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Peer-to-Peer Energy Trading and Localism: The Role of Distributed Ledger Technology in Germany's Energy Transition

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ABSTRACT

The German *Energiewende* (Engl. energy transition) relies increasingly on the interplay of distributed energy resources and digital technologies. Due to the EU Clean Energy package citizens will be empowered to actively engage in the energy sector, which will result in new energy governance concepts on the local level. Distributed Ledger Technologies, often synonymously used with the term blockchain technology, aim to circumvent intermediaries by establishing an environment that allows for direct energy trading between peers. The idea is to enable households that are in close proximity to each other to trade near real-time small amounts of energy. Some sources already attributed revolutionary potential to this technology in the light of the German energy transition. However, P2P energy trading based on a Distributed Ledger Technology exhibits a low maturity level and the diffusion of such projects is constrained by several factors. This thesis includes an analysis on how present structures in the German energy system impact the implementation of this novel technology and derives in this context drivers and barriers with regards to its adoption.

Keywords: peer-to-peer, energy policy, decentralization, distributed ledger technology, complex systems, Panarchy

List of abbreviations

DER	Distributed Energy Resources
DLT	Distributed Ledger Technology
EEG	*Erneuerbare Energien Gesetz*
EnWG	*Energiewirtschaftsgesetz*
ETIBLOGG	Energy Trading via Blockchain Technology in the Local Green Grid
e.V.	*eingetragener Verein*
GDPR	General Data Protection Regulation
GmbH	*Gesellschaft mit beschränkter Haftung*
ICO	Initial Coin Offering
P2P	Peer-to-Peer
PoW	Proof-of-Work
SHA-256	Secure Hashing Algorithm-256
SME	Small and medium-sized enterprise
StromStG	*Stromsteuergesetz*

INTRODUCTION

The transition from depleting fossil resources to renewables for energy supply is seen as one integral element to achieve the climate goals that were stipulated in the Paris Climate Agreement. In Germany, the shift towards sustainable energy generation and distribution was already triggered in the 1970s through several social and ecological movements (Haas 2017, 145) and is nowadays broadly known as the term "*Energiewende*" (Engl. energy transition). While some sources attest to Germany already a remarkable achievement in this effort, other sources claim that the transition is not happening fast enough and demand an even faster shift towards a sustainable energy mix. This transition requires however not only a stronger focus on sustainable energy resources by incumbent energy providers, but also innovative solutions regarding energy generation and distribution through new actors, which might impact the current market structure of the energy eco-system and unfold new dynamics in the future.

The role of spatial scale, particularly local and sustainable approaches in the power sector, has been identified as a crucial factor for the transformation of socio-technical systems (Späth, Rohracher 2014, 106). A broader focus on energy concepts that enable local power generation and consumption was emphasized by several authors to instigate positive implications for the performance of energy systems (O'Brien, Hope 2010; Walker et al. 2007; Manzini, M'Rithaa 2016). Shifting from centralized to decentralized structures in the power sector was also given greater impetus by the European Union, which pushed its member states to empower citizens to actively participate in the energy market by fostering local energy communities (European Commission 2019, 13). Apart from traditional electricity supply systems, which are mainly based on fossil fuels, new technologies in the realm of distributed energy resources (DER) are increasingly complementing legacy electricity systems. These technologies empower usually passive consumers to become prosumers who then take a pro-active role in local energy generation and supply (Morstyn et al. 2019, 2027). The already high amount of DERs in Germany (e.g., small-scale solar power or biogas plants) is expected to keep steadily increasing, which requires novel solutions to integrate these power-generating units into the energy system successfully.

Distributed Ledger Technology (DLT), often used interchangeably with the term blockchain technology, was frequently associated with the energy sector resulting in a variety of potential use cases (Andoni et al. 2019). Some sources have already attributed revolutionary potential to this technology for the German energy transition (Schwöbel et al. 2018, 62). While the current energy paradigm is extensively based on hierarchical structures in which large-scale energy providers generate energy and distribute it via several network levels to the end consumer, DLTs propose to enable a trusted environment that allows peers that are unknown to each other to perform energy transactions on the local level. This particular use case of DLT envisions to reduce the role of intermediaries and to enable the possibility to trade energy directly between households (peer-to-peer energy trading). Due to the inherent features of DLTs, peers can check the validity of transactional data at any time, while the required security for automated processes is provided by cryptography.

The German Federal Ministry for Economic Affairs and Energy (German: Bundesministerium für Wirtschaft und Energie) supported the testing of four pilot projects in the energy sector centered around the key features of DLT. ETIBLOGG (an abbreviation for ‘Energy Trading vIa Blockchain-Technology in the LOcal Green Grid’) is one of these pilots and will be presented as an example to show how a DLT-based P2P energy trading platform can be implemented.

However, a broader diffusion of such peer-to-peer energy trading projects in Germany is primarily limited due to constraints related to present structures in the energy system. These include aspects with regards to the current regulatory framework, missing incentives in present energy policies, the availability of other competitive products but also issues arising due to the requirement of socio-technical transformations on the local level. The principle research question of this thesis is thus how current structures impact the implementation and diffusion of P2P energy trading concepts based on DLTs in Germany. To examine this, an exploratory case study approach will be adopted. During the research, specific propositions have been elaborated to narrow the scope of the case study (Yin 2018, 34). Hence, based on the main research question, the sub-objectives of the thesis are to:

- depict what DLTs purport to solve in the context of local energy trading,
- elaborate drivers that could contribute to the broader adoption of this technology
- identify barriers, that inhibit the implementation of DLT-based P2P energy trading
- and as the last point to review the findings in light of the German energy transition.

1. Methodology

The thesis is based on a qualitative research approach and includes the review of primary and secondary literature as well as the results of the hearing of several stakeholders in the power sector by the German Federal Network Agency (German: *Bundesnetzagentur*) regarding the potential of blockchain technology published in July 2020. Due to the rather broad topic of the influence of DLT on the energy transition, the scope of this thesis will be limited to the specific use case of P2P energy trading and the research objectives indicated in the introduction.

The primary motivation is to explore how present structures in the German energy system impact the implementation of DLT-based P2P energy trading. To investigate the impact of persisting structures in the energy system on this technology, an exploratory case study approach will be adopted. The exploratory case study method has been chosen as it allows to draw data from a variety of resources and then to explore, based on the collected information, current real-life inhibiting and motivating forces with regards to the adoption of this technology. As there is yet no pre-determined outcome for the impact of this specific technology on the energy system in Germany, an exploratory case study is suitable to shed light on its development and to point out to additional future examination (Yin 2018, 50).

Moreover, a conceptual framework will be adopted to provide to the understanding of this phenomenon (Jabreen 2009). The conceptual framework includes a brief discussion regarding the concepts of peer-to-peer and localism/localisation in the context of P2P energy trading and the introduction of Panarchy – a framework that serves to examine complex systems. While P2P and localisation are constituents that directly pertain to the concept of peer-to-peer energy trading, the Panarchy framework has been chosen as it allows to depict the interconnectedness as well as cross-scale effects of structures in complex eco-systems. Under 3. the main idea behind DLTs will be presented. This section includes a classification of DLT sub-types as well as an overview of the underlying technical principles, which will then be linked to the concept of peer-to-peer energy trading.

The main part of this thesis is the case study that embeds the elements of the conceptual framework to derive drivers and barriers for the implementation of this technology in Germany. In this section, the ETIBLOGG project will be briefly presented to give the reader an idea of how a P2P energy trading platform could be implemented.

The foundation of the subsequent analysis are literature resources and the responses of the hearing mentioned above. The hearing conducted by the *Bundesnetzagentur* was based on a questionnaire of eight open-format questions that are translated into English and listed in Annex 3. Apart from power sector related answers, the hearing also included responses from stakeholders of the mail, railway and telecommunication industry. For the purpose of this thesis these answers have been filtered out so that the analysis part only includes statements provided by stakeholders of the power sector. Appendix 2 contains a table that lists the statements of the stakeholders that participated in the hearing.

The summary and concluding remarks represent the final section. This part will reflect on the findings of the thesis and contains an outlook regarding possible future developments and policy implications.

2. Framework introduction

The introduction of the conceptual framework is divided into three sub-parts. First, a brief theoretical discussion will provide the definitions and a discussion of the concept of Peer-to-Peer and localism in the context of energy systems. The subsequent section will then deal with the introduction of the Panarchy framework.

2.1. P2P

Peer-to-peer (P2P) is commonly associated with computer technology and decentralized networks, in which computers are partitioning tasks and interacting in a direct way, without a server as an intermediary in between (Bauwens et al. 2019, p. 1-2). In such a network, peers (nodes) may operate as a 'Servent' - a portmanteau of the words server and client (Schollmeier 2001, p. 1). Other than in traditional Client-Server relationships, the capabilities are not split, and a single node is acting as server and client together (Ibid.), which implies that the peers are capable of consuming and supplying information simultaneously. However, in addition to the aspect of technological infrastructure, P2P can also be differentiated as a type of social relations, characterized by non-hierarchical human networks with "maximum freedom to connect" (Bauwens et al. 2019, 1-10). The amalgamation of this aspect with P2P as a technological infrastructure can be regarded as a form of social dynamics, which utilizes technology as a facilitator to scale and that renders transitions of eco-systems, often with a distinct focus on nature and people, possible (Ibid.).

While the traditional form of energy trading is organized in a unidirectional way, originating from large-scale energy generators and then flowing to the end-consumer, the utilization of P2P infrastructure enables an environment that allows for multidirectional energy trading between consumers and prosumers in local power grids (Zhang et al. 2018, 1).

The potential of distributive control of infrastructure through P2P concepts and the relational dynamics which it unfolds, have been thus linked to the impact on Smart Cities (Kostakis et al.

2015). In the context of P2P energy systems, a peer can stand for various grid participants, such as energy generators, local energy customers, consumers or the so-called prosumers, consumers who consume and produce energy at the same time. Participants in such a P2P system often interact under the assumption of equipotency, which implies that participation does not require a prior screening of the peers (Bauwens 2005, 6). The role of the prosumer is a crucial starting point in the P2P energy trading cycle as surplus energy generated by prosumers can be either exported to the grid, stored for usage at a later time or directly sold to other local participants in the vicinity. This requires however increased engagement of consumers, who are usually taking a rather passive role in the energy system.

2.2 Localism and Localisation

In 2018, stronger participation of citizens in the energy sector has been fostered by the European Union through the coining of the definition ‘renewable energy community’.

„[A] ‘renewable energy community‘ means a legal entity:

(a) *which, in accordance with the applicable national law, is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity;*

(b) *the shareholders or members of which are natural persons, SMEs or local authorities, including municipalities;*

(c) *the primary purpose of which is to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits"* (European Union Directive (2018/2001), L 328/103)

This definition implies a strong emphasis on spatial scale and the distributive character of energy generation. The definition was part of the "Renewable Energy directive" (European Commission 2020), which stipulates to empower citizens with regards to the generation and distribution of renewable energy projects. In addition, this definition also reveals a shift to a local, citizen-centered governance approach and thus excludes deliberately larger corporations from decision-making powers in renewable energy communities (Simon 2018).

Due to scaling costs of communication and coordination, hierarchies and markets were required to mitigate costs in the pre-digital era (Bauwens et al. 2019, 4), which rendered such governance approaches difficult to implement. Now technologies make coordination and communication possible on a broader scale, which allows individuals and small groups to interact on a global level and thus epitomizes slogans such as “[d]igital globalist and physical localist” (Srinivasan 2020).

Localism can be defined as “an umbrella term which refers to the devolution of power and/or functions and/or resources away from central control and towards front-line managers, local democratic structures, local institutions and local communities, within an agreed framework of minimum standards“ (Evans et al. 2013). Hopkins (2010) further differentiates between localism as a form of redistribution of political authority to the local level and the expansion to **localisation**, which reflects “the strengthening of local production to meet local needs, a shift that would financially benefit local communities“ (Hopkins 2010, 4). The term localisation thus comprises political and economic principles by empowering local communities and focusing on the proximity principle - the idea of enabling local production and consumption at once (Felicetti 2013, 565; Hopkins 2010, 238). Besides, Hopkins argues that the notion of sustainability (e.g. renewable energy supply), social justice, and control of assets (e.g., energy generation units) are central to localisation but do not implicitly apply to localism (Hopkins 2010, 238-240).

With regards to the power sector, the perception of control is inherently linked to the concept of ownership regarding renewable energy facilities, which reveals various scale trade-offs depending on the project approach (Strachan et al. 2015, 99). The scales with regards to the implementation of renewable energy projects can reach from small-scale applications in the close proximity to large scale projects that supply a broad range of households with energy (Walker et al. 2007, 64).

Fig. 1 illustrates that community energy approaches do not necessarily coincide with ownership of DER facilities (for a detailed classification of ownership models compare Walker (2008, 4401-4402)).

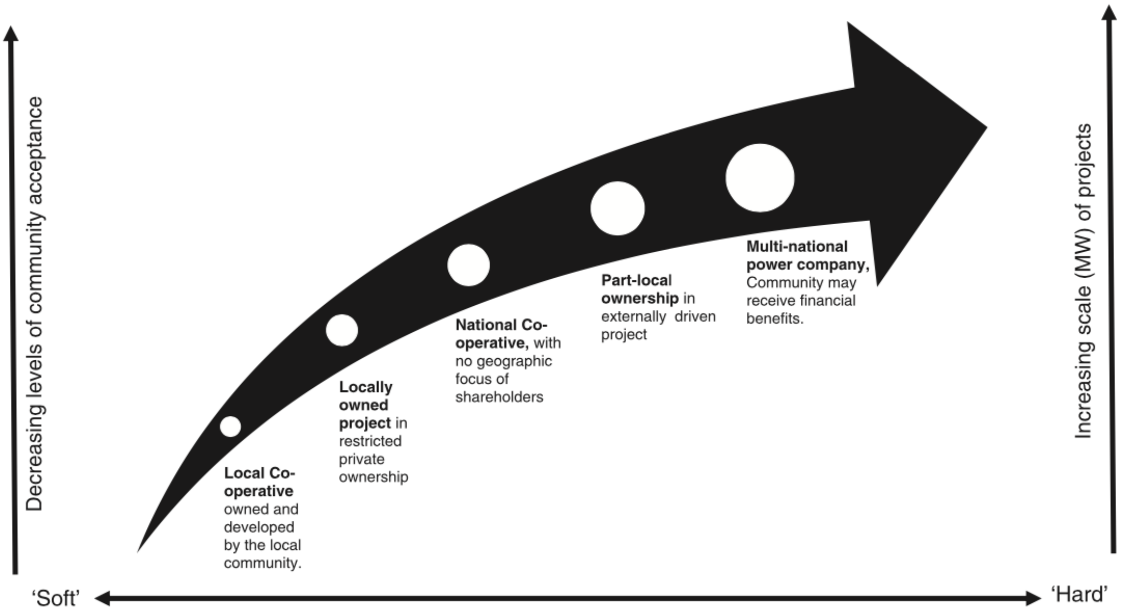

Figure 1: Scale engagement trade-offs in community energy (Source: Strachan et al. 2015, 99)

The horizontal axis with the labels 'soft' and 'hard' refers to a concept developed by Lovin, which analyzes energy developments according to soft and hard paths (Lovin 1977). A soft path indicates an emphasis on decentralization and a rather local and flexible approach regarding energy generation with a focus on technologies that foster renewable energies (Strachan et al. 2015, p. 99). The soft path also leads to the dispersion of risks as the system is organized in a decentralized way with multiple entities. An example of risk dispersion in this context would be the outage of a single actor in a P2P network, which would eventually impact only a certain number of other participants, while a blackout of a big energy corporation could have fundamental impacts on the energy supply of whole regions and could potentially cause system degradation (Linkov, Trump 2019, 41). Local and distributed approaches have thus been identified to potentially decrease systemic vulnerabilities of energy systems (O'Brien, Hope, 2010, 7550). However, due to the intermittent availability of renewable energy resources, such projects heavily rely on energy storage solutions (Ibid.) to enable complete local energy-autarky.

The hard path on the right hand side of the axis is characterized by large-scale multi-national companies focusing on further developing energy generation technologies. This could imply for instance a strong focus on nuclear energy or the expansion of new methods for energy generation and storage, such as power-to-gas, a technology based on electrolysis that allows to store renewable energy in form of 'green hydrogen' (Uniper 2020).

Energy cooperatives are very common in Germany and are mostly formed on a local level, where private individuals or farmers invest jointly in renewable energy facilities such as wind turbines or photovoltaic parks. In 2018 the share of this group on the total capacity of renewable energy generation in Germany amounted to 42 percent (Wettengel 2018). When referring to a peer part of a P2P network in this thesis, the focus will be narrowed to the 'soft path' represented by local prosumers, who own and/or control the respective facilities and engage directly in energy trading activities.

The following drivers of local energy initiatives were elaborated by Walker (2008) and embed governance and ownership elements: "a desire for local income generation and economic redevelopment; the tendency of community ownership and participation to smooth approval and planning processes for projects; a desire to retain local control over decision making regarding energy projects in a region; a belief that such projects can provide affordable, reliable supplies of energy; and community commitments to social and environmental ethics." (Morris 2013, 21; Walker 2008, 4402). These motivations hint also at the potential socio-technical impacts of local renewable energy communities, which will be discussed in more detail under section 4.3.

As far as the governance of localism approaches is concerned, Catney et al. distinguish between positive and negative forms of localism in the context of renewable energy communities and point to the possibility that localism approaches can fall into a "local trap" (Catney et al. 2013, 716). A local trap is characterized by the generalization that initiatives are perceived as beneficial and sustainable only because they are local or decentralized and is labeled by the authors as negative localism (Catney et al. 2013, 726). The terms positive and negative localism refer to the distributional impacts of governance in energy systems and shall elucidate why some local projects are taking off and others not. This concerns in particular issues of distributional justice, since the required resources (material and social capital) for becoming self-reliant are not available for all people in the same quantity (Ibid.). According to Catney et al. a positive localism approach is centered around the idea that the state plays a crucial role as a facilitator regarding the detection and the tackling of uneven distributions to enable a society in which virtuous circles might be triggered by the community (Catney et al. 2013, 717).

Fostering DER through the local emergence of microeconomic P2P energy communities could potentially lead to flatter, horizontal structures in energy eco-systems. However, this would imply a major system transition from a predominantly centralized model of energy generation and distribution, to a decentralized model that is characterized by many interconnected stakeholders (O'Brien, Hope 2010, 7552-7553).

2.3 Panarchy

Eco-systems are composed of several self-organizing variables that show complex dynamics (Garmestani et al. 2009). **Panarchy** is a model that serves as a heuristic to understand the organization and dynamics of complex systems, which are influenced by hierarchies and adaptive cycles (Holling 2001, p. 390; Allen et al. 2014, p. 580). The term Panarchy "was coined as an antithesis to the word hierarchy" (Gunderson, Holling 2002, p. 21) and is derived from the name of the Greek god "Pan" to allude to the rules of nature, which compromise the organization and transformation of systems (Ibid.). A Panarchy is thus distinct from the typical perception of hierarchies as it shows that control is not only influenced by large scale, top-down processes but could also emerge through smaller scale, bottom-up processes (Allen et al. 2014, 578). The model consists of intertwined adaptive cycles, running through a pattern of four different phases (Gunderson, Holling 2002, 32): "exploitation" (r), "conservation" (K), "release" (Ω) and "reorganization" (α). Figure 2 shows the alternating stages of a single adaptive cycle.

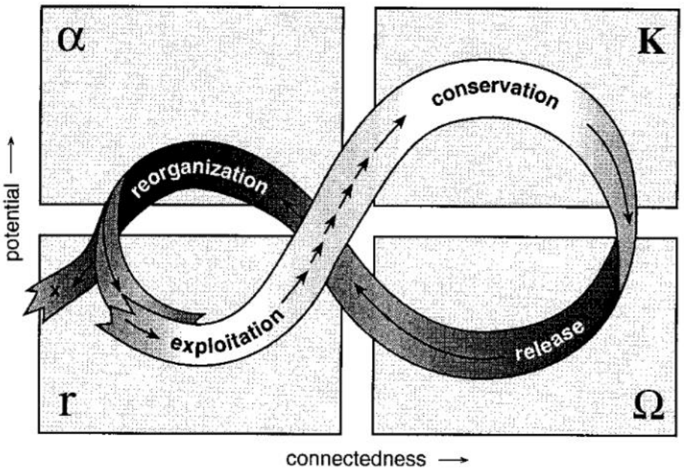

Figure 2: Adaptive cycle (Source: Gunderson, Holling 2002)

The r-phase can be considered the initial development point, characterized by the fast exploitation of resources, which eventually leads to the longer-lasting growth stage that deals with the conservation of the acquired resources (Allen et al. 2014, 579). In an economic system, the r-phase could be for instance represented by the exploitation of resources through entrepreneurs, who act under high competition and emerge as "survivors" of this competition and grow their business. In the conversation stage, the system is slowly maturing and capital is built, leading to a point where established connections or patterns restrict new paths, which is the prerequisite for systemic adaption and evolution of the system (Wahl 2020).

The overly connected structures within the system might lead to a rigidity trap (Holling 2001, 400). In an economic system, this would suggest that established, well-matured companies which are narrowly focusing on a specific product or service, become gradually more fragile due to a lack of agility and innovation. Rigidity makes the system more vulnerable to external shocks, culminating in the end of the "front loop" and the beginning of a phase characterized by uncertainty often referred to as "creative destruction" - a term coined by Joseph Schumpeter (1942) to describe that novelty emerges through the destruction of old structures, but which was originally mentioned by Friedrich Nietzsche when he described Dionysus as "creatively destructive" and "destructively creative" (Taleb 2012, 256). The creative destruction phase can be interchangeably referred to as the release stage Ω and reveals the susceptibility to randomness (external events) and disturbances (Holling 2005, 10). In the context of energy systems, this could mean how the system's trajectory is impacted by sudden events such as nuclear disasters, but also how innovative technologies influence the flow of the cycle. Therefore, this phase can be considered as an indicator to gauge the "resilience" of a system (Holling 2005, 5). Resilience (Latin: "resiliens" = to turn back) is a core element of the Panarchy model and can be defined in this context "as the capability of a system to recover in the midst of shocks or stresses over time" (Linkov, Trump 2019, 36).

At the Ω stage, creativity is high and new knowledge is released, which is characterized by the entering of the "back loop". There the connectedness of the structures within the system decreases. This turning point can be considered as the seedbed of radical innovation, taking place in an environment that is highly uncertain (Slight et al. 2016, 3). Juxtaposing the front loop to the back loop, shows that the former represents incremental innovation, improvements to the system of smaller magnitude and under lower uncertainty, while the back loop stands for tinkering and testing of rather radical innovations under high uncertainty (Biggs et al. 2010; Slight et al. 2016, 3-4). Reorganization (α) can imply a resetting of the system, which follows a predictable trajectory or could lead to novel recombination of structures and processes, thus following a less predictable path (Allen et al. 2014, 579). In this phase, larger and slower-moving cycles can exert control (memory, "remember") over the renewal of smaller ones (Holling 2005, 8) and thus set the requirements for their functioning (Holling 2001, 397). These larger structures could represent for instance legacy systems that regulate reorganization around previously established structures instead of setting up a new regime (Allen et al. 2014, 580), but also institutional structures, which inhibit smaller cycles to renew (Holling 2005, 8).

In the figure below, these cross-scale effects are depicted through three nested adaptive cycles. The figure also shows how smaller and faster-moving cycles can influence larger ones in the creative destruction (revolt) phase, which can ultimately lead to a cross-scale cascading effect within the system (Holling 2001, 398). This effect can take place, when the slower-moving cycles (old established structures) are in the K phase, characterized by low resilience and vulnerability due to a high degree of connectedness and thus rigidity, while the smaller, faster-moving cycles (e.g., innovative solutions) are overpowering and could potentially trigger a crisis that affects the overall state of the system (Ibid.).

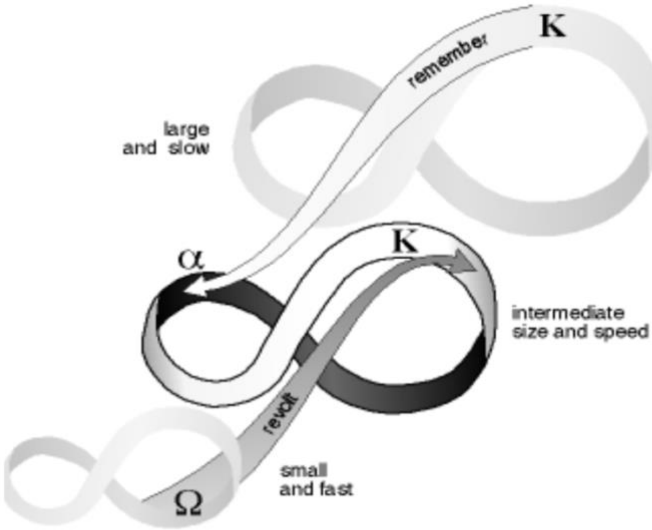

Figure 3: A Panarchy with three nested adaptive cycles (Source: Gunderson, Holling 2002)

Together these nested adaptive cycles form a Panarchy. The Panarchy framework serves as a model to show the alternating states of stability (r and K) as well as revolt and transformation (Ω and α) and reveals how adaptive cycles can emerge and then influence the performance of the system. Whenever the resilience threshold is punctuated, a regime change within the system occurs (Allen et al. 2014, 584). The model thus enables to detect thresholds with regards to the resilience of a system and to derive counteractive intervention measures (Allen et al. 2014, 581).

Therefore, disturbances and the potential “resilient” response play a crucial role in the Panarchy framework. Folke states however, that “resilience is not only about being persistent or robust to disturbance. It is also about the opportunities that disturbance opens up in terms of recombination of evolved structures and processes, renewal of the system and emergence of new trajectories.” (Folke 2006, 259). This aspect of systemic restructuring in times of external shocks can be linked to the term “Antifragility” (Taleb 2012). Taleb defined this term to emphasize that entities cannot only withstand shocks and return to their previous set-up (as in resilience), but could also benefit from randomness and grow from the exposure to stressors or shocks (Taleb 2012, 20).

While some critics have found adaptive cycles to be too deterministic in its structure (Folke 2006, 258), Holling (2001) pointed out that it is possible to impact the trajectory of the adaptive change cycle through leverage points (Slight et al. 2016, 6). The detection of those leverage points and the inference of measures could be crucial for an entity’s performance. A measure could be to slow down the front loop or even to avert the back loop through the fostering of innovation (Ibid). The ability to intervene and impact the flow of the cycle could be thus regarded as a possibility to observe the system’s antifragility. If it is recognized that in or prior to the conservation stage a system gets increasingly rigid, diversification of opportunities could be leveraged through “sowing seeds of innovation” to prevent the release stage and instead cause a return to the exploitation phase (Slight et al. 2016, 9). However, the prevention of the release stage is not to be mistaken with avoidance from randomness or stressors, as these are essential elements for the process of innovation (Taleb 2012, 5), it is rather a way to escape collapse and avoid complete ruin. The implementation of leverage points could be also facilitated by the right policy instruments, such as supporting the development of new products instead of subsidizing a declining industry (Slight et al. 2016, 9).

Another leverage point “cultivation of creativity” could be pinned at the start of the release phase and concerns for instance companies that suffered from a decline in the release phase (Ibid). Slight et al. (2016) have developed exemplary policy instruments that could aid stakeholders with reorientation to quickly overcome the back loop. These include: “(1) retraining programs for workers laid off during business closures; (2) programs that help fund public – private partnerships to allow businesses to access research and development expertise and (3) programs that investigate new value-added products that can be derived from existing resources“ (Ibid.).

The analysis of nested adaptive cycles can be used to reveal the dynamics of complex systems, that stem from self-organization and evolution over temporal scales (Sundstrom, Allen 2019, 9). In section 4.3 the Panarchy framework will be applied to the case of DLT and P2P energy trading in Germany to examine how current structures impact the potential of this technology and to identify in this context barriers and drivers for its adoption.

3. Distributed Ledger Technology

This section includes a definition and a classification of DLT-types. An overview of the technical principles will be provided based on the functioning of the Bitcoin blockchain. In 3.3 the relevance of the technical features and the selection of the DLT-type will be briefly discussed with regards to P2P energy trading.

3.1 Definition and classification

Distributed Ledger Technologies have gained increased public interest in recent years and were often considered to contribute to fundamental changes in many fields across society and beyond the scope of cryptocurrencies and the financial sector (Krause et al. 2017; Fraunhofer FIT 2019, 14). The term DLT is often misleadingly used as a synonym for blockchain technology. Blockchain technology, however, represents a single subset of DLT, which encompasses in addition other forms such as directed acyclic graphs (Fraunhofer FIT 2019, 15). DLTs are based on a distributed computing system, in which the computers (nodes) are acting as 'servents', store copies of the same data and are directly connected and communicating with each other (Vaidya 2016).

> *"DLTs are shared ('distributed' or 'decentralized') digital ledgers that use cryptographic algorithms to verify the creation and transfer of digitally represented assets or information over a peer-to-peer network. They operate via an innovative combination of distributed consensus protocols, cryptography and inbuilt economic incentives based on game theory"* (Ferrarini et al. 2017, 1).

This definition refers to two key features of DLT: **peer-to-peer distribution** and **ledger sharing (**Chuburkov et al. 2019, 5). While the former indicates the distribution of data or digital assets (e.g., digital money or digital representations of physical assets like vehicles or energy) across different locations without an intermediary data repository, the latter refers to the immutability of the stored data through multiple entities that maintain ledgers simultaneously (Ibid.). The main objective of DLTs is to reach an agreement over the validity of shared data in a system with no central administrator (Rauchs et al. 2018, 22-24).

“Economic incentives based on game theory” shall promote fair behavior of the nodes. However, as nodes in a computer system could be faulty or act maliciously, **consensus** over the data has to be reached not only in an honest but also in an ‘adversarial environment’ (Rauchs et al. 2018, 15). Lamport et al. (1982) coined this as the Byzantine’s General Problem to refer to the issue that “[r]eliable computer systems must handle malfunctioning components that give conflicting information to different parts of the system” (Lamport et al. 1982, 382). The bitcoin protocol, introduced by an anonymous individual or group under the pseudonym Satoshi Nakamoto in 2008 with the purpose to create “A Peer-to-Peer Electronic Cash System” (Nakamoto, 2008a), represented a breakthrough in distributed computing and offers a probabilistic solution to this problem via a self-adjusting consensus mechanism (Konstantopoulos 2017). A consensus mechanism serves as an “economic incentive framework” (IRENA 2019, 7) that encourages nodes to enable the functioning of the system.

DLTs can be broadly classified into three types (Youm, Hurwitz 2019):

Permissionless distributed ledger systems like Bitcoin or Ethereum are open to the public without any restriction. Each network user can perform transactions or participate in maintaining the network without prior permission from any type of authority (Ibid.)

Permissioned distributed ledger systems are characterized by centralized authorities that are restricting network access to selected users which could possibly include identity verification processes (Krause et al. 2017, 7).

Hybrid distributed ledger systems, also known as consortium DLTs, are combining elements of permissionless (transparency) and permissioned systems (privacy) and can be considered as partially decentralized. Such a system could be for instance permissioned for the maintenance of the network (mining activities) but permissionless to view data or to perform transactions (Maupin et al. 2017, 26; Welfare 2019, 237).

3.2 Overview of technical principles

To explain the functioning of a DLT, the focus in this section will be shifted to blockchain technology as this particular subset of DLTs has been the underlying infrastructure for many recent P2P energy trading projects. Blockchain technology is popular due to the rise of a plethora of cryptocurrency projects in 2017 (during the so-called ICO boom) but also due to the sudden fall of the majority of those projects shortly after. To exemplify the transactional process within a blockchain, this section will refer to the characteristics of Bitcoin, as it represents a broadly known implementation of blockchain technology that has proven its resilience for over a decade.

A blockchain is a type of DLT that stores compressed transactions in a time-stamped block and links it cryptographically to previously created blocks in a chronological sequence (Andoni et al. 2019, 145). It represents an ever-increasing chain of immutable data records maintained by a distributed computer system that is backed by a consensus protocol and cryptographic algorithms. This method of record-keeping by concatenating blocks of data is not utilized by all DLTs, which implies that all blockchains can be considered a DLT but not vice versa (Strüker 2019, 29). The innovation of blockchain technology lies in the combination of different, previously existing technologies (IRENA 2019, 7), including primarily **cryptographic hash functions** and **public-private key cryptography**.

Blockchains are to a large extent based on hash functions and hashes (Pilkington 2016; Drescher 2017, 104ff.). A hash represents the output of a previously entered information (an input of any length) that has been transformed by a hash function (Pilkington 2016.). A cryptographic hash function is a mathematical algorithm to verify data integrity (Antonopoulos 2014, 170). It holds the characteristics that a calculated hash is almost impossible to revert (preimage resistance) and that it is extremely difficult to detect two different inputs that result in the same hash (collision resistance; Fraunhofer FIT 2019, 31). These features imply that only a slight change of one input character results in a completely different hash. The Bitcoin blockchain is for instance using hashing algorithms like SHA-256 (“secure hashing algorithm 256”; a given input produces a 256 bits long output) during the mining process of new coins, to broadcast transactions or for the creation of new addresses.

To perform a transaction in the Bitcoin network, a participant needs to hold a public-private key pair that is mathematically linked (Bundesnetzagentur 2019a, 7). While the private key serves to sign a transaction and has to be kept secret, the public key is used to derive an address (via the application of hashing algorithms), which can be publicly shared with the purpose to identify the user in the network (Andoni et al. 2019, 145). Figure 4 shows in a simplified way which steps are taken when a blockchain transaction is initiated.

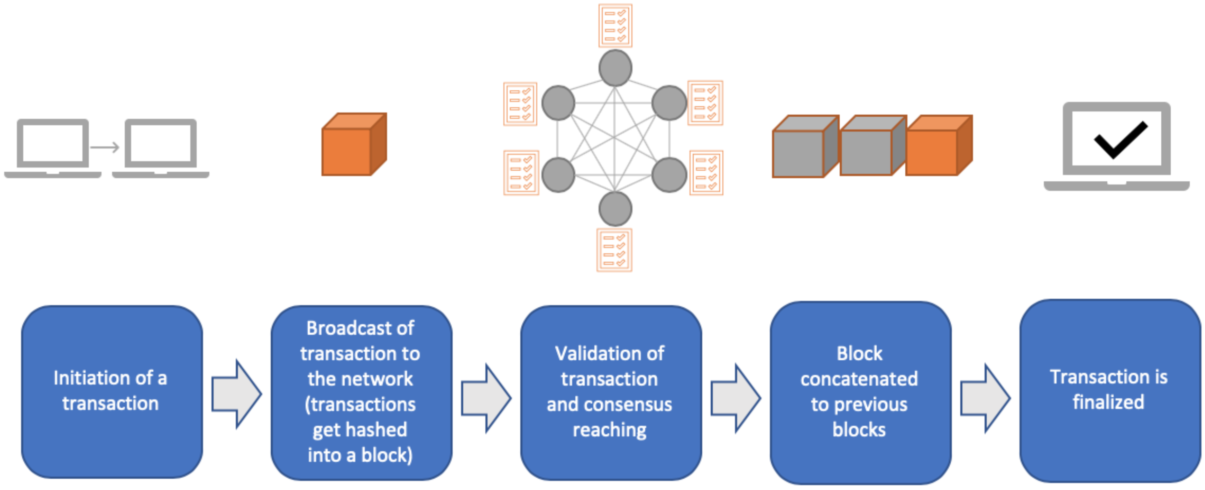

Figure 4: Simplified illustration of a blockchain transaction (own illustration, based on Mika, Goudz 2020, 41; Andoni et al. 2019, 146)

A first requirement to perform a transaction in the Bitcoin network is that the public address of the recipient is known. The process then starts with the initiation of a transaction by a user, who is signing a transaction with a private key. The transaction is then broadcast to the network, where it will be received by a processing node, which checks if the transaction is valid (e.g., if the sender's wallet has the required funds to perform the proposed transaction). If the transaction is valid, the node will propagate the transaction to the network, so that all other nodes (step 3) can validate it separately. Eventually, the transaction will be received by a special type of node, the so-called miners, which are hashing all received transactions into a 'block'.

To determine which miner will be rewarded for appending a new block to the chain, a consensus mechanism is applied. The most popular consensus mechanism is called 'Proof-of-Work' (PoW; Nakamoto 2008b). The miners' economic incentive is a block reward, which is composed of transaction fees and a certain amount of newly created coins (Zimmermann, Hoppe 2018, 20-21). The miners are using specialized computer hardware to solve a cryptographical puzzle that contains several inputs, such as all transactions that shall be aggregated into a block, a timestamp, a hash of the previously found block, and the 'nonce' (Fraunhofer FIT 2019, 32). The nonce is a certain number, metaphorically speaking the secret piece of the puzzle, that can only be guessed by using a trial and error method, due to the previously mentioned properties of hash functions (preimage and collision resistance). The cryptographical puzzle is eventually solved if a specific nonce is found, that together with the other inputs is generating a hash output that is below a predetermined threshold (Ibid.) - in other words, as soon as a miner presented a valid proof of work.

If this is the case, the miner node will propagate the new block to the network, so that all other nodes can confirm the validity of the block (consensus over the block is reached) and check for instance that the miner did not allocate an inappropriate reward. The Proof-of-work algorithm is developed in such a way that it takes approximately ten minutes until a new block is found and added to the chain. After the block was added to the chain and validated, the miners are starting from the beginning and compete to find the next block.

The PoW algorithm is dynamically adjusting its difficulty, which is regarded as a critical requirement for the secure functioning of an open, permissionless blockchain (Meshkov et al. 2017). A transaction in the Bitcoin network is considered as confirmed when six additional blocks have been added to the chain (Bonneau 2015).

Apart from proof-of-work, several other consensus mechanisms have been established. The type of consensus mechanism that is used considerably impacts blockchain's main attributes, such as transaction speed and finality (block time), scalability, network security or energy consumption (Andoni et al. 2019, 147). The Ethereum blockchain is, for example, still based on proof-of-work but aims to switch over to a less energy intensive consensus mechanism called proof-of-stake (Muzzy 2020). Proof-of-stake claims to provide faster transaction settlement while being more energy efficient but has yet to prove that it can ensure the same level of data security as proof-of-work (Bundesnetzagentur 2019a, 20).

In 2019, more than half of all energy-related blockchain projects were built on the Ethereum blockchain as it enables the implementation of so-called 'smart contracts' (IRENA 2019, 3). Smart contracts can be defined as "a computerized transaction protocol that executes the terms of a contract" (Szabo, 1994). The terms of a smart-contract are automatically enforced by each node of the network if pre-agreed conditions are met, with the purpose to promote fast, trustless contract execution and to remove intermediaries from contract construction (De Filippi, Hassan, 2016; Casino et al. 2019, 56; Song 2018). Some authors have identified smart contracts as a key enabler for decentralized market platforms (Mengelkamp 2018, 872) as these could allow for turning consumers into active market participants (IRENA 2019, 9).

3.3 P2P Energy Trading

The application of a DLT can take three generic functions: to improve processes that are already conducted without middlemen, to remodel operations that usually require the participation of intermediaries or to establish novel systems that were technically unfeasible before without the application of a DLT (Fraunhofer FIT 2019, 17). With regards to the energy sector, a DLT could remodel the operations of energy trading by reducing the role of involved intermediaries and thus open the way for local energy trading systems. This is facilitated due to the inherent characteristics of DLTs that were frequently emphasized to imply several benefits for energy related operations. These include the possibility to perform micro transactions, the settlement of transactions without intermediaries via smart contracts, enhanced transparency (e.g., proof of origin of energy for the customer), secure data logging or censorship resistance (Mengelkamp 2017, 873). The association of these features with the energy sector has led to the development of several DLT-based use cases, out of which P2P energy trading has been considered one of the most promising (IRENA 2019, 11; Andoni et al. 2019, 156).

Decentralized trading of energy on a local level is often taking place in microgrids. A microgrid is a small scale energy system, composed of loads and distributed energy sources as for instance photovoltaic panels, that can be connected to the main power grid or operate autonomously in ‘island mode’ (Imbault et al. 2017, Morstyn et al. 2018, 95). Compared to the set-up of a main power grid, a microgrid can be regarded as a miniature system that has with up to 200 kW clearly defined electrical limits (Andoni et al. 2019, 154). Smart meters are sensors that represent a core element in a microgrid grid, as these devices enable a two-way data exchange between prosumers and consumers, which allows to respond quickly to local shifts in energy supply and demand (Amelang 2017). DLTs can provide the technological infrastructure with a decentralized market platform that in conjunction with the usage of smart meters, energy storage devices and access to a transmission grid, enables P2P energy trading. Green and Newman argue for instance that the implementation of a blockchain in this context could increase trust and the resilience of a microgrid (Green, Newman 2017, 289). This refers to the objective that such a trading platform could contribute to an enhanced coordination of DERs that allows for a stable functioning even if the microgrid is operating in island mode and not connected to the main grid (Morstyn et al. 2018, 97).

The prosumers in the network could consume self-generated energy, store it or sell excess energy to local peers in the vicinity through automated processes. Such an energy trading process can be represented in a simplified way through the following steps: 1) energy generation via distributed energy resources (e.g., solar power or bio-mass), 2) energy amount and prices are set, 3) consumer purchases energy (e.g., through automated trading processes), 4) DLT-based smart meters log transaction data in the distributed ledger (Mylrea et al. 2017, 19; Schwöbel et al. 2018, 60).
In addition, through the implementation of smart contracts (as part of the purchasing process step 3), the role of the energy supplier, that acts as an intermediary in traditional energy trading environments between the generator and the consumer, is aimed to be circumvented (Schwöbel et al. 2018, 59).

However, it is controversial if the usage of smart contracts can facilitate such a “trustless” environment. Song (2018) refers to the issue that smart contracts are still requiring trust in a third party as the value of a physical good (e.g., electricity) has to be linked to its digital representation (e.g., electricity in the form of a digital token), which is also known as the “oracle problem”. Thus, peers who engage in energy trading by using smart contracts would still have to trust an entity (the “oracle”) that establishes this link and guarantees the actual value of a digital token (Ibid.). In the case of energy trading, this link could be established by a special version of a smart meter that communicates with nodes operating in a permissioned distributed system. However, this would somewhat contradict the idea of trustlessness that is often associated with DLTs, as in this case, trust would be shifted to certain previously selected nodes that are responsible for validating transactions. Merz (2020, 92-93) concludes that in the realm of blockchain-based energy trading, functions of participants and processes are already defined for an extended period, and that required logic mechanisms are already embedded in respective applications. In addition, if peers frequently engage in trading activities, it is likely that general contracts will be closed or legal frameworks are already established (Ibid.), which questions the purpose of smart contracts for P2P energy trading.

Considering that smart contracts might not be needed for the implementation of a P2P energy platform leads to the question of how a DLT could be actually designed to facilitate peer-to-peer energy trading, as depending on the type of the DLT, several tradeoffs have to be taken into consideration. On the one hand side, scalability is a crucial element to allow for the processing of micro energy transactions, a feature that is mainly attributed to private, permissioned DLTs. On the other hand side, the safety of the network and transparency (regarding transactions and software code) play a decisive role for peers who value open source solutions and aim for complete self-reliance – characteristics that are rather associated with public, permissionless DLTs (Zimmermann, Hoppe 46).

Moreover, the usage of an energy-efficient consensus mechanism plays a decisive role in order not to undermine the motivation of sustainability behind P2P energy trading, which militates against most public DLTs that are known to be based on energy-intensive consensus mechanisms such as proof of work. This is why most DLT-projects related to the power sector are either focusing on permissioned or consortium (hybrid) blockchains, as these allow for a higher degree of configurability and facilitate for instance the implementation of regulatory requirements, such as data privacy (Bundesnetzagentur 2020, 4)

4. Case study: *Energiewende* and P2P energy trading

This section represents the main part of the thesis in which the presented framework will be applied to the case of DLT-based P2P energy trading in Germany. First a brief historical overview and the current status quo with regards to the Energiewende will be provided. With the ETIBLOGG project, an example will be given that shows how an energy trading approach that is based on a DLT can be implemented. Subsequently, an analysis based on the Panarchy framework will investigate current drivers and barriers with regards to the adoption of this energy trading concept.

4.1 Overview of the German *Energiewende* and status-quo

The German energy transition (German: *Energiewende*) implies a significant change in the country's energy policy and has been identified as the largest eco-political endeavor in the history of the republic. Over a long period, the German energy market was dominated by regional monopolies regulated by the government until a novel directive by the EU (EU-directive 96/92/EG) led to a gradual liberalization of the energy market (Khan 2016, 37-38). In August 1998 the directive was enacted as the 'law on the energy industry' (German: *Energiewirtschaftsgesetz*) with the objective to dissolve regional monopolies and to enable freedom of competition (Ibid.). The German Renewable Energy Sources Act (German: *Erneuerbare-Energien-Gesetz* (EEG)) was introduced in 2000 and provided the legal framework for the transition to renewable energy resources (EEG). It regulates for instance, that grid operators are obliged to connect renewable energy facilities to the grid or that renewable energy has a priority for getting forwarded or fed into the main grid (Umweltbundesamt 2019). A further incentive was the enactment of the *Stromsteuergesetz* in 1999, which stipulates the exemption from electricity tax for renewable energy if certain conditions are met (StromStG § 9, 1).

In June 2011, the German government decided to completely phase-out nuclear power until 2022, which was a swift response to the nuclear disaster of Fukushima Daiichi. Three days after the catastrophe took place, chancellor Angela Merkel carried out a moratorium, which led to the immediate removal of seven nuclear power plants from the power grid (Strunz 2014, 153). This can be considered as a crucial turning point in Germany's energy policy, as only two years before the federal government decided to postpone the phase-out of nuclear power (Fuchs, Hinderer2014, 360). However, this decision was quickly revoked and instead the transition to sustainable energy generation accelerated.

In addition to movements against nuclear power, three further main drivers with regards to the *Energiewende* were identified by Radtke et al. (2018, 23-24): the debate about climate change, concerns regarding energy security and the possibility for citizens to engage in energy topics. Considering that Germany is responsible for the sixth-largest carbon dioxide emission worldwide (UCS 2020), climate change debates reinforced the importance of the energy transition to meet climate protection targets. Energy security pertains to the dependency on imports for energy generation. Germany is now to 70% dependent on imports for its energy generation (Umweltbundesamt 2020), which means that the energy transition would not only have economic impacts, but would also improve the security/reliability of the energy supply (Mika, Goudz 2020, 4). The third driver refers to citizen engagement, which pushed the change in energy policy forward. From the 1990's on several municipalities emphasized the role of distributed generation of energy for a sustainability shift and were elaborating local concepts with regards to renewable energy resources (Späth, Rohraacher 2014, 109). This was for instance shown in Germany during the initial dissemination of solar technology, which originated on a local or regional level and rather independently from central actors such as incumbent energy providers or the federal government (Fuchs, Hinderer 2014, 356).

The core objectives of the Energiewende are (Agora 2018, 2; see Appendix 1):

1. Reduction of greenhouse gas emissions
2. Nuclear phase-out
3. Increase the share of renewable energies
4. Promotion of energy efficiency

In 2017 Germany represented the seventh biggest energy market worldwide (Schiffer 2019, 1) and contributed with a share of 15.3 % to the overall energy production in the EU (Eurostat 2019, 11). Nowadays, the German energy market is characterized by an oligopolistic structure, dominated by five utility companies, which contribute to more than 70% of the countrywide energy supply (Statista 2019). However, the number of independent prosumers is steadily growing, which is reflected in the amount of privately installed photovoltaic, wind or biogas plants. In January 2020, Germany counted for instance over 1.7 million solar power energy plants, an increase of approximately 100,000 compared to the previous year (Roider 2020). Table 1 lists the shares of the German electricity mix in the first quarter of 2020.

Table 1: Structure of electricity mix in Germany (in percent), first quarter of 2020

Conventional Energy Resources			Renewable Energy Resources		
Coal	Nuclear	Natural Gas	Wind	Biogas	Solar
22.3	11.6	12.7	34.9	5.5	4.8

Source: Author's illustration, based on data: Destatis (2020)

The first quarter of 2020 marked the first time in history, that the share of renewable energy resources on the overall electricity generation in Germany outperformed the share of conventional energy resources (Destatis 2020).

With the Law on the Digitization of the Energy Transition *(German: Gesetz zur Digitalisierung der Energiewende*), the expansion of ICT for the energy transition was given even greater emphasis (Schwöbel et al. 2018, 55). In the power sector, digital technologies can be used for monitoring, enhanced operation (near real-time), for establishing new market designs or to implement new business concepts (IRENA 2019, 5). The digitalization of the German energy transition is however still in an early development stage and main challenges are to digitize business and administrative processes further, to find new digital models to engage with customers and to implement digital technologies in order to facilitate the operation of new energy networks (Mika, Goudz 2020, 32). The amount of decentralized energy suppliers backed by ICTs is steadily increasing in Germany and multiple utility companies have identified novel platform solutions based on DLTs as a potential driver for the energy transition (Bundesnetzagentur 2020).

4.2 ETIBLOGG

ETIBLOGG is one of four research projects, supported by the German Federal Ministry of Economic Affairs and Energy (German: Bundesministerium für Wirtschaft und Energie) to explore blockchain based initiatives for the power sector. One characteristic of current wholesale energy markets are fixed prices, which do not respond quickly to the volatile availability of renewable energy sources (Mengelkamp 2018, 870). However, the introduction of market-based flexible energy pricing at the local grid level could contribute to a more efficient use of resources and thus improve the system's overall stability, leading to a positive impact on higher network levels (Gitschier et al. 2020, 44). ETIBLOGG seeks to enable such a P2P energy trading environment with market-based, flexible energy pricing by linking smart meters, blockchain technology and smart grids on a local level (Ibid.).

In ETIBLOGG's concept, prosumers and consumers are connected via a "blockchain device" in form of Raspberry Pi's to a decentralized trading platform (ETIBLOGG 2019). The trading of electricity is enabled through a decentralized auction system based on buy and sell orders, which is supported by bidding agents and that allows for electricity trading in 15 minutes intervals (Gitschier et al. 2020, 45).

The main idea is to achieve an approximate equalization of local energy generation and consumption to relieve the main grid and thus to minimize the residual load level (Merz 2020, 584). The residual load is the difference between the electricity demand and the supply of renewable energies that are fed into the grid (Edelmann 2015, 22). Due to the volatility of renewable energies (e.g., dependency on weather conditions) the residual load is fluctuating and the supply of such energy to guarantee the functioning of the system can be expensive (Gitschier et al. 2020, 44). A flexible pricing system, that focuses on near real-time energy trading could counteract the high differences in load and supply of renewable energies and enable customers and producers to respond swiftly to price signals (Ibid.). This could incentivize the participants in the network to conduct regular adaptation with regards to generation/consumption depending on current price developments. Producers could for instance store energy during peaks in batteries or consumers could delay consumption during low levels of energy supply (Gitschier et al. 2020, 46). The proposed approach is planned to be complemented by an external energy supplier that is responsible for providing energy in case the residual load is positive (Ibid.).

The backbone of the ETIBLOGG project is a permissioned blockchain solution developed by a private company that promises fast transaction speed while relying on a consensus mechanism called 'proof-of-authority' (Statement 9). This consensus method to reach an agreement regarding data in a distributed network, promises a block time of one second and final transaction settlement after approximately 600 ms (Ibid.). The proof-of-authority consensus algorithm is for instance also used by Microsoft Azure or IBM's Hyperledger to take the advantages of blockchain technology while also providing privacy benefits (Binance 2020). Consensus mechanisms like proof-of-authority however limit the access for validating nodes to a certain amount and contradict the idea of open source and decentralization that is often associated with blockchain technology.

4.3 Analysis

The German energy system reflects the characteristics of a complex eco-system that is composed of a variety of interconnected technological, political, social and economic structures (Strunz 2014, 150; Miller et al. 2015, 29). Several authors have conducted quantitative and qualitative research to assess the resilience and the transition status of the German energy system (compare Jesse et al. 2019, 8; Strunz 2014; Schlör et al. 2018). In this context, a differentiation between a socio-technical and a techno-economic comprehension of an energy system may be made (Jesse et al. 2019, 8). While the latter reflects "on cost-benefit, cost-effectiveness, and techno-physical integrity" (Ibid.), a socio-technical understanding seeks to include the interconnectedness and interdependence of stakeholders and their social and economic impact on the progress of the system (Ibid.). Strunz (2014, 150) analyzed the German energy system based on a socio-technical understanding and states that a regime transition from depleting fossil fuels to a regime based on renewable energies has already been achieved in Germany, which can be confirmed referring to the performance of renewables in the first quarter of 2020 (Table 1). However, the question arises through which systematic set-up (decentralized vs. centralized) the transition can be accelerated and thus the resilience of this new regime sustained (Ibid.).

A shift from the current energy paradigm based on centralization to a decentralized one entails apart from technological and economic, also social and political changes (Miller et al. 2015), which becomes apparent considering the role of new emerging actors that could challenge the status quo (Fuchs, Hinderer 2014, 355). As indicated in the EU Clean Energy for all Europeans Package (European Union 2019, 13), individuals will be empowered to participate actively in the power sector, which will enable new governance structures on the local level. The policy trajectory of the *Energiewende* towards a 'soft path' with a strong focus on localisation (local generation and consumption) or a 'hard path' with the reliance on large-scale incumbent energy providers for energy supply will be decisive for the development and adoption of emerging concepts on the local level such as decentralized energy trading concepts based on DLTs.

According to Folke et al. (2010) the effect of transformation on smaller scales can positively impact the resilience on larger scales in complex systems. Similar to the diffusion and growth of renewables in general, an impact of larger magnitude on the present energy paradigm through P2P energy trading concepts would require: 1) an increase in the number of initiatives (replication), 2) increase in the size of initiatives (up-scaling; e.g., from the neighborhood to the city district level) and 3) cross-scale effects (jumping-scale; e.g., mainstream adoption by incumbents) that instigate broader implications for the energy system (Seyfang, Haxeltine 2012, 389-390). However, considering the German case, P2P energy trading platforms based on DLTs, as shown with the ETIBLOGG project, are concepts that have not left the simulation phase yet (Statement 2) and hold thus a rather low maturity level. These concepts have to cope with a high level of uncertainty in an extensively regulated market, which presently inhibits the implementation of all of these points.

The transfer of P2P energy trading and DLT to the Panarchy framework allows to analyze the position of this particular energy concept in the constellation of the energy system and to derive motivating as well as inhibiting forces. By adapting the idea of adaptive cycles, such projects can be identified as an emerging niche development in the power sector, which incorporates the characteristics of small, but fast-moving adaptive cycles. Through the identification of trajectories and cross-scale interdependencies in a complex system, barriers and drivers can be derived that inhibit or promote the diffusion and adoption of this energy concept. This includes for instance how a socio-technical system on the local level can counteract restrictive factors persisting in the incumbent energy regime (Späth, Rohracher 2014, 107).

As both, the development of DLTs and especially the particular use case of P2P energy trading, are still in an early development phase, the status in the current trajectory of this alternative energy concept can be pinpointed in the very early exploitation phase. As depicted in Fig. 3 larger and slower moving structures in the system that are in the rigid conservation stage, can influence the trajectory of smaller, faster cycles and control (‘remember’, Figure 3) their performance. In the power sector, these large structures include not only large-scale energy providers, which established extensively interconnected structures over the last decades, but also institutions that have geared the regulatory framework to a centralized mode of energy supply. This results in slowing down and delaying the growth phase of alternative energy concepts due to missing incentives for potential users. Moreover, as the landscape regarding ecological energy solutions is diverse in Germany, the concept of DLT-based P2P energy trading has to compete with many other alternative energy concepts that are built on the promise of sustainability, which results in a higher difficulty to reach a broader target group. Hence, a broader adoption of P2P energy trading is highly dependent on how technological-economic feedback mechanisms encourage local peers to form communities and participate in the energy market (Strunz 2014, 154).

To trigger a cascading effect of small adaptive cycles that impact higher levels of the energy system, it is necessary to approach a critical mass (Dangerman, Schellnhuber 2013, 555). The window of opportunity for broader changes is usually enabled by an exogenous factor that leads to perturbations in a complex system and thus opens up opportunities for socio-economic transformations (Ibid.). An example of such an event could be the nuclear disaster of Fukushima that served as a driver with regards to the regime shift from nuclear and fossil power generation to renewable energy in Germany (Strunz 2014, 157). One could argue that the covid-19 pandemic might serve as a sudden shock for the present system and could thus represent an accelerator for a quicker transition to local P2P movements in the long-run (Bauwens 2020). The global financial crisis of 2008 however has been highly detrimental for the development of alternative energy concepts (Fritz-Morgenthal et al. 2009, 1). Similarly, it is expected that impacts on the economy due to the pandemic will curb investments of non-critical supply infrastructure and thus delay the transition to renewables (Lira, Weko 2020, 6), which particularly affects novel energy concepts.

A cascading effect (Figure 4) that is leading to larger structural changes in the energy system via a bottom-up approach of local initiatives driven by DLTs is currently inconceivable due to further other factors. Thus, in the following two sub-sections drivers and barriers with regards to the implementation of DLT-based P2P energy trading will be elaborated and classified into three sub-types: **Localisation,** according to the definition and the motivations discussed under 2.2, **Regulation** and **Technology**. It is however no claim made that this is a complete listing of all factors, but the following points reflect salient aspects that emerged during the literature research and the analysis of the results of the hearing conducted by the Federal Network Agency.

4.3.1 Drivers

The drivers pertaining to localisation include the socio-economic factors elaborated by Walker (2008) that were mentioned under 2.2, but also new governance forms that are enabled by decentralized energy trading platforms. This entails the emergence of new energy classes as for instance completely self-sufficient prosumers that are exclusively based on local renewables or philanthropic prosumers, who could donate excess energy to low-income households in the vicinity (Morstyn 2018, 97). In addition, an increase of distributed local energy communities could potentially enhance the reliability of the energy supply as the overall system is less vulnerable to shocks (Sieverding, Schneidewidt 2016, 3). This point alludes to the impact of a bottom-up introduction of technologies compared to a top-down adoption approach. A bottom-up adoption of a technology is based on natural selection and comprises tinkering on the local level, which exposes the concept to extensive trial and error events and enhances its robustness until it is adopted by a broader audience (Dellana 2019, 53). Other than with a top-down introduction of a technology, systemic risk is not involved, as errors (e.g. power outages) would only affect peers on the local level until the glitches are eventually addressed (Ibid.).

As far as the regulation of P2P energy-trading platforms is concerned, the challenge remains to transpose the directive of the EU Clean Energy Package regarding energy communities into national law, which would incentivize local and decentralized generation of energy (Statements 3 and 4). A further regulatory driver can be found in the discontinuation of the current energy feed-in remuneration in Germany, which will expire for the first plants in 2021 and for a high number of small photovoltaic plants in 2024 (Statement 2). Due to canceled subsidies, this could incentivize small scale prosumers to increase own consumption of generated energy, which might lead to a decrease of liquidity in the energy market as these resources would not be fed into the transmission grid, and could affect the reliability of the energy system (Strüker 2020, 9). Hence, decentralized solutions via a P2P energy-trading platform could represent a valuable alternative for the operators of these units to sell excess energy (Statement 2) and thus ensure security of energy supply.

In addition to the previously mentioned features of DLTs such as the enabling of micro energy transactions, reducing the influence of intermediaries in the trading process or enhanced transparency of logged transactions and data, DLTs could guarantee the energy’s proof of origin and certify in a tamper-proof way which peer in the network provided the demanded energy (Statement 2). A further transparency benefit is that the prosumer would be in control of her own data and could independently decide when and how the data will be made available for the market (Statement 5). Moreover, new technological developments of DLTs such as off-chain concepts could allow public, permissionless DLTs to enable higher transaction throughput and reach the required scalability for energy trading (Wang et al. 2019). As the number of DERs and Internet of Things devices is expected to keep increasing, DLTs could represent the technological infrastructure for settling and tamper-proof saving of transactions (Sieverding, Schneidewidt 2016, 3).

Table 2: Drivers of DLT-based P2P energy trading

Drivers of DLT-based P2P energy trading	
Key factor	Drivers
Localisation	- Ethical and environmental commitment - Local income generation - Enhanced reliability of energy system (less vulnerable to shocks) - Vision of local energy autarky (independence from fixed prices and centralized suppliers) could incentivize broader establishment of community focused microgrids - Democratization of energy trading could motivate citizens to participate - Enables new classes of energy prosumers – philanthropic (donation of energy to low-income households) and/or green
Regulation	- EU Clean Energy for all Europeans Package (2019): clear focus on empowering consumers and prosumers (renewable energy communities) to actively participate in the power sector - Decreasing EEG feed in numeration after 2021 - GDEW accelerates smart meter distribution
Technology	- Enables micro energy transactions - Can reduce role of intermediaries but not substitute them completely - Data sovereignty with prosumers - New developments of permissionless DLTs - Enhanced transparency for consumers: proof of energy origin - Leverage potential of flexible energy pricing and micro energy transactions – real-time energy trading could contribute to enhanced stability/reliability of main grid through energy communities - Distributed energy resources and Internet of Things are expected to keep increasing

Source: Author’s illustration, based on literature review

4.3.2 Barriers

Compared to the use case of DLTs for financial services (e.g., cryptocurrencies) the implementation of a DLT-based P2P energy trading platform is rather complex as the German regulatory framework is not clearly defined yet and current energy market processes render it more difficult to replace intermediaries (Statement 3). The motivation of complete independence and energy autarky driven by such an energy trading platform is currently hard to realize as intermediaries that ensure security of energy supply are still required.

With regards to barriers pertaining to localisation, the lack of required technical infrastructure on the local level represents a central impediment. This concerns on the prosumer side significant investments in generation units (e.g., photovoltaic panels), energy storage devices and smart meters but also investments to adapt the transmission grid on the side of grid operators to allow for the integration of small scale generation units (Zimmermann, Hoppe 2018, 32). Kalkbrenner and Roosen (2016, 67) conducted research on the willingness of citizens to participate in local community energy projects in Germany and concluded that ownership of the generation units, the location (rural areas favored compared to urban) and the income level play a crucial role for participation. In addition, social norms and trust are essential elements that influence the participation in local community projects (Ibid.). Germany is a country with a very high uncertainty avoidance index, which is reflected in risk aversion towards the adoption of new technologies and thus a high level of trust is required to cope with privacy and data protection concerns (Akkaya et al. 2012, 2532).

When referring to enhanced stability or resilience of the energy grid due to larger integration of DERs, it is however also important to mention that the security of energy supply is already very high in Germany. This is reflected in the average power outage per household which was only about 14 minutes in 2018 (Bundesnetzagentur 2019b). Moreover, other energy concepts by incumbent energy providers, who are mainly focusing on “incremental adaptions” (Strunz 2014, 155) but also focus on possibly cheaper alternative energy solutions (e.g. power-to-gas technologies), could smother the interest in P2P energy trading concepts. Other alternative energy concepts could thus disincentivize the adoption of P2P energy trading concepts if switching costs to solutions based on DLTs are too high. The application of a permissioned DLT causes for instance apart from development costs also fees for administration and maintenance (Statement 6) - costs that are usually passed to the users of the network.

At the moment, an implementation of a P2P energy trading platform cannot succeed especially due to current regulatory burdens and the uncertainty regarding the future development of energy policies. Although citizens are expected to be empowered to actively participate in the power sector, the current legal framework provides no incentives for the adoption of DLTs for energy trading purposes, which becomes apparent considering that the role of the prosumer is not sufficiently defined. Based on the current regulation, a prosumer would be regarded as a conventional power supply company, which includes many obligations as for instance: reporting requirements towards authorities, the definition of supply terms or the payment of network usage charges and several other duties (Statement 1 & 9). If a household is engaging in energy trading, the Federal Network Agency has to be notified and energy supply contracts have to be closed, which implies high administrative efforts (Statement 8). Energy supply contacts require for instance the agreement of terms regarding liability, right of withdrawal from contract, compensation schemes, duration of contract, contract cancellation or price adjustments (Ibid.). These obligations are very difficult to manage for a single prosumer who presumably only aims to trade a low amount of energy. Thus, a matching policy based on technical and economic capabilities is currently missing to enable the prosumer to participate in local energy trading activities (Statement 3).

Compliance with data protection and privacy standards represents a major challenge for DLTs, especially in the EU. Considering the characteristic of DLTs as keepers of immutable data records, the question arises how such systems can ensure the implementation of the General Data Protection Regulation (Statement 2), in particular the “Right to erasure” (“right to be forgotten”; Art. 17 GDPR). The General Data Protection Regulation assumes that a single central point takes responsibility, while in a distributed system multiple nodes are storing the data simultaneously (Fraunhofer FIT 2019, 227). DLTs are saving the data indefinitely and a reversal or alteration of data would contradict the main idea of this technology. This is why many solutions are not saving user sensitive data on the distributed ledger and rather refer to the data via hashes instead (Statement 1). However, the data is still stored in many different places and can be read by all peers that are involved. In addition, the consequences of security breaches are unclear, e.g., which peer in the network would be made accountable in case of an error in the network (Statement 7).

The selection of the consensus algorithm for such a P2P trading platform is also a decisive factor. The application of a permissionless DLT that is based on the PoW algorithm represents currently no viable option, due to the high amount of required energy that is needed by the nodes to reach consensus. As indicated under 3.3, permissioned DLTs have been regarded as the current only viable solution for P2P energy trading that enables required scalability and data privacy features. Unsolved is however the role of a trust establishing authority (oracle function), which could be taken by governmental institutions, associations or infrastructure operators to certify the functioning of transactions (Statement 5).

The regulation of smart contracts, if applied to P2P energy trading, is also still opaque in the German jurisdiction (Schwöbel et al. 2018). If smart contracts should be applied in this scenario, it is not clear how consumer rights are taken into account to provide rights of withdrawal, warranty or how the contractor can fulfill the obligation to remedy a defect (Sieverding, Schneidewidt 2016, 3).

Another technological challenge is the increasing amount of data that the nodes have to maintain, which might contribute to higher costs as it is not possible to delete previously saved data on the distributed ledger (Statement 2). The adaptation of present smart meter gateways represents a further central requirement for the interoperability with DLTs (Statement 3). Future advances in the Law on the Digitization of the Energy Transition (GDEW) that regulates smart meter set-up, readout and data submission, are thus a crucial requirement for P2P energy trading platforms (Mika, Goudz 2020, 72).

Table 3 : Barriers of DLT-based P2P energy trading

Barriers of DLT-based P2P energy trading	
Key factor	Barriers
Localisation	- Willingness to participate in community based projects - Location: urban vs. rural - Requires high investments in infrastructure (e.g. smart meters, solar panels, energy storage devices) - Adaptation of transmission grids that allows for the integration of small-scale generation units - Localism can fall into a trap (issue of distributional justice) - High risk avoidance index in Germany – unfamiliarity with this technology - Broad diffusion dependent on adaptive/transformative capacity of actors in the incumbent energy system - Uncertainty regarding future development of regulatory framework
Regulation	- Compliance with European data protection and privacy standards - ‘Right to erasure’ (GDPR, Art. 17) - Prosumer role not sufficiently defined - currently regarded as a conventional power supply company, which is linked to several obligations (§ 3 Nr. 18 EnWG) - Regulation of smart contracts and compliance with consumer rights - No incentive for local generation and consumption from the policy maker
Technology	- Oracle function (governmental institutions, infrastructure providers, associations) - Smart Meter Gateways are missing API’s for interoperability with DLTs - Management of increasing amounts of data - Development, maintenance and administration costs for permissioned DLTs - Trade-off public (permissionless) vs. private (permissioned) DLTs

Source: Author’s illustration, based on literature review

SUMMARY & CONCLUDING REMARKS

The objective of this thesis was to point out to how present structures in the energy system impact the implementation of P2P energy trading platforms based on Distributed Ledger Technologies in Germany. It was shown that DLTs can be regarded as a digital infrastructure that, in the form of "consensus machines" (Rauchs et al. 2018, 22), seek to enable a trustworthy environment which could facilitate peer-to-peer energy trading between local households while reducing the influence of intermediaries at the same time.

The technical features of DLTs were linked to the idea of P2P energy trading and it was stated that DLTs could take the role to reorganize energy operations and open the window for new energy trading systems on the local level. The differentiation of DLT types revealed that the only current viable option is a permissioned DLT that relies on an energy efficient consensus mechanism and thus provides the required privacy and scalability features for P2P energy trading. In this context, it was shown that the idea of smart contracts in the realm of energy trading is questionable not only due to regulatory but also practical reasons.

The case study pointed to the advanced level of the German energy transition that is increasingly based on distributed energy resources. Coping with the transformation of technological infrastructure that secures energy supply and the consequences with regards to the transition process of socio-technical systems implies the main challenge for the German *Energiewende* (Strunz 2014, 156). The conceptual framework included a discussion on P2P, localism and Panarchy and therefore provided a foundation to approach the analysis. The differentiation of localisation as a sub-type of localism served later in the analysis as a key factor to group aspects pertaining to socio-technical drivers and barriers. The reference to the ETIBLOGG project demonstrated that through the application of DLT-based P2P energy trading platforms economic potentials can be leveraged due to flexible energy prices and the possibility to perform micro transactions. Through the lens of the Panarchy framework, the concept of P2P energy trading was examined in the light of the German energy system. The analysis stated that present structures in the energy eco-system, primarily institutions and incumbent energy providers, extensively influence the trajectory of this technology and thus inhibit its growth phase. An implementation of this technology is for instance depending on the adaptive capacity of incumbent energy providers with regards to novel energy solutions. Energy policies impact the path dependency of the energy transition and navigate it either towards a ‘hard’ (centralized) or a ‘soft’ (decentralized) path. Hence, the future development of the German energy policy framework represents a critical factor for alternative energy concepts such as P2P energy trading based on DLTs.

One central barrier with regards to the implementation of DLTs in the power sector is the issue of immutability of data and the compliance with European data protection (GDPR) and privacy standards. It is thus a main challenge for policy makers to ensure that through the application of a DLT, which saves data in multiple points, no surveillance possibilities emerge.

Moreover, the current regulatory framework provides no incentives for small-scale prosumers to engage in local energy trading. Although a driving force in this context is that citizens will be empowered to engage more actively in the energy sector on local levels due to the EU clean Energy package, the administrative obligations on the prosumers side render it very difficult to implement energy trading concepts.

Overall it can be stated that P2P energy trading concepts are inarguably not ready for a broader market adoption and can thus be merely regarded as an emerging niche development in the German energy system and play at the moment a rather subordinate role in the *Energiewende*. However, it is important to keep an eye on the technological development of this rather young technology. To generate momentum that could impact the current energy regime, a critical mass is needed that adopts this technology. At this time it is however not foreseeable that this critical mass will be reached soon, which is reflected in the low maturity level of the technology, but especially due to the high amount of energy policy related barriers that restrict the diffusion of P2P energy trading platforms.

Hence, a cascading effect as illustrated through the Panarchy framework that would influence larger structures in the energy eco-system via a bottom-up approach is not to be expected soon. In addition, a complete decoupling of local socio-technical systems based on P2P energy trading platforms from the current energy system is very difficult as intermediaries are still required to provide access to the grid infrastructure or the residual load to ensure security of energy supply. Therefore, the wider emergence of local, self-sufficient energy communities that aim for complete independence from intermediaries appears to be unlikely in the near future. It is uncertain if DLT-based energy trading platforms will succeed in the German power sector as the current projects are only test networks and commercially successful platforms are not existent yet. However, depending on the jurisdiction of other countries where such regulatory barriers are non-existent, the concept of P2P energy trading might represent already a valuable solution, especially in rural and remote areas where the provision of energy is limited (Okwuibe 2019).

Related to the present energy paradigm, cities and municipalities are considered as crucial drivers for socio-technical changes (Späth, Rohracher 2014, 118). To unfold dynamics that have a larger effect on the current energy paradigm, the cooperation of cities and municipalities to foster the testing of such trading platforms is required. This would in particular include financial incentives on the prosumers side to cope with the high initial costs for the required technological infrastructure.

Concomitant with matching economic incentives, the attitude of consumers regarding local generation and consumption has to change in order to contribute to the diffusion of this technology. For broader socio-technical transformations to happen, it is thus important to promote to the technical understanding of DLTs. This includes knowledge building and sharing on the local level, which could be facilitated by public authorities in cooperation with regional energy providers. A broader rollout of projects like ETIBLOGG that demonstrate the technical opportunities on the local level and that are fostered by cities and municipalities could be an important factor to investigate the willingness of citizens to participate in local energy communities.

Thus, future research questions include to observe socio-technical transformations that could emerge through the implementation of P2P trading platforms but also the challenge of how utility companies can find new ways to integrate the growing number of prosumers into the energy eco-system while enabling a co-existence of different alternative energy solutions (Green, Newman 2017, 290). In addition, if open, permissionless DLTs allow for the required scalability in the future and become less energy intensive, the investigation of this technology in the context of SLOC scenarios (small, local, open and connected) will open for many research opportunities to examine socio-technical transformations (Manzini, M'Rithaa 2016). The experimentation with this technology could then possibly unfold a variety of local and dispersed grassroots movements.

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APPENDICES

Appendix 1. Energy transition objectives in Germany

		Status Quo	2020	2025	2030	2035	2040	2050
Greenhouse Gas Emissions	Reduction of CO2 emissions in all sectors compared to 1990 levels	27.6 % (2017)	- 40%		-55%		-70%	-80-95%
Nuclear phase out	Gradual shut down of all nuclear power plants by 2022	13 units (2020)	Gradual shutdown of 6 remaining reactors until 31.12.22					
Renewable Energies	Share in final energy consumption	13.1% (2017)	18%		30%		45%	Min. 60%
	Share in gross electricity consumption	36.1% (2017)		40-45%		55-60%		Min. 80%
Energy Efiiciency	Reduction of primary energy consumption compared to 2008 levels	-5.9% (2017)	-20%					-50%
	Reduction of gross electricity consumption compared to 2008 levels	2.9% (2017)	-10%					-25%

Source: Revised from Agora 2018, 2 .

Appendix 2. Overview of statements - Hearing of the Federal Network Agency on Blockchain Technology in the power, mail, telecommunications and railway sector

This table represents an overview of the statements provided by stakeholders in the energy sector with regards to the use of Blockchain Technology. The hearing initiated by the Bundesnetzagentur (Engl. Federal Network Agency) included statements given by stakeholders from the energy, telecommunications, mail and railway sector. For the purpose of this research, only statements with regards to the energy sector were filtered and considered. The answers were published by the Bundesnetzagentur on June 30th 2020. The relevant documents are accessible via (20 July 2020):

https://www.bundesnetzagentur.de/DE/Sachgebiete/Telekommunikation/Unternehmen_Institutionen/Digitalisierung/Grundsatzpapier/grundsatzpapier-node.html

Statement Number	Organization	Date (submitted)
Statement 1	Blockchain Bayern e.V.	N/A
Statement 2	Bitkom Bundesverband Informationswirtschaft, Telekommuniation und Neue Medien e.V.	09.01.20
Statement 3	Blockchain Bundesverband e.V.	31.01.20
Statement 4	OLI Systems GmbH	N/A
Statement 5	Energie Baden-Württemberg AG (EnBW)	N/A
Statement 6	BlockcENtive	15.01.20
Statement 7	50 Hertz Transmission GmbH	N/A

Statement 8	Bundesverband der Energie- und Wasserwirtschaft e.V. (BDEW)	15.01.20
Statement 9	Smart Service Welt II Joint statement of the projects BloGPV, ETIBLOGG, pebbles and SMECS	15.01.20
Statement 10	Transnet BW	14.01.20
Statement 11	Wuppertaler Stadtwerke GmbH	14.01.20

Appendix 3. Questions of the hearing conducted by the Federal Network Agency

Question 1: Please provide a brief description of blockchain projects that you are currently implementing or have already implemented.

Question 2: Please describe the blockchain architecture used in your projects (public, consortium, private blockchains, consensus mechanism etc.) and explain why you have chosen the respective blockchain architecture.

Question 3: What potential and what concrete added value does the blockchain technology offer according to your assessment in the telecommunications, postal, energy or railway sector?

Question 4: What are the legal, technical, and economic challenges associated with blockchain technology and which approaches to solving these challenging appear promising in your industry?

Question 5: Are there any specific regulatory barriers that make certain blockchain applications difficult or impossible to implement?

Question 6: What level of maturity has the technology reached?

Question 7: Are there any other relevant topics or issues related to blockchain technology from your point of view in the network sectors?

Question 8: What are your comments on the discussion paper "The Blockchain Technology – Potentials and Challenges in the Network Sectors Energy and Telecommunications"?

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