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Blockchain-based Peer-to-Peer Energy Trade: A Critical Review of Disruptive Potential

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***Abstract*—Motivated by numerous drivers, blockchain-based peer-to-peer energy trade whitepapers surged in the past two years. Assuming disruption through blockchain technology, they envisioned a transformation of energy systems through techno-socio-economic solutions.**

Few impartial and sober assessments of blockchain-based energy projects exist, and many publications praise disruptive potential without further examination. A more distant and critical perspective, however, is imperative for a responsible use of a novel, in particular disruptive, technology.

This review aims at surveying the energy system envisioned by the projects through discussing the projects by their characteristics, their perspective on the transactive energy lifecycle and the energy ecosystem envisioned in the white papers. This review is descriptive and comparative in nature, and attempts to synthesize topics raised in the white papers through methods of grounded theory, as well as assessing the disruptive potential of blockchain technology in energy systems.

Through this and a critical and neutral perspective, it strives to (soberly) contribute to a discussion on the digitization of elements of the energy system, and how blockchain-based use cases can contribute constructively to the problems at hand.

***Index Terms*—Peer-to-Peer Energy Trade, Blockchain, Transactive Energy, Energy Internet, Review**

I. Introduction

A. Motivation

While blockchain technology (BCT) has been around since early of 2009 ([15]), it took around 8 years to achieve wide attention. Coupled with[1] the meteoric rise and fall of Bitcoin value, attention for both the Bitcoin blockchain and BCT reached its peak around the turn of the years 2017 and 2018. Captivated by the rise of the monetary value of Bitcoins and wide public attention for BCT, many value propositions were made, and BCT seen as panacea for issues of any kind ([1] identified 91 potential use cases for energy sectors alone).

As with many other sectors, energy sectors attracted the attention of projects attempting to unleash BCTs disruptive potential, as seen by [14], who identified 140 commercial and research initiatives in the sector. Yet, most reviews on the topic focus on use cases and classification of identified projects; in-depth reviews about the addressed elements of the envisioned energy systems or the projects' disruptive potential are rarely done.

[1]roughly lagging behind a few weeks.

B. Methodology & Structure

In order to address this gap, this paper reviewed 19 projects ([3–12, 16–22, 24, 26]) addressing peer-to-peer (P2P) energy trade through the use of BCT. While numerous projects were identified in the sector, most projects were barely documented or primarily addressed at other use cases. The projects within the scope of this review were analyzed for disruptive potential by identifying the business processes and information flow between actors for different aspects of the energy system. Disruption is understood as upheaval creating a new market or value network by providing performance attributes of values different to conventional solutions. In their seminal article, [2], Bower and Christensen describe how *"[...] disruptive technologies introduce a very different package of attributes from the one mainstream customers historically value [...]"*, which perform poor on important classical dimensions.

Rather than evaluating these dimensions directly, this paper focuses on the disruptive processes based on BCT. This is grounded in an understanding that the disruptive potential of technology lies in the processes and business models it enables. BCT is thus seen as a tool to transform processes within energy systems. Disruptive potential surges when process requirements align with the characteristics of technology; misalignment of the requirements of processes and traits of technologies are often misinterpreted as shortcomings of the technology in question, making a sober assessment imperative.

Many properties are ascribed to BCT, and wide-ranging definitions of BCT are abundant (see e.g. [13, 25]). Furthermore, different data access and validation role concepts exist[2], often making public discourse somewhat convoluted. For the sake of this paper, a blockchain is understood as a distributed data structure of a linear[3] chain of cryptographically hashed blocks containing a hash of the previous block and a list of transactions. BCT is capable of solving the double-spending problem effectively and is suited to create digital scarcity. It enables market participants to transfer assets across the internet without the need for a centralized third party. This allows for processes and business models not relying on intermediaries and political institutions, with distributed governance processes and prosumer empowerment.

[2]public vs. private, permissioned vs. permissionless.

[3]While several branches exist at different times, only one consensual branch persists over a time range relevant for business processes.

With emotive use of language and a focus on a future energy system, many projects rather developed a vision of an energy system than describing their technical solution. Thus, after sketching the vision and technological basis of projects in section II, the remainder of this paper focuses on aspects of the designed energy system. Two perspectives are employed, namely the information and energy flows (described in section III) and the energy ecosystem as overarching perspective (as described in section IV). The paper concludes with an integrative discussion of the disruptive potential of the envisioned energy systems, as well as an outlook for further research in section V. This structure was built upon a bottom-up, grounded theory-led exploration and a descriptive and comparative analysis of the surveyed papers.

II. Project Characteristics

A. Project Motivation

The reviewed projects were motivated by numerous factors, in particular technical, social, economic and political trends towards decentralization and democratization, economic and ecologic pressures, social value shifts, and the transformation of the character of energy systems.

These drivers can be grouped as being of political, social, economic, technical and ecological nature, and are shown in figure 1 in the appendix.

B. Project Visions & Application Context

The reviewed projects sketched visions around democratization, climate change mitigation and efficiency, as well as economic, monetary, social, cultural and technical aspects. Their multitude is depicted in figure 3 in the appendix, and can further be (non-exclusively and somewhat subjective) classified in system-integrative ([6, 12, 16, 18, 20]), economic ([3, 7, 8, 18, 22, 26]) and social views ([7, 8, 11, 16, 19–22, 26]) of the envisioned system.

Of the reviewed projects, [3–8, 10, 12, 16–20, 22, 24, 26] see themselves as platforms for decentralized energy trade between peers or (open) electricity marketing platforms, where [9, 11, 21] view themselves as supplier.[4]

C. Blockchain Design

The design of the blockchain technological layer shows a large diversity between the analyzed projects. While a number of projects ([3, 5, 22], with [9, 10, 19, 26] mentioning the use of state channels) follow a 'traditional' approach of using the Ethereum blockchain with a proof-of-work consensus mechanism, other projects use different technologies, develop custom approaches ([6, 7, 17, 18, 21, 24], with [6, 21, 24] building their customized approach on Ethereum), or pursue a multi-chain approach ([4, 7, 8, 16, 24]). [17] aims to develop different solutions for different regulatory frameworks. Other technologies used include EcoChain ([16]), Qtum ([4]), Stellar ([11]) and SkyLedger ([20]).

[4][21] presents itself as energy supplier and community, [11] as supplier (without P2P for their project in France and with P2P for their African projects) and [9] as commercial electricity retailer in the short term and P2P trade platform in the long term.

III. Transactive Energy Lifecycle

Interpreting transactive energy as *'[a] system of economic and control mechanisms that allows the dynamic balance of supply and demand [...]'* ([23]) to concern distributed power nodes, BCT as distributed technology between peers has received considerable attention by transactive energy projects. The following discusses elements of the sketched energy systems from this perspective through tokens, the grid edge and transactions.

A. Token Design

While tokens are often seen as the representation of an asset or utility with the ability to operate on top of blockchains or funding mechanisms[5], in the following we understand them as transferable data structures that are assigned to one actor at a time, and derive their value from the techno-social system they are used in. Tokens are often seen as the central element of blockchains. Whereas the tokenization of data and physical assets is possible through other technical foundations, BCT solves the double spending problem, i.e. the duplicability of digital assets representing (non-duplicable) physical assets.

Tokenization is a common characteristic for the surveyed projects, also for those that don't explicitly describe a tokenization coin.[6] Tokens used in P2P trading projects are mentioned to be used for transaction valuation and settling (*valuation tokens*), tokenizing physical (electric) energy fed into the grid or representing the right to withdraw it from the grid (*tokenized electricity*), providing access to the platform, assets or data (*access tokens*), to be redeemed for rewards (*reward tokens*), or to encapsulate data (*tokenized data*). The use of these kinds of tokens within the reviewed projects is shown in table I.

Tokens are inherently linked to blockchain technology and easy to create. They are the foundation for creating digital assets. Since they also solve the double-spending problem, technology and disruptive potential through 'the creation of a market using a smart contract' is decisive here.

Table I
Projects using different token types

Token type	Project used
valuation token	[3, 4, 7–12, 16–20, 22, 24, 26]
tokenized electricity	[4, 5, 8, 9, 12, 16, 18, 19, 26]
access token	[3, 4, 7, 8, 10, 11, 16, 19, 22, 24, 26]
reward token	[3, 7, 12, 16, 18, 19, 24, 26]
tokenized data	[8, 21, 26]

B. Grid Edge

The 'grid edge' is the transactive energy term for the (usually low-voltage) point where the responsibility of the grid operator ends and is transferred to other actors. This is

[5]in the sense of US Securities and Exchange Commission regulated assets.

[6]While technically some 'tokens' within projects can be considered coins, for simplicity of discussion and since the focus of this article are applications rather than technical state of their provenance, within this paper, 'native' coins are called tokens as well.

usually done through a smart meter, which separates energy flows in behind-the-meter flows, where usually the prosumer has the decision authority, and the grid-side flows that are in the realm of the grid operator or other actors. While almost all surveyed projects underscore the importance of blockchain-enabled smart meters and accurate meter data, only [9, 18, 24] go beyond the metering process through the use of Home Energy Management Systems, including a number of services.[7] For the integration of physical energy flows and data on the grid edge, three strategies are used, namely meter as an interface ([3, 10, 16, 19, 24]), data bundling / tokenization ([4, 7, 21]) and the use of smart agents ([5, 9]).

Grid assets beyond the meter as parts of the blockchain ecosystem are electro-vehicles and storage facilities ([4, 16, 17, 24, 26]), generation facilities ([4, 7, 20]), internet-of-things devices ([7, 17, 26]) and flexible assets ([7, 16]). Grid-edge devices are often coupled with data analysis (e.g. in [3, 8–11, 19, 24, 26]), or used in aggregated data analysis ([3, 8, 10, 11, 16, 17, 19, 24]).

The grid edge is not BCT-specific and rather the logical location where the prosumer acts. Its disruptive potential depends on the transactions made on the blockchain from the grid edge.

C. Transaction Process

While transactions are the heart of every blockchain-driven system, many surveyed projects did not detail on the transactions used in their system appropriately, and only remarked on the kind or use of transactions. Transactions can be activities that alter the consensus ([21]), compensated commodity products and grid service provision ([7]) or efficient balancing and clearing of rights and obligations for the underlying services ([7]). Most transactions are meter transactions, market transactions, P2P transactions or data transactions.

Meter transactions can be meter readings ([16, 17]), real-time monitoring ([4]) and guarantee of origin ([6, 8, 26]). Market transactions are often limited to P2P market transactions ([3–5, 7, 9, 16, 18, 20, 22, 26]), usually through double-sided auctions or one-sided reverse tender auctions. Data transactions, as remuneration (or transaction-fee exemption) for the provision of data are used by [7, 8, 17, 18, 24]. Further transactions mentioned were asset management ([16]), power purchase agreements ([26]), asset sharing ([7, 16]), contract tendering ([3]), carbon trading ([16] and [8]), account transactions ([4]), non-energy trading ([7]), distributed grid operation services ([7]), and retail-like transactions ([10]). Since none of these were sufficiently detailed, their true disruptive potential can't be assessed.

[7] such as forecasts of electricity data based on monitoring ([24]), energy consumption profile optimization ([18]), energy behavior adaption ([18]), heating & cooling automation ([9]), appliance-specific cost monitoring, identification deviating behavior and return-of-investment calculation on more efficient products, smart appliance control ([24]), electricity certification ([18]), running an Ethereum light client ([9]), energy trading and scheduling ([9]) and information sharing, e.g. in order to react to price signals ([9]).

D. Transaction Valuation

As the token design showed, valuation tokens were used in all projects but [5] and [21].[8] Transaction valuation was only addressed scantly and can be distinguished into payment, clearing, verification and validation. While 'classical' payment in tokens entirely was the preferred option ([3, 8, 10, 11, 18, 19]), improved billing is seen by [3, 9, 11, 19]. Clearing, as either the matching of supply and demand parings or the activities between the commitment and the settlement of transactions was mentioned for matching powerIN & OUT packages ([21]), energy procurement ([10]) and order-book-style clearing by [4]. For transaction valuation, it can be seen that the use of tokens eases the billing process and makes it more transparent. BCT furthermore allows to deploy standardized tokens within minutes. It thus does not necessarily disrupt this process, which can also be implemented with other digital currencies not based on established blockchains, but eases it. Its influence on existing markets and value networks lies in the potential ease of accounting and fringe products that might mature into a future market disruption.

IV. Energy Ecosystem

A. Grid Role

While grid visions range from leaving it as it is ([18]) up to a global, borderless, virtual power grid ([12]), the reviewed projects primarily address microgrids ([4, 5, 10, 17, 20, 22, 26], with [17] and [5] following an integrative approach), or the system as a whole ([11] and [18] don't address changes to the distribution or transmission grid and [24] does not see balancing responsibility to change). The focus of the whitepapers is on grid management, such as energy accounting ([8, 11, 21, 26]), grid state measuring ([7, 8, 22, 26]), power quality measuring ([19]), grid edge asset measuring ([7]), grid monitoring ([24]), loss measurement ([7]), congestion detection ([7]), demand-side and load management ([9, 16]), ancillary service provision ([5], implicitly also [7] and [24]), congestion management ([21, 24]), non-stationary energy response ([16]), transmission fees ([9]) and the integration of flexible assets ([6, 7, 22, 24, 26]).

A further aspect of grid management is balancing. In the whitepapers this was seen through load planning ([5, 10]), network load balancing ([16]), use of a market simulator ([5]), load coordination ([22]), customer segmentation ([24]) and balancing through accounting ([4, 19, 21]). Since these grid management techniques are situated with the grid-responsible parties, the use of BCT alone is not revolutionary; Disruptive potential would come through a shift in roles, which is done to some extent by [17] and [19], who mention a more collaborative balancing process. [19] and [6] take on the balancing responsibility themselves; however, it is not clear whether this is from a balance-sheet (balancing responsible party) or reserve power perspective. With the diversity of the

[8] The Exergy project ([7]) noted that 'nothing financial' goes over the chain, which is correct for the valuation of energy (only payable in fiat). However, data access is remunerated through the XRG token, including it here.

approaches and the lack of detail about what data is provided by which actor for what process, it is hard to assess the disruptive potential of this process.

B. Social Context & Community Building

While most projects did not remark on either the social context or community building, those that did were rather passionate about it. In the discussion we distinguish between the social context as the more aggregated, institutional societal level,[9] as shown in figure 2 in the appendix, and community-building, aiming at bringing together concrete people in a social institution for change.

Communities envisioned by the projects can be (although non-exclusively) distinguished by whether they are directed at the global and system-specific scope ([4, 5, 12, 21]) or at more specific communities ([10, 12, 16, 24]). Participation is not only limited to being part of the community, but also includes economic participation or responsibility ([10, 19, 21, 24]) and supporting community processes ([8, 17, 21, 24]).

These aspects regard social technology, irrespective of the technical basis, but inspired by the values and motivation for it; these could thus easily be implemented through other technologies, and BCT is not a disruptive factor in itself.

C. Legal Aspects

Despite the importance of legal and regulatory aspects for a project to succeed or fail, few projects address them. Given the legal status of BCT and tokens, which is not yet defined as either digital asset or currency, regulatory burdens to P2P energy trade, market communication responsibilities and questions of liability, this is even more surprising.

The heterogeneity of regulatory frames is appreciated by [3, 17, 22]. While legal aspects are primarily addressed through the inclusion of regulative authorities ([3, 7, 16, 17]), [5] also aims for a transformative political process, lobbying for more dynamic power purchase agreements. [19] and [17] argue they take over responsibilities of Prosumers, which could otherwise be problematic. Compliance is argued for differently in different projects by [8, 11, 19]. Further legal aspects concern less regulated contexts ([5]), governance ([3]), legal uncertainty ([24]) and transaction fees ([8]).

D. Market Design

The major purpose of most surveyed projects is to enable blockchain-mediated decentralized energy exchange without intermediaries, or with a lesser role for them. Exchange however does not take place in an economic vacuum, and disruption often depends on whether social and economic technology is able to take over the role of what is displaced. Thus, the design of markets that can fill this gap is crucial for the adoption of the new technology.

Markets identified can be grouped in P2P markets, flexibility markets, spatially restricted markets and wholesale markets.

[9]In the projects this is distinguished by their motivation of operation on societal scale, operating on the product scale, being directed at the social composition of society and being driven by activities.

Table II
FLEXIBILITY PRODUCTS MENTIONED IN SURVEYED PROJECTS

Product	Project
Demand Response	[5, 6, 9, 10, 16, 24]
Demand-side Management	[5, 16]
Load Management	[10, 16]
Load shifting, shaping and sinking	[10, 16]
shared storage capacity	[6, 17, 24]
shared (ownership of) storage	[17]
neighboring exchange and distribution	[17]
localization of production/consumption	[17]
congestion management	[26]

With the exception of projects where the platform operator functions as supplier and [8], which uses over-the-counter-style markets, P2P market mechanisms are organized as double auctions ([4, 17, 22, 24]) or implicit reverse open-bid, multi-item, single auctions, where one buyer puts their demand out for a tender explicitly, for which the vendors compete (e.g. [26]). Several markets are based on retail markets, where vendors compete for (multi-item) customer demand by putting up offers for customers to agree to. Additionally, [21] uses virtual self-consumption, and [16] fills orders in equal increments and cycles continuously until market clearing. P2P markets are price-limited in [24] and [17], with the latter using standard contracts and algorithmic matching.

For flexibility markets, the focus lies on balancing-centric approaches; further flexibility markets are mostly described through the flexibility products used, as summarized in table II. While [3, 5, 6, 16, 26] mention balancing markets, only [26] details them. Their markets are bid-centric, with indirect communication between market participants and a three-stage market process (inquiry, bidding, clearing). They include frequency regulation services with different activation times and are driven by virtual power plants for support services, such as balancing reserves and frequency regulation. [6] claim that their D3A market model can replace wholesale capacity markets, energy-only markets, primary reserves, secondary markets and ancillary products with bottom-up recursive energy by assuming that necessary grid services can be provided by recursive energy and balancing markets that operate from the bottom up. However, they neither explicate their assumptions, nor detail on implementation.

Spatially restricted markets are used as (existing) regional markets ([16, 17, 19]) and local markets, with the latter motivated through the realization that locality of generation sources and consumption plays a role. The focus of local markets varies by market designs and power structures ([6, 7, 17]) and (locational marginal) pricing ([5–7, 9]) or grid optimization thought from the edges ([16]). [17, 24, 26] warn that local markets need not mean isolated markets.

With wholesale markets, white papers focus on accessibility; in the case of [8] and [7] this is done through the implementation of wholesale markets. Connection to existing markets is chiefly seen by projects acting as supplier ([21] and [11]). Interaction with wholesale markets is further noted by [9, 16, 26]. Beyond these markets, carbon or certificate markets ([6, 8, 16, 19, 26]), algorithmic markets ([5, 16, 22, 24, 26]) and retail markets ([3, 16, 26]) are discussed and unspecified direct and derivative markets ([7]) are mentioned.

Most projects don't assign markets the central role they deserve, and few are comprehensive and detailed. Due to its accessible nature as distributed and open architecture, BCT allows for market participation for many and diverse actors, but also requires detailed analysis of these implications. This is lacking in all projects, and needs to be addressed further. Due to the lack of careful analysis in the projects, disruptive potential can hardly be assessed.

V. Discussion and Outlook

This article discussed several aspects of blockchain-based P2P energy trade, in order to assess disruptive potential of this family of use cases. Due to the brevity of the format and lack of detail in the reviewed white papers, no detailed analyses of the processes and envisioned energy systems were presented, and the conclusion is limited to a general assessment of the disruptive potential of BCT in energy systems.

The discussion shows that many aspects mentioned in the whitepapers do not depend on BCT, but are grounded in the vision inspired by BCT values, in particular prosumer empowerment and trust. Most of these aspects could be addressed by other technologies as well. Due to the centrality of digital scarcity and market accessibility however, BCT seems to be particularly suited for this. Yet, a detailed analysis on the technological basis needs to follow. Disruptive potential of business models, information flows and processes needs to be assessed based on whether the existence of data relative to other data (i.e. temporal order of blocks), its resistance to tampering and social consensus is important for the use cases.

The discussion of the reviewed aspects of the energy system showed that most of them are described too macroscopically to make meaningful statements about the merits of blockchain for the envisioned energy system. This is particularly the case for the grid, the social context, community building, the grid edge and the market design. The importance of the value promises of the role of temporal order, tamper resistance and social consensus for these aspects could not be assessed due the lack of specificity in most projects. The right level of assessing their importance are transactions and their valuation, as well as tokens. The value of immutability and tamper resistance depends on the transactions at hand, and should be evaluated individually. At this stage however, no project other than [5] is explicit enough about transactions to assess this. This is particularly frustrating since at this level the true disruptive potential of BCT comes in. The role of social consensus for transactions and their valuation requires a comprehensive project-specific view of the envisioned energy system.

For the use of tokens, blockchain is a suitable technology, which allows for rapid development and easy asset representation. While this is harder (or at least more laborious) to do based on other designs (e.g. blind signatures), it is not impossible. For tokens, the temporal order of blocks is their ownership history (relevant to prevent double spending), and the merit of its resistance to tampering and the social consensus depends on the use case and nature of the token.

On this level of abstraction, BCT does shine with its traits, which however need to be assessed based on the modeled process and its place in the envisioned energy system. A proper assessment of the disruptive value of BCT for a future energy system thus needs to analyze individual transactions and tokens of well-documented projects, and assess the importance of temporal order, tamper resistance and the social consensus of the modeled process from an energy system perspective of specific projects in order to address this gap, providing a rich source of future, more detailed research.

Theoretically, disruption is aimed at new markets through fringe products. BCT very well qualifies for this, due to its different qualities relative to conventional solutions, in particular its distributed and trustless[10] nature, especially when the processes addressed align well with the properties of BCT. Yet, some white papers address an upheaval of the entire energy system at once, implying a different kind of disruption of a system whose core value is system stability. The fragile physicality of the electrical system led to a complex system of roles and processes for ensuring system stability, posing high requirements on solutions aspiring to replace it. Incremental improvements, pilots and fringe projects proving their merit would face less resistance of system responsible parties then the great attempt to turn the system inside out. Disruption can't be an end in itself, and disrupting a system with a high requirement for stability might not be worth the risk.

System disruption needs to be well-grounded and embedded in solid research. Solutions need to be proven and demonstrated, if not in a field test, then in a synthetic environment with real stakeholders. Disruptive proposals often lack the scientific depth to convince taking real-world risks. This calls for systematic investigations of alternative system designs involving stakeholders within the appropriate research infrastructure, and this is a gap that future research needs to address.

System transformation occurs when pushing and pulling forces come together. This review strongly focused on the push side, with projects developing a product from the technology side that is driven by their vision, while the pull factors need to come from the domain. These factors focus on shifted roles of actors and the energy system paradigm and system stability. Bringing together the push and pull factors requires an integrated vision that understands the role of current stakeholders and processes for disintermediation. It will only work if its technically possible, empowerment is necessary, it is economically favorable and the business cases are attractive. The answer, however, lies not in the technology, but in how the technology can improve inefficient business processes.

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[10]Through transparency, verifiability, immutability, non-dependence on political institutions and process integrity of data.

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Appendix

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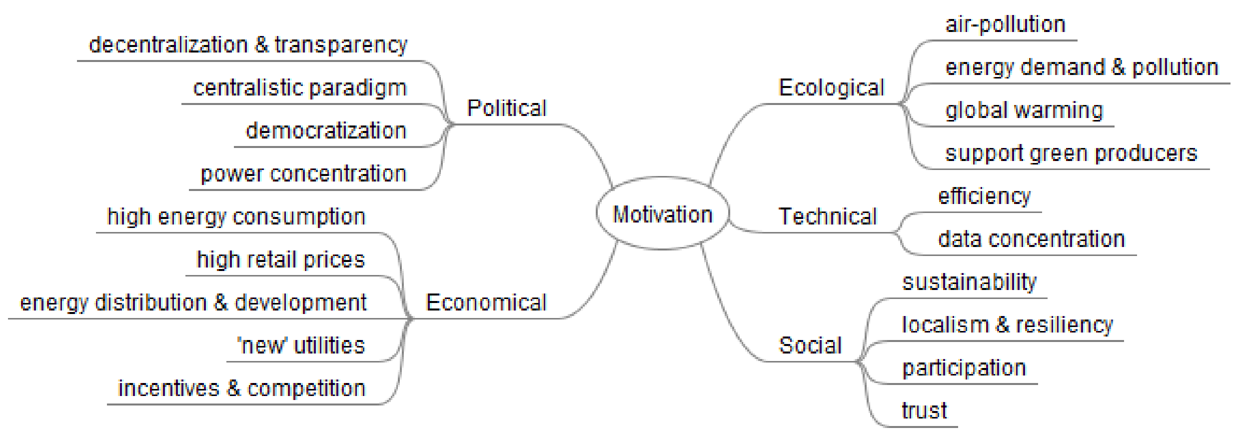

Figure 1. Motivation of Reviewed Projects

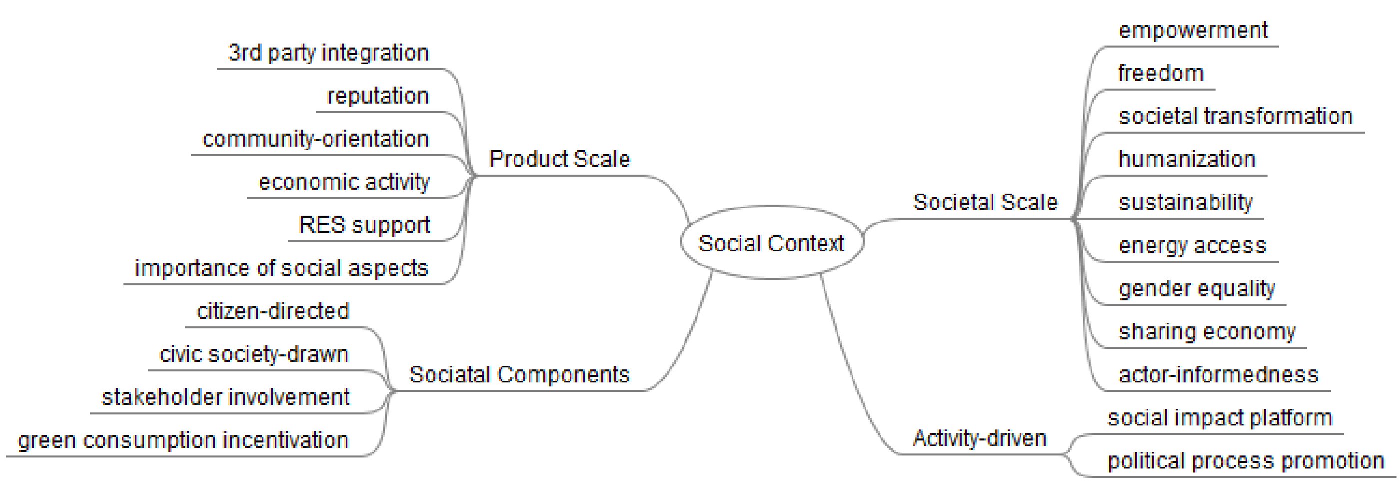

Figure 2. Motivation of the Social Context of Reviewed Projects

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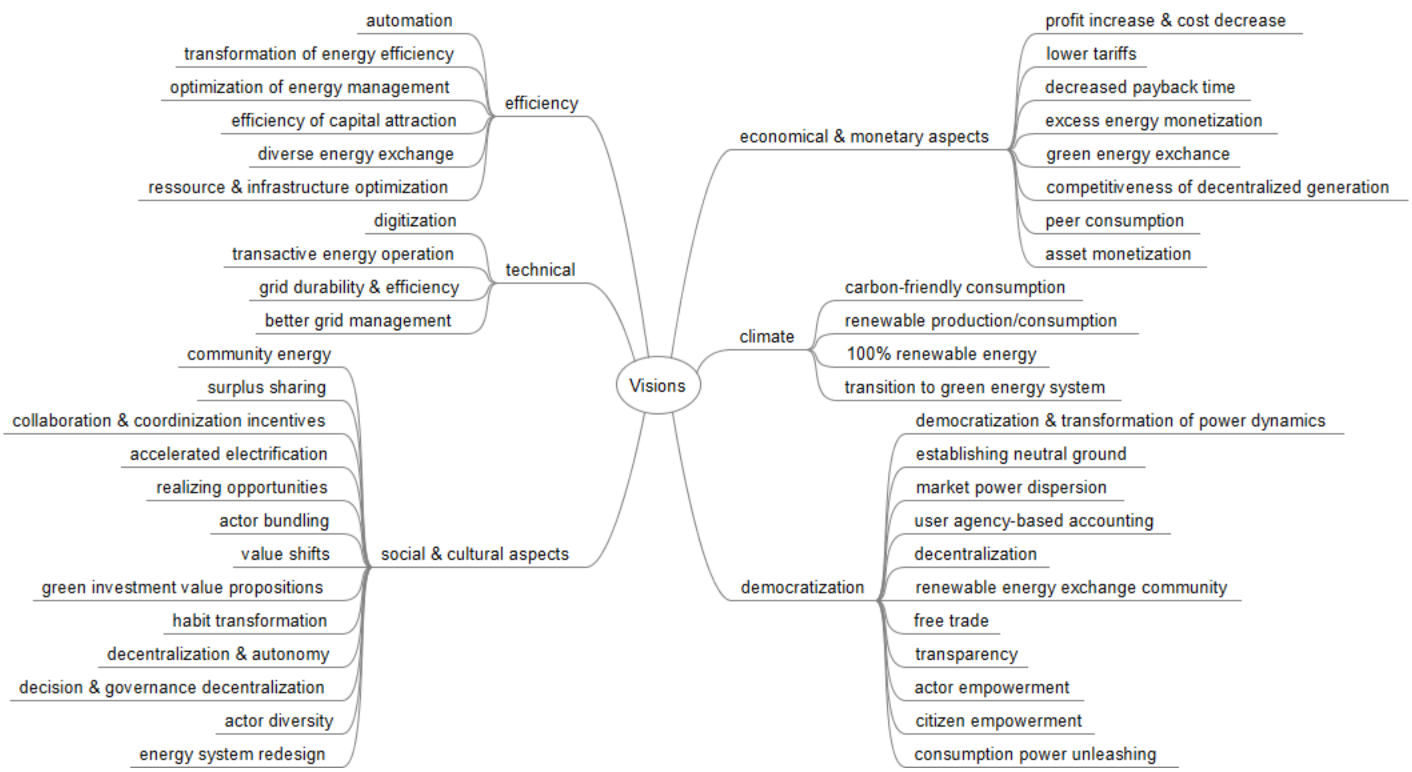

Figure 3. Energy System Visions of Reviewed Projects