang and Huang 2022).

The discourse surrounding CBDCs exemplifies the dichotomy between established centralized systems and the potential integration of blockchain technology. While many central banks develop prototypes that adhere to traditional centralized ledger designs, blockchain proponents argue that the incorporation of blockchain could not only enhance security and traceability but also align with the broader goals of improving public trust in government-issued financial instruments (Zhang and Huang 2022). On the other hand, skeptics argue, supported by the real-world evidence of central bank projects based on centralized ledger models, that blockchain technology does not offer value in systems that are inherently controlled by a central entity, i.e., the central bank (Di Iorio et al. 2024). Therefore, a critical examination of the applicability and efficacy of blockchain in governmental contexts is necessary to ascertain whether it can indeed provide substantial benefits over existing systems, particularly in terms of transparency, efficiency, and user trust. Against this backdrop, we investigate the different value propositions (VPs) and needs within a CBDC ecosystem which act as a foundation for determining the potential of blockchain technology in this field. For this, we seek to answer the following RQ in Essay 5:

RQ 2.1.: What VPs can companies offer in the context of a CBDC ecosystem and which needs do they fulfill?

Another possible application, that has only been touched upon by IS scholars yet, is the application of blockchain within the taxation system, in particular to tackle tax fraud. Most of these works remain at a high level of abstraction, only matching blockchain affordances to issues enabling tax fraud. Hyvärinen et al. (2017) present the only work from the IS domain that proposes a specific blockchain-based IS. However, they only focus on a specific context of tax fraud, i.e., dividend stripping in cross-border settings. Additionally, they neglect application-oriented requirements, in particular, privacy, which was shown to play an important role in blockchain-based tax IS by practitioners (EY 2021) and in blockchain-based IS in general (Sedlmeir et al. 2022). To advance the contribution from Hyvärinen et al. (2017) we broaden the application to all forms of dividend taxation where tax arrangements such as the Cum-Ex and Cum-Cum scheme have caused an estimated loss of € 150 billion across 12 countries. Furthermore, through surveying pertinent literature and engaging in discussions with relevant stakeholders, we aim to compile a complete catalogue of academic und practitioner-driven requirements as a foundation for enable IS design and evaluation. To further enable a better transfer of insights to other blockchain applications and bolster our theoretical contribution, we examine the issue at hand under the principal-agent theory (PAT), which has shown to be a suitable theoretical framework in the context of taxation (Reinganum and Wilde 1985). Thus, we set out to answer the following RQ:

RQ 2.2.: How to design a blockchain-based IS to tackle the principal-agent problem in dividend taxation by preventing agents' malicious behavior and reducing further hazardous information asymmetries while ensuring practical feasibility by minimizing agency costs?

3.3 RG3: *Investigating general blockchain challenges and solution approaches*

Besides ambiguities and open questions regarding specific applications areas, blockchain technology has also many open general challenges and considerations that have not or not fully have been addressed by existing literature (Rossi et al. 2019). Understanding these challenges and the impact of different design choices is not only important for designing blockchain-based systems with better performance, security, or efficiency but also for the understanding and acceptance of the technology that lays the ground for a broader adoption (Beck et al. 2017).

One aspect of blockchain and its design choices that has particularly shaped the public perception of and discussion around the technology is its energy consumption (Sedlmeir et al. 2020). The majority of public discourse centers around the headline "Bitcoin consumes more energy than many countries" (Criddle 2021). This statement is, however, also often generalized to the underlying technology. Similarly, even scholarly literature includes misconceptions and false statements, e.g., that bitcoin alone could cause an exceedance of 2° C global warming (Mora et al. 2018), which was later proven to be based on erroneous assumptions (Masanet et al. 2019), showcasing a partially missing rigor in the literature stream (Sai and Vranken 2024). While the majority of literature employs scientific rigor and valid assumptions, they strongly focuses only on specific aspects, e.g., the energy consumption of bitcoin or other PoW-blockchains while neglecting crucial aspects and blockchain types, e.g., PoS-blockchain, permissioned networks, or the influence of recent developments such as sharding or rollups (Richard et al. 2023). As a result, the overall academic discourse falls short in conveying an all-encompassing understanding of blockchain electricity consumption and the role of different design choices within (Sedlmeir et al. 2020). To fill this gap, we aim to give a comprehensive and holistic answer to the RQ:

RQ 3.1.: What are the key components and factors that influence blockchain electricity consumption?

Another fundamental property of blockchain technology is its security. While blockchain is commonly associated with absolute immutability and availability they offer several attack vectors to these properties (Schlatt et al. 2023). A decentralized IS's formal security is far more nuanced, i.e., consists of more facets than absolute or non, and comprises considerably more aspects, e.g., safety and liveness (Fischer et al. 1985). While the security of distributed systems has been studied by computer scientists since the 1970s, their protocol design and its complexity have significantly evolved overtime (Brewer 2000; Cristian 1991). Especially blockchain technology has introduced a new combination of features, i.e., a tamper-resistant data structure combined with redundant data processing and storage among a network of nodes governed by a (typically byzantine fault tolerant (BFT)) consensus mechanism, that led to a wider array of different security properties and interdependencies. While many researchers since have investigated the security of specific blockchains or blockchain designs, e.g., the bitcoin blockchain (Garay et al. 2015; Gaži et al. 2020), or a subset of security properties (e.g., Graf et al. 2021) a holistic and consistent understanding of all blockchain relevant security properties and the influence of prominent design choices on them is still missing. To fill this gap, we aim to aggregate security properties from pertinent literature and compare the two most prominent choices for consensus mechanisms in permissionless blockchains, PoW and PoS, with respect to these properties. Thus, we seek to answer the following RQ:

RQ 3.2.: What are the commonly considered security properties and commonalities and differences between PoW- and PoS-based consensus mechanisms?

Besides formal, cryptographic aspects, blockchain security also incorporates economic, i.e., game-theoretic, aspects (Daian et al. 2020). Complementing formal security analysis with considerations regarding economic security is essential in gaining a holistic understanding of the exact security properties a blockchain can provide and under which circumstances different attack-vectors can emerge. An aspect of economic security that has strongly gained significance and attention is maximal extractable value (MEV). While blockchain consensus mechanisms are designed to decentralize control, they exhibit a centralized monopoly of power at the level of a single block, i.e., the validator that obtained the right to propose the next block has full control over which transactions to include and their order. MEV refers to the value that can be extracted by the validator by leveraging this monopoly of power, which is especially significant in blockchain applications in the financial system. While the practical significance of the phenomenon is showcased by the amount of extracted value exceeding $ 1 billion between 2022 and 2024 (Chi et al. 2024), academic research is still scattered. Existing literature has only touched upon this rapidly emerging and evolving topic or focused on specific attack-vectors, e.g., front-running (Baum et al. 2023), or specific vulnerable applications, e.g., lending protocols (Perez et al. 2021). However, transaction timing and ordering is a critical aspect in the whole financial system (Röell 1990). Thus, all blockchain-based applications in the financial system beyond DeFi also need to be concerned with the effects of MEV. To provide the underlying fundament that practitioners and scholars can build upon when designing blockchain-based financial applications, we seek to answer the following RQ:

RQ 3.3.: What is the current, common understanding and definition of MEV and how can the MEV-related attack vectors be categorized?

Another aspect that has shown to be a hurdle in the development and adoption of blockchain-based IS, especially in interorganizational settings, is the trade-off between transparency and privacy (Sedlmeir et al. 2022). One the one hand, transparency and immutability of information is often one of the main reasons for the utilization of blockchain technology. On the other hand, however, storing sensitive information, e.g., personal or organizational financial information, in a publicly visible and non-erasable manner is often unfeasible, as it would violate personal data protection laws or leak business-sensitive information (Lautenschlager et al. 2023). Against this backdrop, ZKPs have emerged as a way to mitigate this trade-off, as they enable the proofing and verification of the correctness of a certain statement without revealing the underlying information (Feige et al. 1988). While IS-researchers have begun to study their application possibilities in the context of blockchain technology (e.g., Essay 2 and 6), we extend and abstract the knowledge on the impact of privacy concerns and the possibilities of ZKPs in mitigating them to the more general field of information sharing and reduction of information asymmetries. While signaling theory plays an important role in this field, only limited attention has been paid to the impact of privacy concerns in signaling and, to the best of our knowledge, the applications of ZKPs within signaling have not been explored yet (Benndorf et al. 2015; Connelly et al. 2011). To fill this gap, we aim to answer the following RQ:

RQ 3.4.: What is the influence of privacy calculus on signaling and how can ZKPs mitigate privacy concerns?

4 Research designs

Throughout the 10 essays of my dissertation, I employed several forms of research designs depending on the different context of the study and the objective pursued to answer the essay's RQ. Table 2 provides an overview of the essays and the respective research designs. In the following, these research designs will be laid out in more detail. Thereby, the section will be divided into three subsections: First, the research designs of Essays 1, 5, 7, 8, and 9 will be laid out. These essays aim at aggregating the current body of knowledge on a certain topic and question and by reviewing pertinent literature. Second, the research designs employed in Essays 2, 3, 4, and 6 that pursue the goal of designing tangible artifacts to overcome identified practical and/or theoretical challenges will be detailed. Third, the research design of Essay 10 that extends an existing theoretical model and subsequently empirically validates the new model will be set forth.

Table 2: Research designs of the 10 essays

Title	Research design
RG_1: Understanding the challenges and leveraging the potential of DeFi	
Essay 1: A multivocal literature review of decentralized finance: Current knowledge and future research avenues	**Multivocal literature review:** • Screening 595 academic (AL) and 52 grey literature (GL) items • Derivation of a final set of 79 papers (50 AL, 29 GL) • Quantitative analysis of the literature set and included definitions • Qualitative analysis within a classification framework based upon Risius and Spohrer (2017) • Derivation of a research agenda based on the findings of the quantitative and qualitative analysis
Essay 2: Enabling end-to-end digital carbon emission tracing with shielded NFTs	**Design science:** • Identification of currents problems and existing approaches in pertinent literature and practical implementations • Design and implementation of the blockchain-based IS • Quantitative evaluation through benchmarking
Essay 3: Designing the future of bond markets: Reducing transaction costs through tokenization	**Design science:** • Derivation of 7 Meta Requirements (MRs) and 5 Design Objectives (DOs) from pertinent literature and grounded in Transaction Cost Theory • Design and implementation of the blockchain-based architecture • Evaluation through 14 expert interviews in 3 evaluation cycles and unit testing • Abstracting insights into 5 Design Principles (DPs)

Title	Research design
Essay 4: From bricks to blocks: Designing a framework for the tokenization of real estate for DeFi	**Design science:** • Identification of areas for improvement and derivation of 4 MRs and 9 DOs from pertinent literature • Designing of a tokenization framework and implementation of core functionalities • Summative, naturalistic evaluation of the artefact through 12 expert interviews in 2 evaluation cycles • Deriving design knowledge in the form of 4 DPs
RG_2: Exploring the usage of blockchain in TradFi	
Essay 5: A multivocal literature review on capturing value propositions for private organizations in a CBDC ecosystem	**Multivocal literature review:** • Screening 1014 AL und 120 GL items • Derivation of a final set of 52 papers (39 AL, 13 GL) • Qualitative analysis with a non-exclusive categorization into 22 papers directly stating VPs and 43 papers showcasing needs from which VPs can be derived
Essay 6: Tokens against tax-fraud: Utilizing blockchain technology in the principal-agent dynamics of federated tax systems	**Design science:** • Establishing 2 MRs and 6 DOs from pertinent literature and expert workshops grounded in PAT • Design of the blockchain-based IS • Evaluation through 6 expert workshops and 10 expert interviews in 2 evaluation cycles • Abstracting design knowledge into 3 DPs
RG_3: Investigating general blockchain challenges and solution approaches	
Essay 7: Toward a holistic perspective on blockchain electricity consumption	**Systematic literature review:** • Screening 2078 literature items from 7 academic databases to obtain 24 relevant articles • Forward and backward search to obtain the final set of 35 papers • Qualitative analysis with a non-exclusive categorization of the set into 25 papers discussing PoW and 13 papers on non-PoW blockchains • Derivation of a research agenda based on gaps identified in the qualitative analysis
Essay 8: Unsealing the secrets of blockchain consensus: A systematic comparison of the formal security of proof-of-work and proof-of-stake	**Systematic literature review:** • Screening 746 literature items from 4 academic databases to obtain a final set of 26 papers • Qualitative analysis within the build classification framework consisting of 6 security properties (Dimension 1) and 8 consensus protocol design (Dimension 2)
Essay 9: Maximal extractable value: Current understanding, categorization, and open research questions	**Multivocal literature review:** • Screening 285 papers from 6 AL and 3 GL databases • Derivation of a final set of 72 literature items (37 AL, 35 GL) • Quantitative analysis of the literature set and included definitions • Qualitative analysis with a non-exclusive categorization into four different categories of MEV and the affected applications, respectively • Derivation of a research agenda based upon the qualitative and quantitative analysis
Essay 10: The adverse effect of privacy calculus on signaling and how zero-knowledge proofs can mitigate it	**Game theoretic modelling and survey research:** • Integration of privacy calculus into the game theoretic signaling model • Setting up hypothesis on the impact of privacy concerns in signaling and ZKPs potential to mitigate them within the new model • Quantitative validation of the hypothesis through a survey with365 participants

4.1 Literature reviews

The literature reviews conducted in Essays 1, 5, 7, 8, and 9 can be grouped into two subcategories. Essays 7 and 8 employed a systematic literature review (SLR) established by Webster and Watson (2002), following additional guidance from Kitchenham and Charters (2007), that aims at capturing the state-of-the-art of academic literature (AL) in regards to a certain topic and RQ. For essays 1, 5, and 9 we conducted a multivocal literature review (MLR) that supplements the AL with additional practitioner driven articles, also denoted as grey literature (GL) (Garousi et al. 2019). Especially for novel and practitioner driven fields, such as the topics of Blockchain, DeFi, and CBDCs at hand, including GL can offer important insights that have not yet been included in the AL, e.g., because of a delay in the proliferation of new knowledge due to timely peer-review processes (Garousi et al. 2016).

Both forms of literature reviews start with an unstructured search for and analysis of pertinent literature to derive a search string that captures all aspects, facets, and synonyms that are relevant to the respective RQ (Webster and Watson 2002). Afterwards additional finetuning based on the quality and quantity of search results, the final search string is applied to a set of academic, and in the case of a MLR also grey, literature databases. The choice of these databases also depends on the topic at hand and is influenced by the results of the initial, unstructured search that can help to identify particularly relevant publication outlets and the respective databases that index them (Kitchenham and Charters 2007). After carrying out the search, content related, e.g., restriction to more specific themes and questions, and formal, e.g., language of the publications, in- and exclusion criteria are defined and applied in an iterative screening of title, abstract, and full-text (Kitchenham and Charters 2007). To further enhance the completeness of the collected literature, a forward and backward search, i.e., investigating papers that cite (forward) or were cited by (backward) the literature items, can be conducted to collect additional publications that were not captured by the structured search (Webster and Watson 2002). While AL has already undergone quality control within the peer-review process, this is not the case for GL. Thus, Garousi et al. (2019) propose the assessment of the final set of GL based on 17 quality criteria, e.g., regarding the objectivity of the study or indication of sources, to ensure their reliability and rigor.

The multi-disciplined nature of Essay 7's RQ s resulted in the identification of a broad spectrum of relevant databases: ACM Digital Library, AIS eLibrary, IEEE Explore, Nature, Science Direct, Web of Science, and ArXiv. Applying the search string to these 7 databases resulted in 2078 total records, from which 24 passed all screening steps. The forward and backward search yielded an additional 11 papers, amounting to a final literature set of 35 papers. In the qualitative analysis, these papers were assigned to two non-exclusive categories, 25 papers discussing PoW and 13 papers on non-PoW blockchains. Contrasting these two categories enabled the identification of commonalities and differences of the current state of literature and the derivation of questions for future research in the respective categories.

For Essay 8, we identified the ACM Digital Library, IEEE Explore, Science Direct, and SpringerLink as the most relevant databases, reflecting the RQ's technical and computer science focus. The search yielded 746 results, which were narrowed down to a final set of 26 literature items. From these items, six security properties and eight consensus protocol design choices were identified, and the results were structured in a concept matrix with the respective properties as rows and the different designs as columns.

Similar to Essay 7, the topic of Essay 1 is spanning multiple disciplines which is why we chose a broad range of academic databases too: ACM Digital Library, AIS eLibrary, EBSCO Host, Emerald Insight, IEEE Explore, Science Direct, SpringerLink, Web of Science, and Wiley Online Library, yielded 595 results. Additionally, we applied our search string to Google Scholar, RePeC, and ArXiv to capture pertinent GL, which gave us another 139 results. The subsequent screening resulted in 48 AL and 33 GL items, complemented with 2 AL and 6 GL items from forward and backward search. After the quality assessment of the GL, which ruled out 10 papers, we ended up with a final set of 79 literature items (50 AL and 29 GL). We performed a quantitative analysis to establish a common definition of DeFi and show the development over time of both AL and GL. Subsequently, we adopted the blockchain research framework from Risius and Spohrer (2017) to structure our qualitative analysis of the literature and quantify blank spots in the current literature. Finally, we utilized the findings of the quantitative and qualitative analysis to derive specific RQs within the different dimensions of the framework.

In Essay 5, we conducted a MLR using the databases Scopus, Science Direct, Web of Science, AIS eLibrary, and Google Scholar, which yielded 1134 results. After applying in- and exclusion criteria during the screening process, 50 items remained, which were supplemented by 2 papers found in the forward and backward search. For the analysis, we divided this final set of 52 papers into two non-exclusive categories: 22 papers directly stating VPs and, thus, directly addressing our RQ, and 43 papers showcasing needs of a successful CBDC ecosystem from which VPs can be derived. Subsequently, we superimpose the findings in both categories to identify mismatches from which we derived RQs for future research.

The topic of Essay 9, again, showcased a wide range across various disciplines. Thus, we applied our search in a wide array of 6 AL – ACM Digital Library, EBSCO Host, IEEE Explore, Science Direct, SpringerLink, and Web of Science – and 3 GL databases – Google Scholar, ArXiv, and SSRN. From the initial set of 285 items, a final set of 72 papers remained after screening. Firstly, we performed a quantitative analysis of the definitions of MEV and their sub aspects in our literature to establish a common definition of the phenomenon that exhibits an overlap with the various existing definitions that is as high as possible while still being specific and not too vague. Secondly, we applied a non-exclusive categorization of the literature into four different categories of MEV and the affected applications for qualitative analysis of the literature. Finally, we utilized the insights of both quantitative and qualitative analysis to derive an agenda for future research.

4.2 Design science

The aim of Essays 2, 3, 4, and 6 was to design IS artifacts that address a problem that is both practically relevant and also contributes to theoretical domain and abstract design knowledge. To pursue this goal, in Essay 2, we identified currents problems and requirements in carbon emission tracing. Subsequently, we surveyed existing approaches in pertinent literature and practical implementations from various domains and combined and transferred different approaches to design an IS for the task at hand. Finally, we implemented the IS and carried out a quantitative evaluation of the systems performance on different benchmark devices.

Essays 3, 4, and 6 followed the Design Science Research (DSR) paradigm established by Hevner et al. (2004). There are different approaches and depictions of the exact

DSR process: The three cycled view of Hevner (2007) depicts the DSR research process as iterations that combine different areas – the environments, the knowledge base, and the main design science research process – through the relevance, the design, and the rigor cycle. Peffers et al. (2007) describe DSR as a 6-step approach, acompassing problem identification, objective definition, design and development, demonstration, evaluation, and communication, recently extended to the so called echelon DSR approach by Tuunanen et al. (2024). While the approaches of Hevner (2007) and Peffers et al. (2007) differ in their designation and demarcation of the different steps, the main goal of the research and the reasoning of their approach are the same. The aim of DSR is to guide researchers in designing purposeful artifacts (Hevner et al. 2004). This includes identifying a problem and defining design objectives (DOs) based on the knowledge from the practical application domain and pertinent literature. In order to strengthen the theoretical foundation and contribution, research theories can be used as so-called kernel theories or to derive overarching meta requirements (MRs) (Gregor and Hevner 2013). After designing the artifact according to the established DOs (and MRs) and implementing it in a demonstratable form, the artefact and whether it fulfills the DOs is evaluated. The evaluation can be conducted both quantitatively, e.g., performance measurements and benchmarking, or qualitatively, e.g., through expert interviews. Subsequently, the objective definition and artifact design is adjusted according to the results of the evaluation. Iterations from design and subsequent evaluation end, when saturation, i.e., the complete fulfillment of the DOs, in the evaluation is reached. Through this process, DSR enables both practical impact through the design of a tangible IS artifact and theoretical contributions through the insights gained in the context of the applied theoretical lens and the derived design knowledge, which is often abstracted in the form of design principles (DPs) (Gregor et al. 2020).

For Essay 3, we followed the six-step approach of Peffers et al. (2007). Besides pinpointing both the practical problems of current bond investment vehicles and the research gap on prescriptive knowledge regarding bond tokenization, we identified transaction cost (TAC) theory as a suitable theoretical foundation for our investigation. The TAC theory dimensions of frequency, asset specificity, and uncertainties (Williamson 1981) served as an additional framework for the establishment of seven MRs and the subsequent derivation of five DOs, strengthening both the theoretical foundation and overall structure of our research process. Thereafter, we designed the blockchain-based architecture, implemented core functionalities, and conducted the evaluation through a qualitative evaluation with a total of 13 expert interviews across three evaluation cycles and complementary quantitative evaluation through unit testing. Finally, we derived five DPs which we relate to the established DOs, MRs, and the dimensions of TAC theory as proposed by Giessmann and Legner (2016).

In Essay 4, we also adhered to the six-step DSR approach of Peffers et al. (2007), starting with the establishment of nine areas for improvement based on pertinent literature on traditional, general technology-based, and specific blockchain-based real estate investments. From these areas for improvement, we derived four MRs and nine DOs, which guided the design of our conceptual tokenization framework, complemented by the implementation of our most important smart contract functionalities. Subsequently, we followed the framework for evaluation in design science research (FEDS) from Venable et al. (2016). Within the FEDS, we conducted a summative, naturalistic evaluation of our conceptual framework and its implementation through two cycles of six expert interviews per cycle (12 in total) with subsequent refinement of the design. Finally, we derived four DPs to generalize the gained insights into actionable guidance on the design of frameworks for investment tokens.

Lastly, in Essay 6 we followed the three cycle view of DSR of Hevner (2007). We found this approach to be best suited for this research endeavor as all steps of the DSR process were based on a strong interlinkage and iterations between the foundations of the knowledge base and the application domain of dividend taxation and tax-fraud. We applied the theoretical lens of PAT to establish two MRs and literature on blockchain applications within the tax system and insights through six workshops with experts from the German financial ministry, multiple tax agencies, and financial infrastructure providers to derive six DOs subordinate to the MRs. The summative evaluation within the FEDS (Venable et al. 2016) of the designed blockchain-based IS incorporated both the six expert workshops and a second evaluation cycle encompassing 10 expert interviews with academics and practitioners from the fields of IS, economics, law, and taxation. Conclusively, we derive three DPs to abstract our insights and contribute to design knowledge in the context of blockchain-based solutions to principal-agent problems (PAPs) in general.

4.3 Game theoretic modelling and survey research

In Essay 10, we applied a two-step methodological approach, aimed at an extension of an existing theoretical model and a subsequent empirical validation. In the first step, we integrated privacy calculus (Benndorf et al. 2015) into the model of signaling theory (Connelly et al. 2011) and modelled how the assessing of risks and benefits of information disclosure, i.e., privacy calculus, influences the willingness to signal sensitive information and the consequential impact on the equilibria of the signaling game. Thereupon, we derive three hypotheses from the propositions that follow from the extension of the game theoretic signaling model for empirical validation. Through a survey experiment with 365 participants, we are able to validate the three hypothesis and thus, the new model of a signaling game with integrated privacy calculus, with statistical significance. With this, we showcase the effects of privacy concerns on signaling and the potential of ZKPs to mitigate them not only under the assumption of rational actors in the theoretical model but prove the significance of these effects in a behavioristic setting.

5 Summary of results

In the following section, I will summarize the key findings of my 10 essays. These results provide insights into the foundations, challenges, and potentials of DeFi, the application possibilities of blockchain in permissioned, traditional financial systems, and general challenges and considerations for the usage of blockchain in financial applications.

5.1 Essay 1: A multivocal literature review of decentralized finance: Current knowledge and future research avenues

In Essay 1, we seek to examine the current state of research in the rapidly evolving field of DeFi, focusing on its transformative potential, inherent challenges, and the gaps that still exist in academic and industry discussions. Despite DeFi's growing adoption demonstrated by a rise of assets in the ecosystem to over $80 billion dollars in early 2022 (DeFi Pulse 2022) and the significant disruptive potential attributed to it (Chen and Bellavitis 2020), DeFi is still facing substantial challenges that are reflect in significant gaps in the literature regarding its security, regulatory compliance, systemic risks, and real-world applicability (Schueffel 2021; Zetzsche et al. 2020). To address these gaps, we conduct a MLR (Garousi et al. 2016), integrating insights from peer-reviewed AL and GL, systematically analyzing key themes, emerging challenges, and future research opportunities.

First, we establish a common definition for DeFi which is as specific as possible while aligning with the majority of the collected literature by systematically collecting and coding definitions. With this, we establish that "DeFi is a decentralized financial system that enables financial services and instruments to be offered and used without the need for intermediaries as the system is based on public blockchains and smart contracts". The subsequent analysis of the literature body within the blockchain research framework from Risius and Spohrer (2017) highlights DeFi's core characteristics, including transparency, composability, and permissionless access, which differentiate it from TradFi. However, several critical issues threaten its stability and long-term viability. Security vulnerabilities, including smart contract exploits and the manipulation of decentralized exchanges through MEV, expose users to financial risks. Additionally, DeFi's high reliance on oracles and centralized entities, such as stablecoin issuers, raises concerns about re-centralization, contradicting its foundational principles.

Regulatory uncertainty further complicates DeFi's growth, as global financial authorities struggle to develop frameworks that accommodate its decentralized nature while ensuring compliance and consumer protection. Moreover, the study underscores the systemic risks arising from the interconnected nature of DeFi protocols, where the failure of a single component can trigger cascading effects across the ecosystem. These challenges necessitate further research into governance mechanisms, risk management strategies, and the integration of regulatory safeguards.

The study contributes to both theory and practice by providing a unified definition that can serve as a foundation for future research, advancing the conceptual understanding of DeFi, and outlining pathways for its sustainable development. Theoretically, it enriches the discourse on decentralized financial systems by consolidating existing knowledge within an established blockchain research framework and identifying research gaps. Practically, it provides valuable insights for regulators, developers, and financial institutions on how to navigate the complexities of DeFi, suggesting that hybrid models combining centralized and decentralized elements may offer the best path forward. Additionally, the study calls for the development of scalable security solutions, regulatory adaptations, and improved user experience frameworks to facilitate broader adoption and enhance DeFi’s robustness and legitimacy in the financial sector.

5.2 Essay 2: Enabling end-to-end digital carbon emission tracing with shielded NFTs

In Essay 2, we address the critical need for verifiable and privacy-preserving CO_2 emission tracing in the energy sector. As regulatory frameworks and consumer demand push for greater transparency in carbon footprint reporting, the challenge lies in reconciling fine-granular traceability and verifiability with data privacy for personal or business sensitive information, e.g., fine-granular electricity consumption data of a household or an industrial plant. While researchers have widely acknowledged the potential of tokenizing emissions to enhance data transparency and verifiability, existing solutions either fail to provide granular, real-time tracking of emissions (Sedlmeir et al. 2021) or neglect the importance of data privacy (Sadawi et al. 2021). To enable us in designing a holistic concept that fully addresses the challenges and needs in carbon emission tracing, we establish a set of core design requirements from pertinent literature: 1) Verifiability—ensuring that emission data is tamper-proof and auditable (Sullivan and Gouldson 2012), 2) Distinguishability—allowing unique emission certificates to be linked to specific production plants and points in time (Sedlmeir et al. 2021), 3) Fine-granularity—enabling the precise measurement of emissions regarding time and quantity (Sedlmeir et al. 2021; Watanabe and Robinson 2005), and 4) Privacy and GDPR Compliance—ensuring that all person- and consumption-related information remain confidential (Körner et al. 2022; Sedlmeir et al. 2022). Furthermore, the literature also emphasizes the overall importance of a tamper-resistant and open system with high availability guarantees, again highlighting the suitability of utilizing blockchain technology (Albrecht et al. 2018).

To achieve our design requirements, we integrate multiple cryptographic and blockchain-based approaches into a tokenization concept we name shielded, fractionalizable non-fungible tokens (NFTs). We build upon the ERC-721 and ERC-1155 token standards for non-fungibility and fractional ownership, while incorporating ZKPs (Goldreich and Oren 1994) and Merkle trees (Merkle 1988) to enable privacy-preserving transactions. Inspired by Zcash's shielded transactions (Ben Sasson et al. 2014), we ensure that CO_2 certificate ownership and transfers remain confidential, even as the system maintains traceability and verifiability. We also implemented the core features for proof creation and verification as prototype for performance benchmarking, demonstrating efficient proof creation (the most computation heavy operation) on a commercial grade laptop in 0.23 seconds, ensuring the systems efficiency and feasibility for real-world deployment.

Our contributions span both theory and practice. First and foremost, we introduce the first privacy-preserving fractional NFT model tailored for the tokenization of CO_2 emissions, improving emission tracing and enabling the extension of the asset class carbon credits. Furthermore, our framework extends existing blockchain research by showcasing the affordances of ZKPs in balancing the trade-off between data privacy and verifiability. Practically, policymakers and industry leaders may also leverage our findings to refine emission tracking regulations, enabling more nuanced decision making based upon fine-granular, transparent, and verifiable emission data.

5.3 Essay 3: Designing the future of bond markets: Reducing transaction costs through tokenization

In Essay 3, we investigate how blockchain technology can enhance efficiency in corporate bond markets under the theoretical lens of TAC theory. Traditional bond markets are burdened by complex intermediary structures resulting in high settlement times, and limited liquidity and market accessibility (Edwards et al. 2007). Optimizing transactional efficiency by reducing or eliminating intermediation is a widely studied approach to reducing TAC (Benston and Smith 1976) and also a key affordance of blockchain technology (Feulner et al. 2022). While blockchain-based tokenization has been proposed as a solution to the prevailing challenges of bonds, existing research has either focused on the general suitability of blockchain (e.g., Großmann 2024) or focused on highly specialized applications, e.g., green bonds (Axelsen et al. 2023) or crowdfunding (Guggenberger et al. 2024). To fill this gap and provide concrete guidance and design knowledge for the efficient design of corporate bond markets, we employ a DSR approach (Peffers et al. 2007), leveraging TAC theory as a guiding framework.

First, we establish MRs and DOs that guide the remainder of the prototype. In this context, the expert interviews and pertinent literature highlight the importance of reducing settlement latency and overall complexity (TAC dimension – frequency), removing access barriers (TAC dimension – asset specificity), and ensuring information sharing and regulatory compliance (TAC dimension – uncertainties). Adhering to these requirements for an efficient bond market, we developed our conceptual architecture for bond tokenization, automating typically intermediation-heavy issuance and compliance processes through smart contracts. Furthermore, we implement a prototype to demonstrate our concept using the Ethereum virtual machine (EVM). The subsequent evaluation highlights that tokenized bonds significantly enhance market efficiency by automating key processes such as bond issuance, settlement, and interest payouts. By integrating smart contracts, the system eliminates many intermediaries, thereby reducing asset specificity and transaction complexity. Lastly, we generalized our key findings into five DPs for TAC efficient tokenization that highlight the importance of 1) a modular design with distinctive system components, 2) the exploitation of multi-token standards, and additional functionalities to enable 3) claims on investors behalf, 4) intervention from regulators, and 5) smart-contract based management of crypto securities registers (CSRs).

Through the rigorous design and evaluation of our artifact and the incorporation of TAC theory into our DSR process, the contribution of our research is twofold. First, we guide the TAC efficient design and implementation of asset tokens, particularly bonds, by providing tangible design knowledge through five DPs. Second, we contribute to the broader field of blockchain research by highlighting blockchain's affordances in the context of TAC and showcasing the suitability of studying blockchain applications under this theoretical lens. Furthermore, we provide financial institutions and policy-makers with guidance for the practical implementation of CSRs and optimization of smart contract functionalities. With our work, we hope to lay the groundwork for broader adoption of tokenized debt instruments, fostering a more efficient, transparent, and inclusive financial landscape.

5.4 Essay 4: From bricks to blocks: Designing a framework for the tokenization of real estate for DeFi

Essay 4 explores how tokenization can facilitate the integration of real estate assets into DeFi. While existing research on tokenization primarily focuses on traditional securities like stocks and bonds (Guggenberger et al. 2023), only a few works on real estate tokenization exist (e.g., Gupta et al. 2020; Zhitomirskiy et al. 2023). Despite the significant contribution of these works to design theory, literature on general technology based real estate investments and our expert interviews highlight key aspects that have been neglected thus far, e.g., appropriately representing the broad spectrum of investment product types (Baum 2021), compliance with local and global regulatory frameworks (Garcia-Teruel 2019), and an efficient and fully-fledged integration into the DeFi ecosystem (Gramlich et al. 2023). To address these gaps, we employ a DSR approach (Peffers et al. 2007), systematically surveying areas for improvement in real-estate investments and tokenization, deriving MRs and DOs and rigorously constructing and evaluating a framework for real estate tokenization.

To provide a holistic concept, the designed framework encompasses the entire 6-step real estate investment lifecycle starting from the asset, over the special purpose vehicle (SPV), the different types of financial instruments, the tokenization, and the distribution, up to the onboarding of investors. The findings highlight several key components essential for a successful real estate tokenization framework. The proposed model emphasizes end-to-end compliance with regulatory frameworks, ensuring that tokenized real estate adheres to financial regulations across multiple jurisdictions and leverages them in the most efficient way. Against this backdrop, the design and evaluation highlight the suitability of choosing Lichtenstein financial law as legal foundation by establishing a Lichtenstein-based company as SPV. Additionally, the study underscores the importance of leveraging existing token standards, particularly the ERC-1400, to enhance interoperability and enable a seamless integration with DeFi protocols. However, these token standards need to be extended with additional functionalities to cover specific regulatory or corporate needs and efficient distribution mechanisms. Following the design and evaluation, we abstract the obtained insights into four DPs, highlighting the importance of 1) considering equity and debt product structures to leverage the adoption and versatility of the token, 2) pursuing compliance with a precise and widely accepted regulation to ensure investor and issuer protection and access, 3) leveraging token standards to increase the interoperability and composability, and 4) extending token standards with corporate functions to support an efficient DeFi integration.

The study contributes both theoretically and practically to the fields of blockchain and real estate investment. Theoretically, it advances the discourse on asset tokenization by offering a comprehensive framework for integrating real estate into DeFi, filling a notable gap in AL. Furthermore, our DPs provide generalized design knowledge for the tokenization and successful DeFi integration of financial assets in general. Practically, the findings provide real estate developers, investors, and financial regulators with actionable guidelines on implementing blockchain-based real estate investment products. As such, our research demonstrates how successful tokenization can leverage blockchain and DeFi capabilities to increase market accessibility, improve liquidity, and reduce transaction costs while maintaining product versatility and regulatory protection for asset providers and investors.

5.5 Essay 5: A multivocal literature review on capturing value propositions for private organizations in a CBDC ecosystem

In Essay 5, we investigate the rise of CBDCs which represent a transformative shift in the financial system, blending elements of traditional banking with innovations from DeFi and Fintech. While much research has focused on the design (e.g., Allen et al. 2020), implementation (e.g., Morales-Resendiz et al. 2021), and macroeconomic implications of CBDCs (e.g., Chiu and Davoodalhosseini 2023), there remains a gap in understanding the role of the private sector and the VPs they can capture in a successful CBDC rollout. Thus, we seek to address this deficiency by systematically analyzing pertinent literature to investigate the role of private organizations in a CBDC ecosystem. Through a MLR (Garousi et al. 2016), we examine both white (academic) and grey (industry-driven) literature to achieve a comprehensive understanding of VPs of private organizations, enabling stakeholders to identify market needs, innovate effectively, and align regulatory frameworks with technological advancements.

To obtain a holistic overview of the different VPs of private organizations we survey both VPs directly mentioned in our literature set and general needs for a successful CBDC rollout from which further VPs can be derived. We structure our findings in four major categories of VPs in CBDC ecosystems: 1) accessibility and usability, focusing on wallets, applications, and offline transaction solutions to enhance user engagement, 2) financial infrastructure, including secure databases and efficient transaction systems, 3) regulatory compliance and onboarding, which covers know-your-customer (KYC) mechanisms, anti-money laundering (AML) processes, and privacy-preserving technologies such as ZKPs, and 4) operations and support services, where financial service providers can aid in user education, adoption incentives, and business analytics. Additionally, the needs for a successful rollout emphasized in the literature highlight the critical role of cybersecurity solutions, advanced audit mechanisms, and strategic communication to ensure widespread adoption of CBDCs. This broad spectrum of VPs showcases that private organizations are not only crucial in enabling a smooth CBDC rollout but may also serve as innovators, developing new business models around CBDC usage.

Essay 5 contributes to both theory and practice by highlighting the critical role of private organizations in the successful rollout of CBDCs and the broad spectrum of VPs they can offer. For both academics and practitioners, it establishes the necessity of private sector involvement, demonstrating how financial institutions, fintech companies, and technology providers can enable a smooth CBDC rollout and serve as innovators, developing new business models around CBDC usage. Theoretically, the study lays the foundation for further research into the role of private organizations by providing a structured framework for analyzing VPs, encouraging deeper investigations into individual categories and the derivation of viable business models. Practically, it offers valuable insights for financial sector players by identifying new business opportunities in the context of a CBDC rollout. Furthermore, the study provides guidance for regulators and central banks on effectively integrating private ventures into CBDC frameworks, ensuring a collaborative approach that leverages private sector innovation while maintaining financial stability and regulatory compliance.

5.6 Essay 6: Tokens against tax-fraud: Utilizing blockchain technology in the principal-agent dynamics of federated tax systems

In Essay 6, we investigate fraud in dividend taxation, particularly in the form of Cum-Ex and Cum-Cum schemes that have resulted in estimated fiscal damages exceeding €150 billion across 12 countries (Schubert 2021). From a PAT perspective, this issue stems from information asymmetries and goal incongruence between taxpayers (agents) and tax authorities (principals) resulting in moral hazard (Reinganum and Wilde 1985). Despite blockchains increasing adoption in finance and its suitability to tackle the issues that underly principal-agent dynamics, e.g., through immutability of information and traceability of actions (Carvalho and Karimi 2020), blockchain's application in taxation remains underexplored. Existing work either is limited to the general proposition of blockchain utilization (e.g., Faccia and Mosteanu 2019) or only considers very specific cases and neglects key aspects such as data privacy (EY 2021; Hyvärinen et al. 2017). To address this gap, we apply a DSR approach (Hevner 2007). We rigorously design and evaluate a blockchain-based IS, that tackles the principal-agent problem within taxation while fulfilling holistic requirements for practical feasibility, such as efficiency and data privacy.

Founded in PAT, we derive two MRs for our design: 1) inhibiting moral hazard, i.e., tax-fraud, and 2) minimizing agency costs to ensure practical feasibility. Subsequently, we derive six DOs from expert workshops and pertinent literature to further detail these MRs: DO1 (prevention of tax certificate double spending) and DO2 (reduction of detrimental information asymmetries) extent MR1 while DO3 (regulatory compliance and privacy), DO4 (interoperability with financial markets), DO5 (scalability and availability), and DO6 (implementation and operating cost) are subordinated to MR2. To fulfill these requirements, our IS centers around a tokenized tax-certificate that inhibits double-spending (ex-ante) and is enriched with further, immutable information that enables the investigation against malicious behavior (ex-post). The key processes encompass the permission to issue, issuance, transfer, and redemption of the tax certificate token. They are realized through smart contracts in combination with whitelists that enable the automation of processes while ensuring the obeyance to the pre-determined rules. By integrating ZKPs, the system can provide transparency and verifiability of information and actions while enabling confidentiality for person and business-sensitive information. A rigorous evaluation laid the ground for important adaptations, e.g., the addition of proof of minting and custody from the custodian to his customer to inhibit any possibility of wrongdoing from the custodian, and finally confirmed the effectiveness of our proposed IS. Lastly, our insights enable us to derive DPs for blockchain-based solutions to PAPs to emphasize 1) the potential of blockchain-based rule enforcement to prevent fraudulent claims, 2) the use of traceable yet privacy-preserving transactions to mitigate information asymmetries, and 3) the role of ZKPs in safeguarding sensitive taxpayer data while maintaining regulatory oversight.

With our research, we aim to achieve three key contributions. First, we propose a practical, blockchain-based IS to counter tax fraud, validated through expert evaluations, ensuring its effectiveness and feasibility. Second, we extend blockchain research by demonstrating its applicability in a highly regulated financial domain, challenging the notion that blockchain is only valuable in fully decentralized settings (O'Leary 2023). Finally, we contribute to PAT research by showcasing how blockchain, in combination with ZKPs, can effectively reduce information asymmetries and mitigate agency problems, offering insights for broader applications beyond taxation. By providing a verifiable, privacy-preserving, and rule-enforcing solution, our study lays the foundation for further exploration of blockchain's role in tax compliance and closely regulated and controlled financial systems in general.

5.7 Essay 7: Toward a holistic perspective on blockchain electricity consumption

In Essay 7, we examine blockchain electricity consumption, a topic that remains highly contentious, with media and academic discussions often presenting misconceptions and oversimplifications (Masanet et al. 2019; e.g., Mora et al. 2018). This topic is highly relevant, as concerns about blockchain electricity consumption influence public perception, acceptance, and adoption of the technology (Shi et al. 2023), while researchers must rely on accurate assessments to make informed judgments when investigating or designing blockchain applications, even more when they use blockchain to propel sustainability (e.g., Babel et al. 2022). While a rich research body investigates the electricity consumption of specific blockchains with a strong focus on PoW networks (e.g., Vranken 2017; Vries 2021), many papers suffer from methodological weaknesses and an all-encompassing overview of the different aspects of a blockchain network and the impact of corresponding design choices is missing (Lei et al. 2021; Sai and Vranken 2024). To address these gaps, we conducted a SLR (Kitchenham and Charters 2007) to consolidate existing knowledge and holistically identify key determinants of blockchain electricity consumption.

The first finding from reviewing our literature set is the strong distinguishment that must be made between blockchains utilizing the PoW consensus mechanisms and other blockchains that we coin non-PoW networks. We categorize the literature analysis accordingly and identify three main research approaches to determine the electricity consumption of a PoW network: a technical approach, which estimates consumption based on hardware specifications and hash rates, an economic approach, which assumes rational miner behavior constrained by profitability, and hybrid approaches, which integrate both perspectives. These studies consistently emphasize that efficiency of mining hardware, electricity costs, and block rewards are the primary drivers of electricity consumption. In contrast, research on non-PoW networks primarily examines blockchain node operations, estimating electricity usage based on hardware configurations and node counts. Our review also highlights that the literature neglects broader network participants, such as users or third-party service providers, suggesting a gap in fully understanding electricity consumption of a blockchain network as a whole.

Our findings call for a more nuanced perspective on blockchain electricity consumption by distinguishing between three participant groups: consensus participants, blockchain nodes, and broader network participants. The contributions of this essay are twofold: 1) we systematize the body of knowledge on blockchain electricity consumption, giving the broader public, policymakers, and researchers a foundation for more informed decision making on technology adoption, regulation, and design. 2) We propose a holistic framework to assess blockchain electricity consumption across diverse participant groups, highlighting the state-of-the-art and future RQs within the different areas of the framework and laying the foundation for future research to build upon.

5.8 Essay 8: Unsealing the secrets of blockchain consensus: A systematic comparison of the formal security of proof-of-work and proof-of-stake

In Essay 8, we investigate the formal security of PoW and PoS blockchain protocols. While security is at the core of blockchain applications, many mistakenly directly equate blockchain with immutability, integrity, and availability without recognizing the underlying complexities. In reality, consensus security depends on a multitude of design choices that influence a variety of security properties (Butijn et al. 2021). While prior research has analyzed specific consensus mechanisms in depth or compared a broad set of mechanisms at a high level (e.g., Singh et al. 2022; Yadav et al. 2023), no comparison of consensus protocols with regard to a holistic set of formal security properties exists. To address this gap, we conduct a SLR (Kitchenham and Charters 2007), providing the first structured analysis of security properties of the two most popular consensus mechanisms for permissionless blockchains: PoW and PoS.

First, we identify and categorize key security properties, in part underlying established consensus security theorems such as the Fischer-Lynch-Paterson (FLP) impossibility theorem (Fischer et al. 1985) and the consistency, availability, and partition tolerance (CAP) theorem (Brewer 2000), from the literature: safety, liveness, common prefix, finality, and dynamic availability. Subsequently we survey the existing consensus constructions and systematically analyze how different PoW and PoS designs impact these properties. For PoW, security is inherently linked to the cost of mining, making attacks such as selfish mining, block withholding, and majority attacks costly but not impossible. PoS, in contrast, faces unique challenges such as long-range attacks, nothing-at-stake problems, and grinding attacks, which require additional cryptographic or game-theoretic safeguards, such as stake slashing and checkpointing mechanisms. A central finding of our study is that the dual-ledger approach in modern PoS implementations, e.g., last message-driven greedy heaviest-observed sub-tree (LMD GHOST), helps overcome key trade-offs between safety and liveness, offering an alternative to PoW while maintaining strong security guarantees.

Our findings challenge the widespread assumption that PoW inherently provides superior security, showing that PoS can emulate nearly all formal security properties of PoW when designed correctly. While PoS introduces additional complexity, such as the need for BFT-style finality gadgets or randomized leader elections, it does not exhibit the centralization tendencies often attributed to the economic security model of PoW (Arnosti and Weinberg 2022). The contributions of our essay are two-fold: 1) it provides a holistic security framework for evaluating blockchain consensus mechanisms, serving as a foundation for future research and 2) it advises blockchain developers, policymakers, and researchers on the nuanced differences between PoW and PoS across the broad spectrum of security properties, enabling them to make informed decisions tailored to their specific application.

5.9 Essay 9: Maximal extractable value: Current understanding, categorization, and open research questions

In Essay 9, we investigate MEV, which has become a significant phenomenon in DeFi, with validators extracting values surpassing $1 billion from users transactions (Chi et al. 2024). These exploits undermine market efficiency, fairness, and security, creating adverse conditions for blockchain-based applications (Daian et al. 2020). While previous research has explored specific manifestations of MEV, such as front-running (Eskandari et al. 2020) and sandwich attacks (Chi et al. 2024), a comprehensive categorization of MEV, especially from an IS perspective concerned with the operating principles, affected applications, and mitigation strategies is missing. To address this gap, we conducted a MLR (Garousi et al. 2016), bridging both academic and practitioners driven insights to establish a holistic definition of MEV and identify the various ways in which it manifests across different blockchain applications.

By systematically coding the literature, we establish a definition of MEV that is as specific as possible while being consistent with the majority of papers: "Miner or maximal extractable value (MEV) corresponds to the value that can be extracted on a blockchain by miners and other stakeholders at the cost of users by leveraging control of transaction inclusion, exclusion, or ordering in a block" (Gramlich, Jelito and Sedlmeir 2024, p. 6). We establish four MEV categories from the literature and structure our analysis accordingly: 1) Front-running, where attackers place transactions ahead of others, e.g., to exploit arbitrage before others do, 2) Back-running, where transactions are inserted after other transactions, e.g., after large trades to benefit from price fluctuations, 3) Sandwich attacks, combining both front- and back-running, e.g., to exploit price slippage on AMMs, and 4) Suppression attacks, where transactions are deliberately excluded, e.g., to manipulate outcomes of lotteries. There are many different approaches aimed at mitigating MEV from an economic, e.g., proposer-builder separation (PBS) (Bahrani et al. 2024), a technical, e.g., commit-reveal schemes (Arulprakash and Jebakumar 2022), and a regulatory perspective, e.g., legally classifying MEV as market abuse (European Securities and Markets Authority 2024). However, our analysis shows that they are very specific and not generally applicable to mitigate all forms of MEV for all blockchain applications.

Our research provides three key contributions. First, we establish a structured framework for understanding MEV, offering the first consolidated definition and classification of MEV types. Second, we contribute to blockchain research by illustrating fundamental categories and operating principles. Furthermore, we showcase that MEV is not exclusive to DeFi but may pose risks to broader blockchain-based applications widely investigated in the domain of IS research, e.g., event-ticketing (Regner et al. 2019) or interorganizational information sharing (Bossler et al. 2024). Third, we outline open RQs and mitigation strategies, urging researchers and practitioners to consider MEV when designing blockchain-based systems and laying the groundwork for future research that is vital for blockchain technology.

5.10 Essay 10: The adverse effect of privacy calculus on signaling and how zero-knowledge proofs can mitigate it

In Essay 10, we examine the fundamental trade-off between information sharing and data privacy and the potentials of ZKPs in balancing this trade-off. On the one hand, information asymmetries can lead to inefficiencies and market failure (Akerlof 1970), highlighting the importance of information sharing e.g., through signaling, to enhance market efficiency, trust, and decision-making (Spence 1973). On the other hand, considering data privacy, i.e., weighing up the pros and cons of information disclosure in the form of privacy calculus, is essential for protecting individuals and businesses from misuse, discrimination, and security risks (Dinev 2014). While prior research has extensively studied signaling theory to address information asymmetries and privacy calculus to model how individuals weigh the risks and benefits of disclosure, no work has yet amalgamated these two theoretical models (Benndorf et al. 2015; Connelly et al. 2011). Moreover, ZKPs present themselves as a promising cryptographic tool to balance this trade-off, yet their potential in the context of signaling has hardly been explored yet (Chod et al. 2020). To fill this gap, we extend the traditional game-theoretic signaling model by incorporating privacy calculus and empirically validating its findings through a survey experiment, demonstrating the potential of ZKPs to mitigate privacy concerns and increase the effectiveness of signaling mechanisms.

Our results establish a new signaling model with integrated privacy calculus, showing that privacy concerns increase signaling costs, reducing the benefits of signaling for sender and receiver. If the privacy cost of signaling is too high, senders may opt for non-disclosure, changing separating into pooling equilibria and leading to a deterioration of the signaling mechanism. Our survey experiment validates these theoretical findings, demonstrating that participants perceive privacy concerns when disclosing information through signaling, requiring them to have a higher benefit from partaking.

However, when ZKPs are used instead of direct disclosure of the underlying information, these privacy concerns are significantly reduced, increasing the likelihood of effective signaling. The results not only validate our theoretical model of a signaling game with integrated privacy calculus but also showcase that ZKPs allow individuals to share verifiable information while maintaining confidentiality, thereby restoring the efficiency of the signaling mechanism.

Our study makes three key contributions. First, we bridge signaling theory and privacy calculus, providing a unified theoretical model that explains how privacy concerns influence signaling behavior. Second, our newly established model highlights the potential of ZKPs in improving the effectiveness of signaling by reducing privacy concerns, opening the path for future research on incorporating ZKPs into signaling mechanisms. Third, we provide empirical evidence through a behavioral experiment, validating the new theoretical model and the potential of ZKPs to mitigate privacy concerns. With this, we provide an empirically sound fundament for future research both on the role of privacy calculus and the potential of ZKPs to mitigate adverse effects of privacy concerns in signaling or information disclosure in general.

6 Discussion and conclusion

To close the introductory chapter of this dissertation, I first recap the main insights from my 10 Essays (Section 6.1). I then elaborate on the theoretical contributions and practical implications of the individual essays, as well as their aggregated insights regarding the three RGs and the overarching research objective (Section 6.2). Subsequently, I critically reflect on the limitations of the individual essays and the dissertation as a whole (Subsection 6.3) and conclude by outlining promising directions for future research (Subsection 6.4).

6.1 Summary

The overarching research objective of my dissertation was to explore and leverage the potentials of blockchain-based financial systems. To achieve this, I structured my research around three core RGs: RG1) understanding the challenges and leveraging the potential of DeFi, RG2) exploring the usage of blockchain in TradFi, and RG3) investigating general blockchain challenges and solution approaches. To fully capture the multidisciplinary facets of the field, I employed a variety of research designs, including SLR or MLR, DSR, game-theoretical modeling, and empirical survey studies.

The dissertation consists of 10 essays, each addressing a specific RQ within the scope of the three RGs. The first essay provides a MLR of decentralized finance, synthesizing existing research and identifying gaps that future work must address. Building upon the insights of Essay 1, especially the recognized need for RWAs in DeFi that can reduce its dependency on cryptocurrency and foster broader adoption, I investigate the tokenization of different assets in Essays 2-4. In Essay 2, we develop shielded, fractionalizable NFTs for carbon emission. This concept shows how blockchain-based tokenization can enable traceability and verifiability. Furthermore, the paper highlights the importance of ZKPs in combining these properties with privacy-preservation that is especially important in this application, that centers around personal and business sensitive data. Complementing this, Essay 3 explores bond tokenization, demonstrating how blockchain can reduce transaction costs in corporate bond markets. In Essay 4, we developed a framework for real estate tokenization, proposing a design and DPs particularly focused on a full-fledged integration of the asset class and its different product types into the DeFi ecosystem.

For Essays 5 and 6, I shifted my research focus to financial applications in TradFi, that typically exhibit strong centralized control. In Essay 5 we investigated CBDCs, presenting a structured analysis of VPs for private organizations and how they can fulfill essential needs for a successful CBDC ecosystem. Addressing blockchain's role in taxation, Essay 6 proposes a token-based framework to prevent tax fraud, leveraging the insights on ZKPs obtained in Essay 2 to balance transparency and privacy in tax reporting, another application that strongly involves personal and business sensitive data.

Throughout my research on a diverse set of financial blockchain applications, I also identified a broad set of underlying technological, application-agnostic challenges, some of which I investigated in Essays 7-10. Essay 7 assesses blockchain electricity consumption, systematically categorizing the energy implications of different consensus mechanisms and highlighting stark difference between PoW and PoS and the currently missing holistic view on the different participant groups within a blockchain network. Essay 8 provides a formal security analysis of PoW and PoS, offering a structured comparison of their security properties and demonstrating how PoS, with some more complex ledger designs, can emulate PoW's security guarantees. Complementing the formal security of blockchain, Essay 9 investigates MEV as an important aspect of game-theoretic security, categorizing its various forms and evaluating potential countermeasures. Finally, Essay 10 integrates signaling theory with privacy calculus, showing how ZKPs can mitigate privacy concerns in signaling games, thus extending the contributions of Essays 2 and 6 by offering a broader perspective on the potentials of ZKPs within blockchains and beyond.

6.2 Contributions to theory and implications for practice

This dissertation makes significant theoretical and practical contributions to the domains of blockchain-based financial systems and blockchain-based IS in general. These stem both from the individual essays and their cumulated insights answering my three RGs and the overarching research objective of my dissertation.

The first four essays contribute to RG1, examining the potential and challenges DeFi as an open, permissionless blockchain-based financial system. Essay 1 provides fundament both for my and other researchers' study of DeFi by consolidating existing, fragmented academic and grey DeFi literature, highlighting key issues such as real-world applicability, regulatory uncertainty, security risks, and scalability limitations, and setting a structured agenda for future studies. Essay 2 – 4 aim to fill one of the most critical gaps identified by the MLR of Essay 1: the underrepresentation of RWAs in DeFi, in particular carbon emission certificates (Essay 2), bonds (Essay 3), and real estate (Essay 4). All three essays provide comprehensive frameworks for practitioners to leverage for RWA tokenization of the specific asset class. Furthermore, Essay 2 highlights the importance of privacy in blockchain applications, encompassing personal or business-sensitive information and further advances the research stream on ZKP application in blockchain-based IS (Sedlmeir et al. 2022). Essay 3 further contributes to blockchain research by introducing TAC theory as a suitable lens to evaluate and providing design knowledge in the form of DPs on how to utilize blockchain technology to minimize TAC (Ahluwalia et al. 2020; Schmidt and Wagner 2019). Finally, the design and the DPs developed in Essay 4 guide academics and practitioners in successfully integrating assets into DeFi, highlighting the importance of all-encompassing reproduction of the regulatory certainty and product variety, especially for such complex asset class like real estate (Hanneke et al. 2024; Sunyaev et al. 2021). Together, these essays illustrate both the transformative potential and inherent limitations of DeFi. They showcase that while blockchain can enable a more open, transparent, and efficient financial system, fully leveraging its potential requires careful consideration of the requirements of different asset classes, especially regarding suitable regulatory frameworks, efficient implementation of key functionalities, representation of the whole product variety, and data privacy.

Addressing RG2, Essays 5 and 6 investigate how blockchain can enhance TradFi that exhibit strong institutional control. Essay 5 informs both practitioners, e.g., policymakers and financial institutions, and researchers on how private-sector collaboration can drive CBDC adoption and efficiency. However, the MLR also highlights the discrepancy between academic design propositions often incorporating blockchain technology (Zhang and Huang 2022) and practitioner-driven endeavors mostly using centralized ledger models (Di Iorio et al. 2024). Essay 6 investigates tax fraud under the theoretical lens of PAT, proposing a blockchain-based IS leveraging ZKPs to combat the PAP by preventing moral hazard while minimizing agency costs and preserving privacy. The contributions of this research, manifested in the derived DPs, pertain to both the utilization of blockchain technology in the context of PAT (Hyvärinen et al. 2017) and further advancing the research stream of applying ZKPs in the context of blockchain technology (Principato et al. 2023; Sedlmeir et al. 2022). Together, these two essays provide a more accurate assessment of the possibilities of blockchain technology in the context of traditional, rather centralized financial systems: While blockchain can provide benefits in the right context, e.g., in the case of an PAP like in taxation, blockchain usage is not an end in itself and its meaningfulness needs to be critically evaluated in the specific context. This assessment not only guides practitioners but also advances the academic discourse on the viability of permissioned blockchain applications (Fridgen et al. 2021; O'Leary 2023).

Essays 7-10 address RG3, exploring some of the broad variety of application-agnostic technological, economic, or security challenges for blockchain adoption in more detail. By illustrating the major differences in electricity consumption of different blockchain designs, Essay 7 conveys a more holistic understanding of blockchain electricity consumption to both the general public and researchers, combatting the myth that blockchain is always associated with tremendous electricity consumption (Mora et al. 2018) and broadening the understanding of the driving factors (Rieger et al. 2022; Sai and Vranken 2024). Essay 8 provides more clarity on the formal security of PoW and PoS consensus mechanisms, systematically evaluating their security guarantees and demonstrating that PoS can almost completely replicate PoW's security properties. By embedding blockchain properties into existing formal security theorems such as CAP (Brewer 2000) and FLP (Fischer et al. 1985), it advances both blockchain and general computer science research. Essay 9 pursues another field of blockchain security, i.e., game theory and mechanism design (Daian et al. 2020), by categorizing the different forms of MEV and assessing their impact on market fairness, efficiency, and stability. Finally, Essay 10 integrates signaling theory with privacy calculus, showing how ZKPs can mitigate privacy concerns while preserving verifiability, thereby advancing the literature streams on signaling (Connelly et al. 2011), privacy calculus (Dinev 2014), and ZKP's potential to mitigate the negative effects of privacy concerns (Benndorf et al. 2015). All four essays, structure and advance the existing understanding of the respective blockchain challenge under investigation, i.e., electricity consumption (Essay 7), formal (Essay 8) or game theoretical security (Essay 9), enabling both verifiability and privacy through ZKPs (Essay 10). As such they collectively enable researchers and practitioners to make better-informed decisions and design choices in the adoption or development of new blockchain applications. They furthermore highlight the multi-facedness of the research stream, its challenges, and possible solutions to them, incentivizing active participation from different domains ranging computer science, IS, economics, and social and legal sciences.

Beyond the individual contributions of the essays, the dissertation as a whole provides a comprehensive and interconnected assessment of blockchain-based financial systems, their different application areas, and their underlying challenges. From a theoretical standpoint, it mainly advances research on blockchain in many different subareas, especially financial applications. However, the dissertation also contributes to broader research fields such as IS, economics, and computer science by investigating blockchain and its application under existing theoretical lenses or theorems such as TAC theory (Benston and Smith 1976), PAT (Reinganum und Wilde 1985; Laffont und Martimort 2009), signaling theory (Connelly et al. 2011; Spence 1973), or the CAP (Brewer 2000) and FLP theorem (Fischer et al. 1985). For practitioners, the dissertation provides concrete guidance on designing and implementing blockchain-based financial solutions, including tokenization frameworks, applying ZKPs to mitigate the trade-off between verifiability and data-privacy, and design options for more secure and less resource demanding blockchain designs. By systematically addressing blockchain's role in both DeFi and TradFi, this dissertation fulfills its overarching research objective, presenting a nuanced, multi-faceted perspective on blockchain's role in the future of financial markets. Ultimately, it serves as a foundational resource for researchers, policymakers, and industry leaders seeking to harness blockchain technology while navigating its complex economic, regulatory, and technical challenges.

6.3 Limitations

Exploring blockchain-based financial systems presents inherent challenges due to their complexity, multi-faceted nature, and rapid evolution across technological, economic, societal, and regulatory dimensions (Beck et al. 2017; Rossi et al. 2019). This dissertation highlights these challenges, demonstrating that blockchain finance is not a static field but one shaped by continuous innovation and external influences. While each essay within this dissertation has specific constraints that are acknowledged in their respective discussions, this section aims to abstract these constraints into overarching limitations of my dissertation as a whole.

One key limitation stems from the rapid advancement of blockchain technology, which can render certain technological assumptions or benchmarks outdated over time. For instance, in Essay 2, benchmarking ZKP generation time demonstrating the practical feasibility under the current technological state-of-the-art, yet these figures may further improve due to advances in hardware or algorithm design (Principato et al. 2023). Similarly, the prototypes implemented in Essays 3 and 4 were based on the most popular blockchain framework at the time of research, the EVM. While these prototypes were primarily used to demonstrate and validate the design, evolving blockchain infrastructures could alter the implementation details, potentially affecting the direct transferability of findings. However, since the main artifacts of the essays were conceptual architectures and generalized design knowledge in the form of DPs, the core contribution is likely to remain intact, even if the underlying technology keeps evolving (Gregor and Hevner 2013).

Beyond technological evolution, blockchain-based financial systems are also highly dynamic in terms of application development, regulatory frameworks, and shifting economic or societal factors (Gramlich et al. 2023; Risius and Spohrer 2017). This creates an inherent limitation, especially for literature reviews, as they capture the state of knowledge at a specific point in time but may not fully reflect subsequent developments, such as new applications or regulatory frameworks (Webster and Watson 2002). However, the establishment of common definitions, consolidation of the state-of-the-art within existing or new research frameworks, and development agendas for future research present an important fundament for the future development of the research stream (vom Brocke et al. 2015). In the DSR papers, certain design options were dismissed due to current feasibility constraints, e.g., the use of blockchain-based securities registries and settlement in Essay 6, but may become viable in the future. For example, regulatory actions such as the German electronic securities law (BaFin 2021) and the EU-DLT Pilot Regime (ESMA 2023) suggest that blockchain integration into traditional financial systems is progressing, potentially unlocking new pathways for further improvements to the proposed designs.

A further limitation of this dissertation lies in the predominantly conceptual and qualitative nature of the designed frameworks. While prototyping and expert interviews enabled naturalistic validation and quantitative benchmarking, the proposed frameworks have not undergone full-scale real-world implementation (Venable et al. 2016). Field testing the proposed blockchain-based systems in real-world financial environments would provide stronger empirical validation and enable further quantitative assessments of their effectiveness. Real-world deployment could enrich the findings, especially regarding user adoption, which could provide valuable insights into socio-technological aspects that have not been at the center of my research.

6.4 Future research

The overarching goal of this dissertation was to explore the diverse potentials and challenges of blockchain-based financial systems. Each individual essay highlights specific questions for future research. In the following, however, I will focus on the broader research opportunities opened up by the overarching limitations and insights of this dissertation.

One crucial area for future research is the real-world implementation and evaluation of the proposed blockchain designs. While this dissertation provides well-founded conceptual models and prototypes, practical deployments would not only enhance the validity of these studies but also generate new empirical insights. Particularly, leveraging emerging regulatory frameworks such as Germany’s electronic securities law (BaFin 2021) or the European DLT Pilot Regime (ESMA 2023) could provide an opportunity to test blockchain-based financial instruments under real-world regulatory conditions. Such implementations could establish precedents for future legislative development, demonstrating the practical feasibility of blockchain technology and accelerating its proliferation within financial markets. Another particularly interesting technological and regulatory advancements is the adoption of digital identities, e.g., by the European Union (2024), which could further advance the uptake of digital wallets and promote a reliable digital identity system (Babel et al. 2025). These developments could also help mitigate challenges related to technological literacy and reliable identification in blockchain applications (Gramlich et al. 2023; Gramlich, Guggenberger, Principato et al. 2024).

I position interdisciplinary research as a key direction for future research, as bringing together different disciplines is critical to fully address the multi-faceted nature of blockchain-based financial systems. Advancing this field requires collaboration across computer science, IS, economics, and law to leverage potentials and tackle challenges holistically. From a technological standpoint, research should focus on enhancing blockchain scalability and refining privacy-preserving technologies such as ZKPs. Meanwhile, economic research must develop sustainable business models for DeFi applications, tokenized asset markets, and CBDCs, ensuring that blockchain-based financial systems can function efficiently within existing economic structures. Additionally, regulatory scholars and policymakers should investigate governance frameworks that strike a balance between decentralization and regulatory compliance, enabling blockchain adoption without stifling innovation. The role of IS, from my point of view, is to facilitate the intersections of these disciplines by informing economists and legal experts on new advancements from computer science and, vice versa, translating economic or legal demands into technological designs or requirements. Facilitating this exchange will be crucial in shaping a mature, legally compliant, and economically viable blockchain-based financial ecosystem.

Ultimately, blockchain technology has the potential to reshape financial systems, fostering greater transparency, efficiency, and accessibility. However, realizing this potential requires continued research and practical efforts to overcome current challenges and refine existing frameworks. It is my hope that this dissertation has laid the foundation for further research and practical endeavors that contribute to the maturation of blockchain-based financial systems. By fully leveraging the technological affordances of blockchain while ensuring economic viability and regulatory alignment, future research can help shape a robust and sustainable financial ecosystem that integrates the best of decentralized and traditional finance.

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Appendices

Appendix A: Declarations of co-authorship and individual contributions

In the following, I describe the co-authors' contributions to the essays.

Essay 1: A multivocal literature review of decentralized finance: Current knowledge and research agenda

This research paper was co-authored by Vincent Gramlich, Tobias Guggenberger, Marc Principato, Benjamin Schellinger, and Nils Urbach. The co-authors contributed as follows:

Vincent Gramlich (co-author)

Vincent Gramlich co-developed the research project. He contributed by analyzing the results of the literature review, developing the theoretical contribution, and engaging in textual elaboration, especially in the results and discussion section. Additionally, he participated in research discussions and provided feedback on the paper's content and structure. Thus, Vincent Gramlich's co-authorship is reflected in the entire research project.

Tobias Guggenberger (co-author)

Tobias Guggenberger co-initiated and co-developed the research project. He contributed by developing the paper's theoretical foundation, analyzing the results of the literature review, developing the theoretical contribution, and engaging in textual elaboration, especially in the introduction, conceptual background, method, discussion, and conclusion section. Additionally, he participated in research discussions and provided feedback on the paper's content and structure. Thus, Tobias Guggenberger's co-authorship is reflected in the entire research project.

Marc Principato (co-author)

Marc Principato co-developed the research project. He contributed by developing the paper's theoretical foundation, analyzing the results of the literature review, developing the open research agenda, developing the theoretical contribution, and engaging in textual elaboration, especially in the conceptual background, method, results, discussion, and conclusion section. Additionally, he participated in research discussions. Thus, Marc Principato's co-authorship is reflected in the entire research project.

Benjamin Schellinger (co-author)

Benjamin Schellinger co-initiated and co-developed the research project. He contributed by developing the paper's theoretical foundation, analyzing the results of the literature review, developing the theoretical contribution, and engaging in textual elaboration, especially in the introduction, conceptual background, results, discussion, and conclusion section. Additionally, he participated in research discussions and provided feedback on the paper's content and structure. Thus, Benjamin Schellinger's co-authorship is reflected in the entire research project.

Nils Urbach (subordinate co-author)

Nils Urbach supervised the research project and provided mentorship. Further, he participated in research discussions, provided feedback on the paper's content and structure, and engaged in textual elaboration. Thus, Nils Urbach's co-authorship is reflected in the entire research project.

Essay 2: Enabling end-to-end digital carbon emission tracing with shielded NFTs

This research paper was co-authored by Matthias Babel, Vincent Gramlich, Marc-Fabian Körner, Johannes Sedlmeir, Jens Strüker, and Till Zwede. The co-authors contributed as follows:

Matthias Babel (co-author)

Matthias Babel co-developed the research project. He contributed by analyzing the paper's theoretical and technical foundation, developing the concept of the solution artifact, implementing the prototype, and engaging in textual elaboration. Additionally, he participated in research discussions and provided feedback on the paper's content and structure. Thus, Matthias Babel's co-authorship is reflected in the entire research project.

Vincent Gramlich (co-author)

Vincent Gramlich co-developed the research project. He contributed by analyzing the paper's theoretical and technical foundation, developing the concept of the solution artifact, implementing the prototype, and engaging in textual elaboration. Additionally, he participated in research discussions and provided feedback on the paper's content and structure. Thus, Vincent Gramlich's co-authorship is reflected in the entire research project.

Marc-Fabian Körner (co-author)

Marc-Fabian Körner co-developed the research project and provided mentorship. He contributed by analyzing the paper's theoretical foundation and engaging in textual elaboration. Additionally, he participated in research discussions and provided feedback on the paper's content and structure. Thus, Marc-Fabian Körner's co-authorship is reflected in the entire research project.

Johannes Sedlmeir (co-author)

Johannes Sedlmeir co-developed the research project. He contributed by analyzing the paper's theoretical and technical foundation, developing the concept of the solution artifact, and engaging in textual elaboration. Additionally, he participated in research discussions and provided feedback on the paper's content and structure. Thus, Johannes Sedlmeir's co-authorship is reflected in the entire research project.

Jens Strüker (co-author)

Jens Strüker supervised the research project and provided mentorship. Further, he participated in research discussions, provided feedback on the paper's content and structure, and engaged in textual elaboration. Thus, Jens Strüker's co-authorship is reflected in the entire research project.

Till Zwede (co-author)

Till Zwede co-developed the research project. He contributed by analyzing the paper's theoretical and technical foundation, developing the concept of the solution artifact, and engaging in textual elaboration. Additionally, he participated in research discussions and provided feedback on the paper's content and structure. Thus, Till Zwede's co-authorship is reflected in the entire research project.

Essay 3: Designing the future of bond markets: Reducing transaction costs through tokenization

This research paper was co-authored by David Cisar, Benjamin Schellinger, Jens-Christian Stoetzer, Nils Urbach, Florian Lennart Weiß, Vincent Gramlich, and Tobias Guggenberger. The co-authors contributed as follows:

David Cisar (co-author)

David Cisar initiated and co-developed the research project and key artifact. He contributed by developing the paper's methodological approach. Jointly with the other authors, he developed and evaluated the artifact. He was responsible for writing parts of the original draft and was involved in reviewing and editing the entire paper. Thus, David Cisar's co-authorship is reflected in the entire research project.

Benjamin Schellinger (co-author)

Benjamin Schellinger initiated and co-developed the research project. He contributed by developing the paper's theoretical foundation and curating the methodological approach. Jointly with the other authors, he developed and evaluated the artifact. He was involved in reviewing and editing the entire paper. Thus, Benjamin Schellinger's co-authorship is reflected in the entire research project.

Jens-Christian Stoetzer (co-author)

Jens-Christian Stoetzer co-developed the research project. He contributed by developing the paper's theoretical foundation and curating the findings of the paper. Further, he was responsible for data collection. Jointly with the other authors, he developed and evaluated the artifact. He was responsible for writing parts of the original draft and was involved in reviewing and editing the entire paper. Thus, Jens-Christian Stoetzer's co-authorship is reflected in the entire research project.

Nils Urbach (co-author)

Nils Urbach provided mentorship and feedback on the paper's content and structure. Jointly with the other authors, he developed and evaluated the artifact. He also engaged in the textual elaboration with respect to reviewing and editing of the entire manuscript over the course of multiple rounds of revisions. Thus, Nils Urbach's co-authorship is reflected in the entire research project.

Florian Lennart Weiß (co-author)

Florian Lennart Weiß co-developed the research project. He contributed to the paper's theoretical foundation and contributed to the data collection. He participated in developing and evaluating the artifact. He was responsible for writing parts of the original draft and was involved in reviewing and editing the entire paper. Thus, Florian Lennart Weiß co-authorship is reflected in the entire research project.

Vincent Gramlich (subordinate author)

Vincent Gramlich provided mentorship and feedback on the paper's content and structure. He also engaged in the textual elaboration with respect to reviewing and editing of the entire manuscript over the course of the initial submission. He contributed as subordinate author of the research paper. Thus, Vincent Gramlich's co-authorship is reflected in the entire research project.

Tobias Guggenberger (subordinate author)

Tobias Guggenberger provided mentorship and feedback on the paper's content and structure. He also engaged in the textual elaboration with respect to reviewing and editing of the entire manuscript over the course of the initial submission. He contributed as subordinate author of the research paper. Thus, Tobias Guggenberger's co-authorship is reflected in the entire research project.

Essay 4: From bricks to blocks: Designing a framework for the tokenization of real estate for DeFi

This research paper was co-authored by Tobias Kranz, Vincent Schaaf, Tobias Guggenberger, and Jens Strüker. The co-authors contributed as follows:

Tobias Kranz (co-author)

Tobias Kranz initiated and co-developed the research project. He contributed by establishing design objectives, designing and implementing the tokenization framework, conducting and analyzing the evaluation interviews, and developing the theoretical contribution in the form of design principles. Additionally, he engaged in textual elaboration, participated in research discussions and provided feedback on the paper's content and structure. Thus, Tobias Kranz's co-authorship is reflected in the entire research project.

Vincent Schaaf (co-author)

Vincent Schaaf co-developed the research project. He contributed by constructing the motivation of the paper, restructuring the meta-requirements and design objectives, developing the theoretical contribution, and refining the discussion with existing literature. Additionally, he engaged in textual elaboration, participated in research discussions and provided feedback on the paper's content and structure. Thus, Vincent Schaaf's co-authorship is reflected in the entire research project.

Tobias Guggenberger (subordinate co-author)

Tobias Guggenberger supervised the research project and provided mentorship. Further, he participated in research discussions, helped refine the paper's motivation, design objectives and design principles, and provided feedback on the paper's content and structure. Thus, Tobias Guggenberger's co-authorship is reflected in the entire research project.

Jens Strüker (subordinate co-author)

Jens Strüker supervised the research project and provided mentorship. Further, he participated in research discussions and provided feedback on the paper's content and structure. Thus, Jens Strüker's co-authorship is reflected in the entire research project.

Essay 5: A multivocal literature review on capturing value propositions for private organizations in a CBDC ecosystem

This research paper was co-authored by Vincent Schaaf, Jonathan Lautenschlager, Hannes Voucko-Glockner, Tobias Plank, Tobias Guggenberger, and Nils Urbach. The co-authors contributed as follows:

Vincent Schaaf (co-author)

Vincent Schaaf co-developed the research project. He contributed by structuring the results of the literature review, developing the motivation and theoretical contribution of the paper. Additionally, he engaged in textual elaboration, participated in research discussions and provided feedback on the paper's content and structure. Thus, Vincent Schaaf's co-authorship is reflected in the entire research project.

Jonathan Lautenschlager (co-author)

Jonathan Lautenschlager co-developed the research project. He contributed by structuring the results of the literature review, developing the motivation and theoretical contribution of the paper. Additionally, he engaged in textual elaboration, participated in research discussions and provided feedback on the paper's content and structure. Thus, Jonathan Lautenschlager's co-authorship is reflected in the entire research project.

Hannes Voucko-Glockner (co-author)

Hannes Voucko-Glockner co-initiated and co-developed the research project. He contributed by conducting the literature review, analyzing the results, and deriving avenues for future research. Additionally, he engaged in textual elaboration, participated in research discussions and provided feedback on the paper's content and structure. Thus, Hannes Voucko-Glockner's co-authorship is reflected in the entire research project.

Tobias Plank (co-author)

Tobias Plank co-initiated and co-developed the research project. He contributed by conducting the literature review, analyzing the results, and deriving avenues for future research. Additionally, he engaged in textual elaboration, participated in research discussions and provided feedback on the paper's content and structure. Thus, Tobias Plank's co-authorship is reflected in the entire research project.

Tobias Guggenberger (subordinate co-author)

Tobias Guggenberger supervised the research project and provided mentorship. Further, he participated in research discussions, provided feedback on the paper's content and structure, and engaged in textual elaboration. Thus, Tobias Guggenberger's co-authorship is reflected in the entire research project.

Nils Urbach (subordinate co-author)

Nils Urbach supervised the research project and provided mentorship. Further, he participated in research discussions, provided feedback on the paper's content and structure, and engaged in textual elaboration. Thus, Nils Urbach's co-authorship is reflected in the entire research project.

Essay 6: Tokens against tax-fraud: Utilizing blockchain technology in the principal-agent dynamics of federated tax systems

This research paper was co-authored by Vincent Schaaf, Jan Stramm, Tobias Guggenberger, Marc-Fabian Körner, and Nils Urbach. The co-authors contributed as follows:

Vincent Schaaf (co-author)

Vincent Schaaf co-initiated and co-developed the research project. He contributed by conducting the expert workshops and interviews that established the design requirements and evaluation, developed the framework and the theoretical embedding and contribution of the paper. Additionally, he engaged in textual elaboration, participated in research discussions and provided feedback on the paper's content and structure. Thus, Vincent Schaaf's co-authorship is reflected in the entire research project.

Jan Stramm (co-author)

Jan Stramm co-developed the research project. He contributed by conducting the expert interviews to evaluate the artefact evaluation and developed the theoretical embedding and contribution of the paper. Additionally, he engaged in textual elaboration, participated in research discussions and provided feedback on the paper's content and structure. Thus, Jan Stramm's co-authorship is reflected in the entire research project.

Tobias Guggenberger (co-author)

Tobias Guggenberger co-initiated and co-developed the research project. He participated in research discussions, helped in refining the paper's theoretical embedding and contribution, and provided feedback on the paper's content and structure. Thus, Tobias Guggenberger's co-authorship is reflected in the entire research project.

Marc-Fabian Körner (co-author)

Marc-Fabian Körner co-developed the research project. He participated in research discussions, helped in refining the paper's theoretical embedding and contribution, and provided feedback on the paper's content and structure. Thus, Marc-Fabian Körner's co-authorship is reflected in the entire research project.

Nils Urbach (co-author)

Nils Urbach supervised the research project and provided mentorship. Further, he participated in research discussions and provided feedback on the paper's content and structure. Thus, Nils Urbach's co-authorship is reflected in the entire research project.

Essay 7: Towards a holistic perspective on blockchain electricity consumption

This research paper was co-authored by Vincent Gramlich, Tobias Guggenberger, Felix Paetzold, Johannes Sedlmeir, and Jens Strüker. The co-authors contributed as follows:

Vincent Gramlich (co-author)

Vincent Gramlich co-initiated and co-developed the research project. He contributed by conducting the literature review, analyzing the results, and developing the theoretical contribution. Additionally, he engaged in textual elaboration, participated in research discussions and provided feedback on the paper's content and structure. Thus, Vincent Gramlich's co-authorship is reflected in the entire research project.

Tobias Guggenberger (co-author)

Tobias Guggenberger co-developed the research project. He contributed by developing the paper's theoretical foundation and contribution. Additionally, he engaged in textual elaboration, participated in research discussions and provided feedback on the paper's content and structure. Thus, Tobias Guggenberger's co-authorship is reflected in the entire research project.

Felix Paetzold (co-author)

Felix Paetzold co-initiated and co-developed the research project. He contributed by conducting the literature review, analyzing the results, and developing the theoretical contribution. Additionally, he engaged in textual elaboration, participated in research discussions and provided feedback on the paper's content and structure. Thus, Felix Paetzold's co-authorship is reflected in the entire research project.

Johannes Sedlmeir (co-author)

Johannes Sedlmeir co-initiated and co-developed the research project. He contributed by developing the paper's theoretical foundation and contribution. Additionally, he engaged in textual elaboration, participated in research discussions and provided feedback on the paper's content and structure. Thus, Johannes Sedlmeir's co-authorship is reflected in the entire research project.

Jens Strüker (subordinate co-author)

Jens Strüker supervised the research project and provided mentorship. Further, he participated in research discussions, provided feedback on the paper's content and structure, and engaged in textual elaboration. Thus, Jens Strüker's co-authorship is reflected in the entire research project.

Essay 8: Unsealing the secrets of blockchain consensus: A systematic comparison of the formal security of proof-of-work and proof-of-stake

This research paper was co-authored by Iván Abellán Álvarez, Vincent Gramlich, and Johannes Sedlmeir. The co-authors contributed as follows:

Iván Abellán Álvarez (co-author)

Iván Abellán Álvarez co-initiated and co-developed the research project. He contributed by conducting the literature review, analyzing and structuring the results, and discussing the paper's contribution. Additionally, he engaged in textual elaboration, participated in research discussions and provided feedback on the paper's content and structure. Thus, Iván Abellán Álvarez's co-authorship is reflected in the entire research project.

Vincent Gramlich (co-author)

Vincent Gramlich co-initiated and co-developed the research project. He contributed by structuring the results and developing the theoretical motivation and contribution of the paper. Additionally, he engaged in textual elaboration, participated in research discussions and provided feedback on the paper's content and structure. Thus, Vincent Gramlich's co-authorship is reflected in the entire research project.

Johannes Sedlmeir (co-author)

Johannes Sedlmeir co-initiated and co-developed the research project. He contributed by structuring the results and developing the theoretical motivation and contribution of the paper. Additionally, he engaged in textual elaboration, participated in research discussions and provided feedback on the paper's content and structure. Thus, Johannes Sedlmeir's co-authorship is reflected in the entire research project.

Essay 9: Maximal extractable value: Current understanding, categorization, and open research questions

This research paper was co-authored by Vincent Gramlich, Dennis Jelito, Johannes Sedlmeir. The co-authors contributed as follows:

Vincent Gramlich (leading co-author)

Vincent Gramlich initiated and led the development of the research project. He contributed by analyzing the paper's literature data set, developing the structure of the literature review, and engaging in textual elaboration. Additionally, he participated in research discussions, provided feedback on the paper's content and structure, and managed the revision of the manuscript. Thus, Vincent Gramlich led the entire research project.

Dennis Jelito (subordinate co-author)

Dennis Jelito co-developed the research project. He contributed by collecting and analyzing the paper's literature data set, developing the structure of the literature review, and engaging in textual elaboration. Additionally, he participated in research discussions and provided feedback on the paper's content and structure. Thus, Dennis Jelito's co-authorship is reflected in the entire research project.

Johannes Sedlmeir (subordinate co-author)

Johannes Sedlmeir joined the ongoing research project and provided guidance and mentorship. He engaged in textual elaboration, participated in research discussions, and provided feedback on the paper's content and structure. Thus, Johannes Sedlmeir's co-authorship is mainly reflected in the restructuring and refinement of the paper.

Essay 10: The adverse effect of privacy calculus on signaling and how zero-knowledge proofs can mitigate it

This research paper was co-authored by Marc Principato, Vincent Schaaf, Tobias Guggenberger, and Nils Urbach. The co-authors contributed as follows:

Marc Principato (co-author)

Marc Principato initiated and co-developed the research project. He contributed by developing the paper's theoretical foundation, conducting and evaluating the survey, and developing the theoretical contribution. Additionally, he engaged in textual elaboration and participated in research discussions. Thus, Marc Principato's co-authorship is reflected in the entire research project.

Vincent Schaaf (co-author)

Vincent Schaaf co-developed the research project. He contributed by developing and revising the paper's theoretical foundation, evaluating the survey, and developing the theoretical contribution. Additionally, he engaged in textual elaboration, participated in research discussions, and provided feedback on the paper's content and structure. Thus, Vincent Schaaf's co-authorship is reflected in the entire research project.

Tobias Guggenberger (co-author)

Tobias Guggenberger co-developed the research project. He contributed by revising the paper's theoretical foundation and developing the theoretical contribution. Additionally, he engaged in textual elaboration, participated in research discussions, and provided feedback on the paper's content and structure. Thus, Tobias Guggenberger's co-authorship is reflected in the entire research project.

Nils Urbach (co-author)

Nils Urbach supervised the research project and provided mentorship. Further, he participated in research discussions, provided feedback on the paper's content and structure, and engaged in textual elaboration. Thus, Nils Urbach's co-authorship is reflected in the entire research project.

Appendix B: Other publications

Table 2: Overview of other publications

Reference	Titel	Publication Type	Outlet/Publisher
Gramlich and Urbach (2022)	Wie das Taproot-Upgrade das Bitcoin Netzwerk verändert	Professional Journal	Recht der Zahlungsdienste
Gramlich, Principato, Schel-linger, Sedlmeir, Amend et al. (2022)	Decentralized Finance (DeFi) Foundations, Applications, Po-tentials, and Challenges	Whitepaper	Fraunhofer FIT
Gramlich, Principato, Schel-linger, Sedlmeir and Urbach (2022)	Decentralized Finance - The rise of a new paradigm	Professional Journal	Rethinking Finance
Babel et al. (2023)	Trust through digital identifica-tion: On SSI's contribution to the integration of decentralized ora-cles in information systems	Peer-Reviewed Journal	HMD Praxis der Wirtschafts-informatik (VHB 2024 – C)
Cop-penholle et al. (2023)	SSI in the Energy sector: A study	Study	Elia Group
Skaurad-szun et al. (2023)	Zur Auswirkung eines Stakings auf die Rechtsposition der Kun-den im Falle der Insolvenz des Kryptoverwahrers	Peer-Reviewed Journal	Zeitschrift für Bankrecht und Bankwirtschaft (VHB 2024 – C)
Richard et al. (2023)	Rethinking Blockchain's Electri-city Consumption	Study	German Energy Agency
Gramlich, Guggen-berger, Principato et al. (2024)	In Decentralized Finance No-body Knows You Are a Dog	Peer-Reviewed Conference	Hawaii Interna-tional Confer-ence on System Sciences (VHB 2024 – B)

Reference	Titel	Publication Type	Outlet/Publisher
Gramlich, Guggenberger, Ismer et al. (2024)	Untersuchung zur Eignung der Blockchain-Technologie als Mittel gegen Gestaltungen zur Umgehung der Besteuerung von Dividendenzahlungen	Study	German Federal Ministry of Finance
Gramlich, Guggenberger, Lichtmannecker et al. (2024)	Decentralized Finance and Decentralized Digital Identities: Opportunities and Challenges of Identity Solutions	Book Chapter	Decentralization Technologies – Springer
Gramlich, Körner et al. (2024)	Decentralization Technologies in the Context of ESG Accounting and Reporting	Book Chapter	Decentralization Technologies – Springer
Babel et al. (2024)	On the Energy Consumption of a Decentralized Financial Sector	Book Chapter	Decentralization Technologies – Springer
Gramlich et al. (2025)	Gestaltung von Blockchain-basierten Kryptowertpapierregistern	Anthology Contribution	Tokenized Finance – Mohr Siebeck

A multivocal literature review of decentralized finance: Current knowledge and future research avenues[1]

Authors

Vincent Gramlich, Tobias Guggenberger, Marc Principato, Benjamin Schellinger, Nils Urbach

Abstract

While decentralized finance (DeFi) has the potential to emulate and, indeed, outperform existing financial systems, it remains a complex phenomenon yet to be extensively researched. To make the most of this potential, its practitioners must gain a rigorous understanding of its intricacies, as must information systems (IS) researchers. Against this background, this study uses a multivocal literature review to capture the state of research in DeFi. Thereby, we (1) present a consolidating definition of DeFi as we (2) analyze, synthesize, and discuss the current state of knowledge in the field of DeFi. We do so while adapting the blockchain research framework proposed by (Risius and Spohrer, Business & Information Systems Engineering 59:385–409, 2017). Furthermore, we (3) identify gaps in the literature and indicate future research directions in DeFi. Even though our findings highlight several shortcomings in DeFi that have prevented its widespread adoption, our literature review shows a large consensus on DeFi's many promising features and potential to complement the traditional financial system. To that end, this paper is presented to encourage further research to mitigate the current risks of DeFi, the payoff of which will be an enriched financial ecosystem.

Keywords: Blockchain, Crypto finance, DeFi, Literature review, Research agenda, Smart contracts

[1] This essay has been published as:
Gramlich, V., Guggenberger, T., Principato, M., Schellinger, B., & Urbach, N. (2023). A multivocal literature review of decentralized finance: Current knowledge and future research avenues. Electronic Markets, 33(1), 1–37. https://doi.org/10.1007/s12525-023-00637-4

Enabling end-to-end digital carbon emission tracing with shielded NFTs[2]

Authors

Matthias Babel, Vincent Gramlich, Marc-Fabian Körner, Johannes Sedlmeir, Jens Strüker, and Till Zwede

Abstract

In the energy transition, there is an urgent need for decreasing overall carbon emissions. Against this background, the purposeful and verifiable tracing of emissions in the energy system is a crucial key element for promoting the deep decarbonization towards a net zero emission economy with a market-based approach. Such an effective tracing system requires end-to-end information flows that link carbon sources and sinks while keeping end consumers' and businesses' sensitive data confidential. In this paper, we illustrate how non-fungible tokens with fractional ownership can help to enable such a system, and how zero-knowledge proofs can address the related privacy issues associated with the fine-granular recording of stakeholders' emission data. Thus, we contribute to designing a carbon emission tracing system that satisfies verifiability, distinguishability, fractional ownership, and privacy requirements. We implement a proof-of-concept for our approach and discuss its advantages compared to alternative centralized or decentralized architectures that have been proposed in the past. Based on a technical, data privacy, and economic analysis, we conclude that our approach is a more suitable technical backbone for end-to-end digital carbon emission tracing than previously suggested solutions.

Keywords: Blockchain, Certificate, Decarbonization, Distributed ledger technology, Electric vehicle, Guarantee of origin, Non-fungible token, Personal carbon tracing, Privacy, Sustainability, Zero-knowledge proof

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Designing the future of bond markets: Reducing transaction costs through tokenization[3]

Authors

David Cisar, Benjamin Schellinger, Jens-Christian Stoetzer, Nils Urbach, Florian Lennart Weiß, Vincent Gramlich, Tobias Guggenberger

Abstract

Corporate bonds are an attractive option for corporate financing. However, current bond markets face many challenges and inefficiencies, resulting in high transaction costs (TAC). In recent years, technological advancements like blockchain technology have enabled the possibility of reducing TAC in bond markets. Even though practice experiments with such solutions, academic literature lacks generic design knowledge under the TAC lens to design blockchain-based bonds. Thus, our research follows the design science research (DSR) paradigm to design and develop a bond prototype using the Ethereum blockchain protocol. Our results highlight the capability of blockchain-based bond markets to reduce TAC in the three dimensions of asset specificity, uncertainty, and transaction frequency. Further, our research provides design principles to contribute to both practice and the academic discourse on developing blockchain-based bond markets with reduced TAC.

Keywords: Blockchain, Bonds, Design science research, Transaction cost theory

[3] This essay has been published as:
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From bricks to blocks: Designing a framework for the tokenization of real estate for DeFi

Authors

Tobias Kranz, Vincent Schaaf, Tobias Guggenberger, and Jens Strüker

Extended Abstract

Decentralized Finance (DeFi) has evolved from a fringe experiment to an ecosystem that at its peak in 2022 secured more than $ 180 billion total value locked (TVL), promising an open, programmable alternative to incumbent financial infrastructure. Yet the sector's dependence on volatile crypto-native collateral has repeatedly exposed systemic fragilities, highlighted by a steep decline of over 70% in its TVL caused by the crash of the cryptocurrency market in 2023 (DefiLlama, 2025). One of the main reasons for the struggle of DeFi and its protocols to scale beyond the cryptocurrency market and obtain mainstream adoption is the absence of suitable and efficient wrappers for real-world assets (Gramlich et al., 2023).

Real estate, in contrast to cryptocurrencies, is one of the world's largest and most stable asset classes, worth about $ 19.5 trillion. However, it remains burdened by high entry tickets, long lock-in periods, multi-layer intermediation, and paper-heavy post-trade processes (Baum, 2021). The integration of assets into DeFi through tokenization has been widely suggested to tackle these challenges (Gramlich et al., 2023).While the tokenization is rapidly maturing in other asset classes, e.g., the bond market highlighted by the acquisition of a treasury worth $ 1.23 billion by the DeFi protocol MakerDAO (Sandor, 2023), fewer than 0.02% of real-estate holdings are currently accessible in token form (Prophecy Market Insights, 2023). A tokenization of real estate that obtains mass adoption, however, could represent a double dividend: DeFi gains the stability and familiarity of a tangible asset class, while real estate markets gain the efficiency and programmability of DeFi.

Although several studies have proposed real-estate token solutions (e.g., Kreppmeier et al., 2023), they typically narrow their scope to single jurisdictions or single product types. Furthermore, technical guidance on the efficient implementation of real estate tokens and their effective integration into the DeFi ecosystem is missing. To fill this gap, we seek to answer the following research question:

How to design a tokenization framework for real estate token to enable a fully-fledged integration of real estate into the DeFi ecosystem?

By explicitly targeting previously neglected but important aspects such as diversified product structures, end-to-end compliance, and seamless DeFi connectivity, we seek to close a critical research gap and provide prescriptive guidance for both academics and practitioners.

Methodologically, we follow the six-step design science research process of Peffers et al. (2007) to iteratively build and evaluate an artefact driven by four meta-requirements and nine design objectives. The conceptual architecture maps the complete lifecycle, encompassing the asset, the special purpose vehicle, different types of financial instruments, the tokenization, the distribution, and the investors. Furthermore, we implement the core smart-contract functionalities, extending the ERC-1400 token standards with batch transfers and a gas station network that can cover transaction fees. We perform a naturalistic, summative evaluation (Venable et al., 2016) through two cycles of semi-structured interviews with 12 experts spanning legal experts, practitioners in the real estate market, and DeFi and blockchain researchers to refine functionality and validate objective fulfilment.

Our architecture provides researchers and practitioners with tangible guidance on the efficient tokenization of real estate. Furthermore, we contribute to the research stream on asset tokenization by abstracting the generated insights into four transferable design principles: 1) Consider equity and debt product structures to leverage the adoption and versatility of the token; 2) pursue compliance with a precise and widely accepted regulation to ensure investor and issuer protection and access; 3) leverage token standards to increase the interoperability and composability; and 4) extend token standards with corporate functions to support an efficient DeFi integration. Collectively, our insights contribute to unifying traditional real-estate finance and emergent DeFi markets, enhancing liquidity, transparency, and global investor reach while mitigating DeFi's over-reliance on crypto-native collateral. Beyond the real-estate context, the artefact and accompanying principles furnish a reusable template for tokenizing other real-world assets, signaling a practical pathway toward a more resilient and more widely adopted decentralized financial system.

Keywords: Blockchain, DeFi, Design science research, Tokenization

A multivocal literature review on capturing value propositions for private organizations in a CBDC ecosystem[4]

Authors

Vincent Schaaf, Jonathan Lautenschlager, Hannes Voucko-Glockner, Tobias Plank, Tobias Guggenberger, and Nils Urbach

Abstract

Central Bank Digital Currencies (CBDC) are a novel phenomenon gaining widespread attention from academics and practitioners in recent years. CBDCs combine new technology-enabled infrastructure and service innovation from the realm of FinTech and Decentralized Finance with the well-established and highly regulated area to central banking. While current practice and research primarily focus on designing specific CBDC systems or the governmental role, the role of companies and the private sector in the CBDC ecosystem still needs to be explored. Addressing this gap is particularly pertinent given the uncertainty surroundings which value propositions from traditional financial ecosystems and those from Fintech and blockchain-based financial ecosystems might be transferable to the realm of CBDCs. In this regard, the potential emergence of entirely novel value propositions companies could offer uniquely to CBDCs adds another layer of complexity. This paper aims to fill this gap by shedding light on private organizations' value propositions in CBDC ecosystems. Through a multivocal literature review we comprehensively gather both academic and practitioner insights. We aggregate value propositions directly stated in the current literature base and verify and complement these findings by mapping the needs of a CBDC ecosystem to value propositions companies might offer to fulfill these needs.

Keywords: Blockchain, CBDC, Financial sector, Value proposition

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Tokens against tax-fraud: Utilizing blockchain technology in the principal-agent dynamics of federated tax systems

Authors

Vincent Schaaf, Jan Stramm, Tobias Guggenberger, Marc-Fabian Körner, and Nils Urbach

Extended Abstract

Dividend-stripping scandals such as the Cum-Ex and Cum-Cum schemes have siphoned an estimated € 150 billion from public budgets in a dozen countries, revealing issues arising from missing data exchange, verifiability, and rule enforcement in the federated tax system (Schubert, 2021). The Cum-Ex scheme involves claiming multiple tax refunds for a single tax payment, while the Cum-Cum scheme enables foreign taxpayers to circumvent their otherwise unavoidable tax burden through opaque transactions. At the same time, legislatures and industry initiatives are increasingly exploring the utilization of blockchain technology as financial infrastructure, e.g., Germany's electronic-securities law that enables the issuance of blockchain-based bonds such as Siemens' issuance of € 60 million in 2023 and € 300 million in 2024 (Siemens, 2023, 2024). While the underlying problems of Cum-Ex and Cum-Cum, i.e., double-spending of tax certificates and creating opacity of ownership, strongly resonate with the key affordances of blockchain-based tokenization, the application of blockchain technology in the tax system has obtained very limited attention yet.

From a theoretical perspective taxation fraud can be viewed as a principal-agent problem (PAP): the taxpayer (agent) ascertains what to declare while the tax office (principal) can only verify those claims at high cost, creating moral hazard arising from information asymmetries and goal incongruence (Crocker & Slemrod 2005). While blockchain's transparency and immutability has been proposed as a solution in similar contexts, e.g., interorganizational information sharing (Bossler et al., 2024), tax research has mostly concentrated on typical game-theoretic measures like audit optimization and penalty rules. Hyvärinen et al. (2017) present the only work from the information system (IS) domain investigating the problem of dividend stripping in detail. Additionally, there are practitioner-driven efforts, such as the "Withholding tax distributed ledger report" published by a large consortium led by EY (2021). However, their scope is limited to the specific problem of tax evasion aiming at multiple tax refunds in cross-

border settings. Furthermore, critical aspects such as the burden placed on individual investors or balancing the trade-off between verifiability enabled through transparency and privacy for confidential data are overlooked. To fill this gap, we seek to answer the following research question:

How to design a blockchain-based information system to tackle the principal-agent problem in dividend taxation?

In particular, we seek to design a blockchain-based IS that prevents agents' malicious behavior and reduces hazardous information asymmetries while ensuring practical feasibility by minimizing agency costs and protecting sensitive data. To achieve this goal, we apply a design science research approach, following the guidance of Hevner (2007). In six expert workshops with representatives from Germany's Ministry of Finance, tax agencies, settlement providers, and banks, complemented by literature from the domains of blockchain-based IS, principal-agent theory (PAT), and tax fraud, we identified two meta-requirements and six design objectives. After the design-cycle, we evaluated the effectiveness of the blockchain-based IS with ten semi-structured expert interviews spanning IS scholars, legal practitioners, and tax experts, following the framework for the evaluation of design science (Veneable et al., 2016).

Our study proposes a blockchain-based IS that utilizes smart contracts and zero-knowledge proofs (ZKPs) to mitigate moral hazard and information asymmetries between tax authorities and taxpayers while maintaining privacy for confidential data. As such we aim to tackle a salient problem in the taxation system causing damages of € 150 billion in 12 countries. Furthermore, we distill three design principles: 1) Leverage Smart Contracts and Modifiers to enforce clear rules that minimize the agent's potential to deviate from the principal's goals (ex-ante); 2) utilize blockchain traceability and immutability for further information that enables (ex-post) monitoring of the agent where it is impossible to define clear rules that inhibit misbehavior; and 3) utilize blockchain traceability and ZKPs data minimization to reduce harmful information asymmetries while maintaining desirable ones. By exploring blockchain through the lens of the PAT, these principles can guide the utilization of blockchain-based IS in other application areas exhibiting PAPs.

Keywords: Design science research, Principal-agent theory, Taxation, Tokenization, Zero-knowledge proofs

Toward a holistic perspective on blockchain electricity consumption[5]

Authors

Vincent Gramlich, Tobias Guggenberger, Felix Paetzold, Johannes Sedlmeir, and Jens Strüker

Abstract

The awareness of Bitcoin's problematic electricity consumption has carried over to the underlying technology as a whole, leading to a widespread and controversial discourse on the sustainability of blockchain networks that still reveals knowledge gaps. In this paper, we conduct a systematic analysis to identify the scientific body of knowledge on key components and factors that impact blockchain electricity consumption. We find that most research so far has focused on Bitcoin and proof-of-work-based cryptocurrencies, with less attention given to blockchain networks that operate with far less electricity-intensive consensus mechanisms or employ emerging scaling solutions. Building on a systematic literature review and additional explorative and inductive reasoning, we present a comprehensive list of determining factors of blockchain electricity consumption and discuss how they are interconnected. Our research structures methodologies and parameters for measuring the electricity consumption of blockchains and identifies important gaps and avenues for future research.

Keywords: Cryptocurrency, Distributed ledger technology, Energy demand, Proof-of-Stake, Proof-of-Work

[5] This article has been published as:
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Unsealing the secrets of blockchain consensus: A systematic comparison of the formal security of proof-of-work and proof-of-stake[6]

Authors

Iván Abellán Álvarez, Vincent Gramlich, and Johannes Sedlmeir

Abstract

With the increasing adoption of decentralized information systems based on a variety of permissionless blockchain networks, the choice of consensus mechanism is at the core of many controversial discussions. Ethereum's recent transition from proof-of-work (PoW) to proof-of-stake (PoS)-based consensus has further fueled the debate on which mechanism is more favorable. While the aspects of energy consumption and degree of (de-)centralization are often emphasized in the public discourse, seminal research has also shed light on the formal security aspects of both approaches individually. However, related work has not yet comprehensively structured the knowledge about the security properties of PoW and PoS. Rather, it has focused on in-depth analyses of specific protocols or high-level comparative reviews covering a broad range of consensus mechanisms. To fill this gap and unravel the commonalities and discrepancies between the formal security properties of PoW- and PoS-based consensus, we conduct a systematic literature review over 26 research articles. Our findings indicate that PoW-based consensus with the longest chain rule provides the strongest formal security guarantees. Nonetheless, PoS can achieve similar guarantees when addressing its more pronounced tradeoff between safety and liveness through hybrid approaches.

Keywords: Distributed ledger technology, Dynamic availability, Finality, Liveness, Proof-of-Stake, Proof-of-Work, Safety

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Maximal extractable value: Current understanding, categorization, and open research questions[7]

Authors

Vincent Gramlich, Dennis Jelito, and Johannes Sedlmeir

Abstract

In traditional financial markets, front-running is a well-structured phenomenon. It represents a form of privileged actors utilizing knowledge or power advantages to extract undue profit at the cost of other stakeholders. Various mitigation strategies have emerged, ranging from market design to regulatory measures. More recently, a similar and substantially richer variety of means to gain unethical profit from power asymmetries has appeared in the context of blockchain-based decentralized applications. This phenomenon is called "maximal extractable value" (MEV). Despite the decentralized nature and inherent transparency of blockchain ledgers, MEV is particularly prevalent and challenging to mitigate. While related work in computer science and algorithmic game theory has already identified several different ways in which MEV manifests in decentralized finance (DeFi) and outlined partial solution approaches, a discussion of its impacts in the information systems (IS) domain is still absent. A holistic definition of MEV and how it can be exploited is necessary for the discussion of its potential implications for blockchain-based IS for businesses and public institutions. This paper conducts a systematic literature review to close this gap. It consolidates the diverging definitions of MEV and provides a categorization of the different ways in which it can manifest. As such, we synthesize and review the existing state of knowledge on MEV and point to undiscovered areas relevant to decentralized electronic markets in the form of a research agenda.

Keywords: Blockchain, Decentralization, DeFi, Front-running, MEV, Sandwich attack

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The adverse effect of privacy calculus on signaling and how zero-knowledge proofs can mitigate it

Authors

Tobias Guggenberger, Marc Principato, Vincent Schaaf, and Nils Urbach

Extended Abstract

Digital markets increasingly rely on the voluntary exchange of information to resolve information asymmetries that inhibit market efficiency and reduce their overall welfare. Signaling theory formalizes a mechanism with which a well-informed actor can send information, i.e., a signal (e.g., inventory records, diplomas), that enables less-informed counterparts to make better-informed decisions, thereby reducing the risk of adverse selection (Connelly et al., 2011). Yet in practice those same signals often encompass large amounts of additional, sometimes highly sensitive data (e.g., trading partners on invoices, personal information on diplomas). As a result, according to privacy-calculus theory, prospective senders will weigh the benefits of disclosure against the anticipated privacy risks (Dinev, 2014). When perceived privacy risks dominate, actors may simply refuse to signal, impeding the effectiveness of the signaling mechanism and leading to a potential deterioration of the market caused by information asymmetries.

Despite extensive research on factors influencing the willingness to signal, privacy related aspects have been largely overlooked. While initial studies suggest that especially the disclosure of additional information discourages signaling (Benndorf et al., 2015), the mechanisms and circumstances underpinning this phenomenon remain largely unexplored within signaling theory. To address this gap, we aim to enhance the existing signaling model by integrating privacy calculus theory, seeking to answer our first research question (RQ):

Under the privacy calculus, what is the effect of privacy concerns on signaling?

Although privacy concerns may prevent individuals from signaling, recent cryptographic advances suggest a technological remedy. In particular, zero-knowledge proofs (ZKPs) allow a sender to prove that a statement is true (e.g., "my balance exceeds € 1,000") without exposing any other underlying data, thus unbundling the signal from its evidence and keeping the message verifiable yet private (Chod et al., 2020). As a result, ZKPs may improve the privacy calculus of the sender in favor of signaling and consequently, we ask the following second RQ:

> *Can ZKPs help to improve signaling by reducing privacy concerns in the sender's privacy calculus?*

To answer our first RQ we extend the canonical game theoretical signaling model with privacy calculus by adding a message-specific privacy-cost term to the sender's utility function. The enriched model predicts that heterogeneous privacy costs can overturn the incentive-compatibility conditions that normally secure a separating equilibrium, resulting in a pooling equilibrium. Incorporating ZKPs could lower those costs, restoring a separating equilibrium whenever the proof sufficiently reduces privacy concerns.

To validate our model, we implemented a survey experiment (N = 365). Participants were randomly assigned a "high" or "low" liquidity type and faced two disclosure mechanisms: 1) a traditional bank-statement upload and 2) a ZKP that revealed only whether the balance exceeded the cutoff. For each mechanism participants decide whether to send the signal and, if so, state the minimum bonus they would require doing so. The experiment shows that privacy costs reduce sender utility and, when sufficiently uneven across messages, can collapse a separating into a pooling equilibrium. Empirically, traditional disclosure triggered significantly higher privacy concerns than ZKP disclosure and depressed the willingness to signal. Senders who nonetheless signaled demanded materially larger incentives when using traditional statements, while ZKPs lowered the required benefit and accentuated type separation. Thus, the experimental results confirm our newly established model of a signaling game with integrated privacy calculus and the effectiveness of ZKPs in reducing privacy concerns and reestablishing the effectiveness of the signaling mechanism.

The study advances signaling theory by formally embedding privacy calculus, providing a formalized model that highlights the role of privacy concerns in signaling and confirming the newly established model through quantitative evidence. Furthermore, we provide theoretic and practical evidence for the affordances of ZKPs in not only protecting sensitive information but providing tangible economic value by restoring the effectiveness of signaling mechanisms previously inhibited by privacy concerns.

Keywords: Economics of IS, Signaling, Privacy calculus, Questionnaire survey, Zero-knowledge proofs

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