Micro Scale, Macro Impact: The Outcomes and Landscape Features of Blockchain-Based Peer-To-Peer Microgrids

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Abstract

As the climate crisis threatens lives and livelihoods, innovations of energy systems across the globe to become cleaner, more efficient, and resilient will be crucial in the struggle to reduce greenhouse gas emissions and mitigate the adverse effects of global warming. In the last decade, blockchain technology has been implemented in many fields, including the energy sector. Extensive literature discusses the potential applications of blockchain technology, a secure peer-to-peer networking paradigm, to energy projects, but relatively few blockchain-enabled projects have actually been implemented. Based on case studies of three peer-to-peer electricity microgrids that utilize blockchain-based trading platforms, this study examines outcomes that blockchain can bring to an energy project, whether environmental- and energy-related, or social and economic. The study examines the Brooklyn Microgrid, the Landau Microgrid Project, and the Water Lilies project in Bristol, UK, three of the relatively well-covered microgrid projects. The analysis finds that blockchain synergizes well with clean energy technologies like rooftop PV solar and electric vehicles, decreases the cost of renewable energy for consumers, and increases the resilience of energy systems. The findings suggest that blockchain-based peer-to-peer microgrids are beneficial energy projects and may be worthwhile investments for broader implementation.

Introduction

The energy system is perhaps the most critical factor in the looming climate crisis. The EPA (2021) reported that 25% of greenhouse gas emissions came from the energy sector in 2020, second only to transportation (27%). The transformation of energy systems of all scales to be cleaner and more efficient would have a drastic impact on society's global ecological footprint. A great deal of research has been invested in exploring the ways technology can be used to improve energy systems.

Blockchain is an emerging technology that offers decentralization and security to applications. There is extensive literature surveying the proposed uses of blockchain in the energy sector. Current research mainly focuses on the technology proposals themselves, the possible implementations of different energy technology ideas, and the scope of which some of these projects have been implemented. Because most of these technologies are in the early stages of development and propagation, there are few reviews evaluating the existing projects that applied these ideas to energy systems. This paper aims to fill this gap by evaluating the outcomes and value of three microgrid energy projects involving blockchain and distributed learning technology. This study finds that these projects bring energy- and emissions-related benefits to their respective broader energy ecosystem, as well as other non-environmental social and economic advantages.

The paper first reviews the technology and architecture behind blockchain technology to give the reader adequate foundational knowledge that is needed to understand how blockchain impacts broader energy projects. The second part of the literature review explores different consensus algorithms that are implemented in different blockchain applications and how this can affect the energy footprint of blockchain platforms. The final part of the review surveys the existing applications of blockchain in the energy sector and informs the choices made for the case studies. Three microgrid projects are then compared to see what outcomes are associated with blockchain energy projects and what social, economic, and political landscape features are present.

Literature Review

The literature review will first consider the design and architecture of blockchain and distributed ledger technologies, then zoom in on scholarly assessments of blockchain's applicability in the energy sector. The first subsection constructs a sufficiently technical understanding of blockchain technology in order to review the environmental and energy footprints of various blockchain implementations. The second subsection explores theorized applications of blockchain technology to energy grids, microgrids, infrastructure systems, renewable energy systems, and other areas within the energy sector, which will inform the cases explored later in the paper. This paper does not focus on cryptocurrency, a well-known application of blockchain technology, nor on any other blockchain applications outside of the energy sector. Also, the review spotlights how blockchain could benefit sustainable energy projects and potential outcomes and benefits, but it does not dive into how these projects can be implemented or subsidized.

Blockchain is a hot topic in the technology sphere, but its definition is not always clear. In this paper, blockchain will refer to distributed ledger technology over a peer-to-peer network that uses a growing list of records, called blocks, to verify transactions on that network. The overarching idea behind blockchain is that it allows an online system to authenticate transactions without relying on one central computer. In the following subsection, the technical foundation will be reviewed to develop a deeper understanding of blockchain and distributed ledger technology. This paper will also define the energy sector as all actors related to energy infrastructure, including energy extraction and refinement, utility companies and co-ops, consumers, producers, prosumers, distribution system operators (DSO), energy policymakers, and others. Much of what this paper focuses on will involve electricity distribution rather than energy production, but all are important and interconnected so a broad definition of the energy sector is appropriate.

Understanding Blockchain

Diving into the technical aspects of blockchain is necessary for understanding the magnitude and variation of the energy footprint of blockchain, as well as why it can revolutionize the energy sector.

Blockchain’s decentralized ledger technology allows for transactions to be peer-to-peer and localized (Swan 2015), a stark contrast to the status quo of network transactions. The term “blockchain” reveals to us the structuring of data in a blockchain network and elucidates the need for distributed ledger technology.

The Internet was popularized as a form of communication between computers across the world as early as the 1980s. The need for transactions to occur over the Internet became more and more apparent as the number of Internet users grew. The most obvious form of transaction is purchasing from some source online, but it also includes currency trading (traditional and cryptocurrency), stock trading, and many other forms. The majority of online transactions rely on a trusted, centralized third party to verify these transactions (Nakamoto 2009); for example, eBay verifies (to a degree) that a retailer will not scam buyers by taking their money without sending the purchased product in return. This verification is guaranteed to happen because all eBay transactions go through eBay servers. The introduction of Bitcoin in 2009 was a proof of concept showing that reliance on a third party is not the only possible implementation of a system for which online transactions could occur. Bitcoin uses a distributed ledger approach, a decentralized alternative to the trust third party status quo.

A blockchain network is a network of computers that all store a copy of a ledger, or record of transactions that have occurred on that network. The term “blockchain” comes from the structure of the data in each ledger: each ledger is a growing list, or chain, of blocks. Blocks are bundles of data that contain a record and timestamp of some number of transactions. This chain of blocks is the underlying structure of each ledger, all of which should be identical in a blockchain network. Note that the term “blockchain” does not specifically refer to the chain of blocks that makes up a digital ledger; rather, it refers to a technology or application that uses this data structure. Transactions are carried out on the network when they are bundled into a block and that block is added to the ledger that each computer keeps a copy of. The protocol by which new blocks are added is explored in the following subsection.

Understanding Distributed Ledger Technology

The revolutionary aspect of blockchain is the protocol by which nodes on the network communicate and add the collective, distributed ledger that each node keeps. Decentralized transaction networks must be defended against double-spending, which is when a malicious actor attempts to spend or send a cryptographic asset, such as a bitcoin, twice. With physical currency, this is defended against because every dollar, for example, is associated with some tangible bill stored somewhere. A computerized asset is stored as a sequence of zeroes and ones, which could be duplicated or double-spent without proper safeguards in the transaction system.

Bitcoin was the first cryptocurrency and popularized much of the technology associated with blockchain technology today. While all nodes store the distributed blockchain ledger, some nodes are also validators, which contribute to the process by which transactions are added to the ledger. On the bitcoin network, these validators are also called miners because the process of augmenting the bitcoin chain and minting new bitcoins is called mining. To prevent double-spending, the bitcoin network uses a protocol that makes verification very computationally expensive for miners. The underlying idea behind this consensus algorithm is that since miners have sunk many resources into the network, they are not likely to undermine the value of a cryptocurrency on that network (Pilkington 2016). To incentivize miners to make this investment, when a new block is added to the blockchain, the miner that constructed that block is rewarded with newly minted bitcoin.

The verification process, or consensus algorithm, that bitcoin uses is the Proof-of-Work algorithm. Every time a new block is to be added to the blockchain, bitcoin miners collect publicly-transmitted, approval-pending transactions and bundle them into a block. Miners check through their copy of the ledger to verify that no bitcoin is being double-spent in any of the pending transactions they collected. Miners then try to solve a cryptographic SHA-256 problem (Nofer et al. 2017) and the first to solve the problem gets their block approved as the newest addition to the ledger. Subsequently, all other nodes on the network will update their ledger to include the newest block. The specifics of the SHA-256 are not covered in this paper, but the crux of the cryptographic problem is that it is essentially guesswork. It is expected that miners must take many guesses (on the order of billions or more) before finding a solution, making the process very computationally expensive.

The Proof-of-Work system has been heavily criticized for its energy footprint. Ensmenger (2018) explained that bitcoin essentially uses exorbitant electricity consumption as its verification system and criticized the technology for its unreasonable energy footprint. O’ Dwyer (2014) found that even back in 2014, bitcoin mining consumed about as much electricity as Ireland. He also found that bitcoin mining was only profitable by using specialty computing equipment built just for mining. Lally et al. (2019) examined a “crypto mining town,” a town in rural Washington with extremely low energy prices that inadvertently attracted many blockchain miners to the area. These miners irrevocably changed the economic and political landscape of the town. Much of the criticism focuses on cryptocurrency applications of blockchain, but some scholars (Leia et al. 2021) call for attention to the energy footprint of blockchain applications outside cryptocurrency, including the energy sector. This investigation of energy sector blockchain application is a key priority of this literature review, which will provide insight into evaluating blockchain’s potential in applications in the energy sector.

Proof-of-Stake (PoS) is another relatively popular consensus algorithm (Nguyen and Kim 2018). Proof-of-Stake requires that validators invest in a stake in a network; they must own some number of coins on that blockchain network. Unlike PoW, validators are not directly competing to mine the next block (via solving the hash problem). Instead, each consensus round, a validator is randomly selected to construct the next block. Other nodes in the networks then verify the transactions in the new block. Validators, both those who construct blocks and those who verify blocks, are rewarded with newly minted coins. If a validator verifies a block that is ultimately determined to be invalid by the consensus, the validator is penalized, losing some or all of its stake in the network. This system disincentivizes malicious attacks in a similar way to PoW, by requiring infeasible costs to be sunk into taking over a network. The difference is that in PoS, that cost is sunk into assets stored on the network itself, rather than computation and energy expenditures.

There are several other consensus algorithms that are variations of PoS (Bach et al. 2018). Proof-of-Burn is very similar except it requires validators to “burn” coins, or delete them from circulation, to achieve validator status. In this system, not only do validators have to sink capital into buying up some number of coins, but they do not even get to hold onto the coins as capital (Karantias et al. 2020). Proof-of-Authority is another algorithm where validator status is earned via some external validation process, perhaps through an organization that manages a blockchain network. This algorithm does undermine some of the decentralization of blockchain, and security concerns exist for some implementations (De Angelis et al. 2018). All of these algorithms require nodes to tie themselves to the network in some way in order to become a validator, whether it be via coin ownership, coin expenditure, or some outside verification.

The Stellar Consensus Protocol (SCP) is another alternative consensus algorithm (Mazieres 2015). Instead of validators being responsible for bundling an assortment of transactions into a block on a candidate chain and the veracity of candidate chains being judged on some anti-malice proof, whether stake or work, SCP provides a structured protocol for the network to collectively review transactions individually, which after consensus and verification, could be bundled into the next block in the ledger. For each transaction, nodes review their copy of the distributed ledger to determine if that transaction is valid. Each node in the network has a set of other nodes in the network it trusts; this set is called that node’s “quorum slice.” If all of the nodes in a particular node’s quorum slice find that a transaction is valid, then that particular node votes to verify the transaction. If some majority of the network votes to verify a transaction based on each node’s personal quorum slice, then that transaction is verified and in a blockchain implementation, bundled into the next block. This consensus algorithm does not rely on computational work as proof of veracity and also eliminates the need for many redundant blocks to be generated and then judged.

It is also worth noting that an underlying principle of blockchain is finding safety and verity in numbers. In each consensus algorithm, all or many nodes must each verify each transaction and all nodes must store the ledger itself. Compared to a centralized system, where one computer is responsible for verification and ledger storage, much of the computation and storage required of a blockchain network is redundant. This redundancy is necessary for the security of the distributed ledger, but this costliness is the price of a decentralized system. Bach et al. (2018) found that one bitcoin transaction consumes more energy than 300,000 Visa transactions. When designing a transaction system, opting for a centralized system, if possible, is much more energy-efficient than a decentralized system, regardless of consensus algorithm.

This section of the literature review is not intended to give the reader expertise in blockchain implementation, nor even to give a well-rounded basic understanding of blockchain; rather, this section serves just to inform the reader about how consensus algorithms play a part in blockchain technology and how different consensus algorithms can influence the energy footprint of a blockchain network. The inner workings of blockchain and variations in the implementation of blockchain networks are too complex for this literature review to cover in full.

The energy requirements of blockchain technology and variations in energy requirements based on consensus algorithms construct an important context for an analysis of applications of blockchain technology in the energy sector. If the overarching goal of the subsequent applications is energy efficiency, saving, and cleanliness, the energy characteristics of blockchain itself must be considered. Blockchain-based solutions that create other problems elsewhere or come at an exorbitant energy cost are not worth pursuing.

Potential Applications of Blockchain in the Energy Sector

As a ubiquitous system that is becoming increasingly decentralized, the energy sector is well-suited for blockchain-based projects. The security that blockchain systems provide also aligns well with the need for reliability and resiliency in energy systems (Andoni et al. 2019). Though the applications of blockchain to the energy sector are limitless, this subsection summarizes three of the most reviewed use cases: microgrids, smart grids, and electric vehicle (EV) networking.

Microgrids are relatively small networks of energy producers and consumers that typically are part of a larger, traditional energy grid, but may break off and function autonomously in island mode. The high diffusion of microgrid systems in the broader energy sphere would create a more decentralized energy grid that would rely less on large energy producers via utility companies and more on local prosumers (Tushar et al. 2020). Prosumers are parties on an energy grid that both produce and consume electricity. An example of a prosumer is a residential complex with solar panels installed on the roof that connects those panels back to the grid (rather than directly powering appliances in the complex). Microgrids are noted for their resilience, responding well to energy grid failures (Siano et al. 2019). Relying on many prosumers rather than one or a few centralized producers lessens the effects of infrastructural damage on the delivery of electricity. In a microgrid with many prosumers, peer-to-peer trading is a significant development that could be enabled by blockchain (Tushar et al. 2020). A blockchain-based platform would enable prosumers and consumers to buy, sell, and trade energy efficiently and securely, while also retaining the ability to trade when switched to island mode. This augmentation of microgrids with blockchain is an example of how blockchain technology can impact energy system resilience and electricity trading.

Smart grids are another improvement of energy systems receiving investment and investigation. Smart grids employ sensors to gather data about energy consumption, production, and distribution, and they attempt to use this data to optimize grid performance and detect anomalies and system faults. As sensor networks are grown, the amount of data generated is enormous; Ahsan and Bais (2017) found that one regional grid in Austin, Texas generated hundreds of terabytes a day. Attempting to transmit this data to a centralized location to process the data puts a burden on IT infrastructure and, at best, precludes real-time data processing. Decentralizing this data processing could create huge gains with real-time optimizations based on the data. Using blockchain as a data management platform for subgroups of nodes accomplishes decentralized data processing and management without compromising the security of the data in the system. Additionally, this decentralization via blockchain might allow consumers to monitor and control their consumption more directly (Aklilu and Ding 2022). As grid management becomes more complex with the rise in sensors and monitoring, decentralizing the management of the generated data might improve the functionality of the energy grid. As such, this application of blockchain technology to smart grids might decrease the energy demands, and subsequent greenhouse-gas emissions, for the area that the smart grid services.

Transportation consumes a large amount of the world's energy; the EIA (2020) reported that 26% of that year's energy consumed in the United States went to transportation. Although the percentage of that that was consumed by electric vehicles was small, the proportion is growing. Vehicles on the highway transportation system all have energy needs and are a part of a system that is far too complex and dynamic to be managed by a centralized source. In a transportation system of electric vehicles, stored electricity could be traded to optimize the efficiency of the entire system; this development is part of the Internet of Vehicles (IoV) idea. Two main systems of electricity trading are investigated in IoV: vehicle-to-vehicle trading, where vehicles directly communicate and transact (Foti and Varvalis 2021); and vehicle-to-network, where vehicles communicate with charging stations or some other part of electric vehicle infrastructure (Elagin et al. 2020). Coupling cyber-physical systems and blockchain networks preserve the ubiety necessary for vehicle-to-vehicle or -network interaction, which otherwise would be impossible to maintain in a centralized system encompassing an entire transportation network. The potential for blockchain technology to impact vehicle-to-vehicle systems may help expand the benefits associated with electric vehicles.

Summary

The interest in utilizing blockchain in energy projects is not limited to academic sources, either. A survey in Germany found that policymakers and utility companies are also aware of blockchain's potential, and many parties are working towards some sort of blockchain-enabled project right now (Burger et al. 2016). Most of the literature seen in this review surveys and compares theoretical use cases, investigates potential drawbacks, and summarizes existing literature. A few journal articles looked at actual projects in development based on the ideas above, but those reviewed dozens of projects, only skimming the surface of each. Few case studies of blockchain-enabled energy projects were found. The subsequent section serves to fill this gap in the literature by deeply reviewing two microgrid projects utilizing blockchain.

As mentioned above, blockchain applications in the energy sector may impact broader energy systems both environmentally, such as grid efficiency and EV prevalence, and socially and economically, such as through grid resilience. This literature review found a lack of consideration in the existing literature of outcomes outside of energy efficiency. Energy systems are deeply intertwined with social, economic, and political systems. Radical changes to energy systems are bound to have significant effects outside the energy sector. Energy projects should be evaluated holistically and from an interdisciplinary perspective. These two identified gaps inform the following research questions: 1) What kinds of energy-related and environmental effects do blockchain-enabled energy grids bring about? 2) What non-environmental outcomes are associated with these blockchain-enabled energy projects? 3) What landscape features are present with microgrid projects?

Methods

This paper examines three energy projects that involve blockchain-backed microgrids: the Brooklyn Microgrid Project in New York, the Landau Microgrid Project in Germany, and the Water Lilies project in Bristol, UK. These three projects were selected for review based on the availability of media and literature covering and reviewing each project. To date, very few microgrids are using blockchain technology, and these three cases are the only ones with public information. Their variation in location, project stage, and project goal also made these projects good selections for comparison. This paper does not cover any energy sector projects besides microgrids, like data management platforms or Internet-of-Vehicle systems. Information about these microgrid projects was gleaned from news outlets (mostly local and regional); stakeholder websites, blogs, and gray literature; academic journals reviewing microgrid projects; and websites about microgrid technology.

Results

Cases are reviewed in the following order: the Brooklyn Microgrid Project, the Landau Microgrid Project, and the Water Lilies project. The review of each case includes background information on project location, the scope of the project, the status of the project and its development, the size of the project, and the stakeholders involved. A technical overview of the project and the architecture of the microgrid is also given. Energy- and environmental-related features and outcomes are given, along with any non-environmental benefits from the project as a whole or the microgrid specifically. Last is a review of pertinent landscape features that may have influenced or driven the funding and development of each project.

Brooklyn Microgrid

Background

The Brooklyn Microgrid, located in the Gowanus and Park Slope areas of Brooklyn, New York, is an older and relatively well-known peer-to-peer trading microgrid. Electricity consumers in the neighborhood can opt in to the network and receive locally generated renewable energy. Homes and businesses in the neighborhood with small-scale renewable generation facilities, like rooftop PV solar, can also opt in to the network to sell excess energy to their neighbors (Brooklyn Microgrid 2019).

The Brooklyn Microgrid primarily consists of two components: a physical electrical grid, and a virtual, blockchain-based platform for transactions. The physical grid primarily consists of existing local electrical infrastructure (owned by the area's independent system operator, Con Edison, Inc.) which is used most of the time to deliver energy to consumers (Zia et al. 2020). Most of this energy comes from local prosumers with rooftop solar photovoltaic panels. However, a key feature of this microgrid is that it also has its own independent, separate infrastructure to support islanding, or the microgrid functioning autonomously.

The Brooklyn Microgrid's infrastructure only encapsulates a 10-block square in Brooklyn and uses traditional electrical infrastructure to reach more prosumers and consumers in western Brooklyn. The project is looking to expand its reach and get more people connected to the network. It also recognizes its status as a pilot project, offering educational services to inform the public about the microgrid and working with numerous researchers studying the feasibility, conditions, and effectiveness of microgrids.

Findings

The transaction platform, originally called Transactive Grid and now called Pando, was originally developed by LO3 Energy, a company specializing in microgrid development (Solutions & Co N.d.; LO3 Energy 2021). It utilizes smart meters that are installed in prosumer and consumer buildings that connect via the Internet to the blockchain platform. LO3's blockchain platform utilizes the Tendermint Protocol, which uses a Proof-of-Stake consensus algorithm (Kwon 2014). Consumers bid their maximum buying point while prosumers bid their minimum selling point. Transactions automatically go through when a price point can be agreed upon. It should be noted that the solar energy a consumer buys from a prosumer is not directly pipelined to that consumer; it is fed back into the grid, and the consumer is effectively paying for the solar energy to be generated for the grid, with certification that that consumer paid for some amount of renewable energy on the grid. However, because this prosumer and consumer network is localized, it's possible that the environmental benefits of rooftop solar are felt by the consumer as they are guaranteed to be proximate to the prosumer.

The project has also recently expanded to include electric vehicles and EV charging stations in its network. EVs and EV stations can sell surplus electricity to the grid as well, allowing for energy to be redistributed to EVs that may be running low, and utilizing EVs as a sort of energy storage. The inclusion of EV charging stations in the microgrid increases the accessibility of charging for EV owners. As such, this increased ease-of-use may in turn incentivize buying electric vehicles and increase the proportion of EVs on the roads around the Brooklyn Microgrid area.

Localization is another key feature of microgrids. It is estimated that 5% of energy in traditional, large-scale, centralized electrical grids is lost in transmission (Lempriere 2017). Localizing energy production and consumption, as the Brooklyn Microgrid does, reduces distribution requirements and likely reduces transmission losses. This makes a grid more efficient overall, decreasing the amount of electricity that needs to be generated to meet consumption levels.

Additionally, as seen with the Brooklyn Microgrid, microgrids enable more renewable energy sources to be connected to the grid, increasing the proportion of renewable energy being generated on that grid. The accessible transaction platform allows consumers to become prosumers without worrying about in-house distribution infrastructure or the economic costs of having surplus electricity generation.

Being able to easily sell surplus small-scale renewable energy, like rooftop PV solar, incentivizes installing rooftop solar. Microgrid projects like this allow for more renewable energy sources in a grid in the form of prosumers.

Some features of the Brooklyn Microgrid bring about social benefits as well as environmental ones; particularly, the islanding ability of the grid. An impetus for the development of the Brooklyn Microgrid project was Hurricane Sandy in 2012. The storm hit New York hard and wiped out its entire electrical grid. If microgrids capable of islanding had been installed at the time, some neighborhoods would have been able to resiliently keep power grids active and better respond to the natural disaster. Resilient electrical grids, such as microgrids, also allow power to be channeled to the most important facilities like hospitals and disaster relief centers, keeping key social and health services open when they are needed most.

An economic benefit of microgrids is that it enables peer-to-peer trading, rather than traditional centralized energy consumption. Consumers who buy renewable energy in traditional grids are essentially paying for utility companies to buy renewable energy from renewable energy generators. Buying energy from prosumers in the neighborhood cuts out the middleman (utility companies), eliminating any price premiums imposed by utility companies in a traditional setup (Zia et al. 2020). This might lower the cost of renewable energy and thus more economically accessible and may increase public support for expanding renewable energy in electrical grids.

After Hurricane Sandy, microgrids were of particular interest to New York state energy policymakers (New York State 2015). Hurricane Sandy exposed the fragility of the energy infrastructure of New York City, and energy policymakers were invested in looking for ways to improve energy infrastructure to withstand future hurricanes and natural disasters. Microgrids were of particular interest; several non-peer-to-peer microgrids were funded, and the feasibility and outcomes of a pilot project peer-to-peer grid were worth investing in as well.

The Brooklyn microgrid has increased the proportion of electricity sourced from renewable energy (solar PV in this case) for the neighborhood in Brooklyn where the microgrid resides. It also has likely increased the number of prosumers in the area, increasing the level of energy generation from renewables. The localization that microgrids like the one in Brooklyn bring might help communities stay resilient in the face of natural disasters, such as Hurricane Sandy. The devasting effect of this hurricane was a key impetus in the public support behind investing in the microgrid project in Brooklyn.

Landau Microgrid Project

Background

Several parties came together to develop the Landau Microgrid Project in Germany. Local energy providers EnergieSudwest and Allgauer Uberlandwerk were working with the nearby Karlsruhe Institute of Technology (KIT) to revamp their energy grid using experimental technology and design ideas to understand what advancements can be made to local energy grids. The groups contacted LO3 Energy about implementing a blockchain-based peer-to-peer transacting platform after learning about the Brooklyn Microgrid Project (Mengelkamp et al. 2018).

The Landau Microgrid is in the Lazarettgarten neighborhood of Landau in Rhineland-Palatinate, Germany. Originally encompassing only 5 homes in 2018, it now includes 20, with plans to expand to more than 100 buildings in the area. The microgrid relies on newly built wiring infrastructure but is connected to the local traditional grid at a single connection point (Richter 2021). Rooftop photovoltaic panels are again the predominant source of energy in the microgrid, in addition to a portion of the grid's energy coming from combined heat and water cogeneration. To supplement the existing rooftop solar, local authorities also have installed additional solar PV in the area connected to the grid. Customers on the grid use a mobile app to adjust their energy consumption preferences, bid price points, and monitor their energy consumption (Wagman 2017). Like the Brooklyn Microgrid, all these data is collected via a custom smart energy meter installed on each building, which communicates with the network to transact. One study (Kirpes et al. 2019) found that a less computationally expensive consensus algorithm than Proof-of-Work would be necessary because computation must be done on user-side devices like these smart meters. This study also found that the blockchain layer of the microgrid was the most important to consider and plan attentively with regard to grid implementation. The blockchain platform communicates with smart meters over the Internet, which monitor the usage rates of the physical electrical grid.

A notable problem faced by the Landau Microgrid project is the inter-seasonal variability in conditions. Solar is much more viable as an energy source in the sunny summers in southern Germany than in the overcast winters. Minimizing the problems associated with this variability is a key priority of the project. Energy storage is a key feature of the grid, connecting batteries to the grid for a more reliable energy supply during the winter months.

Findings

The Landau Microgrid Project recognizes its status as a proof-of-concept and pilot study, but it is just as much of an economic experiment as an energy one. The transaction trends are an important interest of the researchers in the project. They plan to use the results of studying the trading patterns to inform energy policy decisions and incorporate seasonal variability into future microgrid designs (Burger 2017). Most energy markets are on the regional if not national scale, so this is a useful case study of what energy trading can look like at the local level.

Another notable emphasis of the Landau Microgrid Project is allowing customers and prosumers to easily monitor electricity consumption and production. This is necessary for consumers to feel comfortable buying and selling over the blockchain platform. Another beneficial outcome may be an increased awareness and consciousness about consumer electricity by exposing consumers to their exact consumption data.

Germany's *Energiewende*, the country-wide energy transition away from fossil fuels and nuclear energy, is one landscape feature that was directly an impetus for this project's development. Karlsruhe Institute of Technology is a public research center and university, and the two local energy providers involved are both majority-owned by local municipalities. These parties have a direct interest in advancing Germany's nationwide vision of a clean, renewable energy future. Hoping to leverage the existing prevalence of rooftop solar, the project leaders thought a blockchain-supported platform would enable rooftop PV owners to transition to the role of prosumers and allow them to sell surplus solar energy to their neighbors. There was pre-existing popularity in rooftop solar because the local energy providers made it easy and relatively cheap to get a consultation and install panels (Energie Sudwest 2018).

Also related to Germany's *Energiewende,* German energy policymakers saw decentralized renewable-energy networks like the Landau project as easier to develop and implement than sweeping changes to existing energy infrastructure (Karlsruhe Institute of Technology 2021). Rather than tearing down the current energy systems, allowing small, clean, local grids like the one in Landau to pervade the energy landscape of Germany is seen as more feasible and cost-efficient. This notion led to support for investigating blockchain-supported microgrids in Landau.

Again, the synergy between renewable energy sources and microgrids makes these projects worthwhile ventures in energy transitions. The combination of peer-to-peer trading and effective energy storage extends the ability of solar PV networks like the one in Landau to provide clean energy to users well into months with lower sunlight. Germany's *Energiewende*, or nationwide push towards a clean energy transition, was a major factor in the funding and genesis of the Landau Microgrid Project, which was directly influenced and inspired by the Brooklyn Microgrid Project that was analyzed above.

Water Lilies

Background

The Water Lilies project, located in Bristol, UK, is another example of blockchain-supported microgrids. The project is primarily a net-zero emissions housing development that aims to showcase the feasibility of net-zero housing. The project is an eco self-build community, in which shells of houses and apartments are built so that future tenants can customize and put the finishing touches on each home themselves, whether through a DIY plan or by arranging for independent contractors to come (Bristol Energy Cooperative 2022). As the name suggests, all the design is done with sustainability in mind.

Completed last year in 2021, the housing development utilizes rooftop PV solar panels, on-site energy storage in Tesla batteries, heat pumps for heating and water, and energy-efficient building design to reach its net-zero status. The community of 33 residences is fossil fuel-free. EV charging stations in the community are also coupled to the microgrid, allowing electric vehicles to share energy (Jackson 2022). There was no published data found about the blockchain platform used in the Water Lilies project, particularly about the consensus algorithm used. A likely explanation for the lack of information is that project is the newest out of the three analyzed in this study.

Findings

As a component of a larger eco self-build community, the environmental impacts of the Water Lilies project are made possible by the blockchain technology that enables the microgrid aspect of the community. As mentioned earlier, the Water Lilies community is a proof-of-concept for net-zero housing. The need for net-zero and green buildings is critical because over 40% of emissions come from buildings (EESI 2022). The community, which could support over 100 occupants in the near future, is designed to be self-reliant in terms of electricity, too. The microgrid is connected to the city's grid, but the majority of the energy consumed will be produced on-site (O Brien 2020). A key concern of the developers when planning the project was the relatively low number of sunlight hours each year. As such, efficient and capable battery storage is a necessity, especially for the winter months. The developers brought in a 566-kWh Tesla battery for community storage (Bristol Energy Cooperative 2021). The problem of sunlight is also seen in the Bristol Energy Cooperative's decision to invest in a hydroelectric power project elsewhere in the city because renewables beyond solar are necessary for the town to approach net-zero emissions.

In addition to the environmental advantages of this housing project, the Water Lilies project showcases some of the social and economic benefits that can come from eco-friendly housing schemes. First, electricity costs are expected to be lower for residents of the community (O Brien 2020). This might be due to the peer-to-peer nature of the energy trading platform where premiums that would be instituted by middleman energy distributors are avoided.

Second, Newberry et al. (2021) suggest that self-build housing, where buyers expect to build some amount of the house, whether that be the finishing touches or everything except the frame, might be a more cost-effective solution for everyone. They also suggest that self-build houses can allow low-income buyers to concentrate capital on their own personal necessities in the home, and for high-income buyers, they allow customization and free expression in the building. Lastly, self-built communities are also seen as nice places to live with close-knit communities. This may be due to both the design of the community, where community space and walkability are prioritized over individual-centered and car-designed spaces, and the design process of the community, where future homeowners work together to develop values and design requirements to guide the architecture of the community.

Several notable landscape features are found that may have influenced the development of the Water Lilies project. Bristol's local government has declared a "climate emergency" and has pledged net-zero emissions by 2030, a progressive target date compared to other climate goals. Bristol's energy policymakers and decision makers are all-in on clean energy and sustainability. This political stance reflects a public sentiment for sustainability, as Bristol is renowned in the UK for having a history of environmental activism and progressivism (Chitchyan and Bird 2021; Torrens, Johnstone, and Schot 2018).

Additionally, the Bristol Energy Cooperative tied much of the publicity of the Water Lilies project to their then-current round of funding via share offer, allowing Bristol residents or anyone to invest in the cooperative and its projects. As such, they needed to make the image of the project one that is attractive to potential investors, emphasizing the cutting-edge nature, aesthetics, and cost-effectiveness of the project. This may be partly why this microgrid contrasts the others analyzed in that it is being built into a new community rather than on top of existing infrastructure. However, Clean Energy Prospector (CEPro), the company designing the Water Lilies microgrid and starting an organization to manage the microgrid after construction, cited "prohibitively high" costs of integrating the features of ESBCs into existing communities and neighborhoods as reason for not building on existing infrastructure: "engaging and onboarding of each dwelling owner to commit to energy efficiency and retrofit at personal cost, as well as agreeing to communal ownership and use of energy resources against new build's working with a single builder and architect" (Chitchyan and Bird 2021:77). Interestingly, it was also noted that a CEPro project to install a microgrid on an existing, nearby neighborhood stalled when searching for funding.

In this case, blockchain-supported microgrids were a defining feature in a new-age housing development in Bristol, UK, enabling residential buildings to reach a new status of eco-friendliness. Increasing the prevalence of green housing will help reduce the exorbitant ecological costs of construction and building maintenance. Additionally, eco self-build communities that are supported by microgrids bring social benefits thanks to their community-centered design, increasing the quality of life for its residents. A culture of environmental progressivism was a notable landscape feature that may have stimulated the development of and investment in this project.

Table 1. Environmental and Non-environmental outcomes of three microgrids

Project	*What kinds of energy-related and environmental effects do blockchain-enabled energy grid projects bring about?*	*What non-environmental outcomes are associated with these blockchain-enabled energy projects?*
Brooklyn Microgrid	- Disaster resilience: increasing the area's grid ability to stay live during disaster. - Electric Vehicle charge sharing, increasing EV prevalence - Incentive to invest in rooftop solar (as a homeowner and business) - Grid efficiency through localization - Greater share of renewables in the grid - Cheaper renewable energy than sold by local utility company	- Disaster resilience: keeping core health and social services open - Electric Vehicle charge sharing, increasing EV convenience - Lower renewable energy rates
Landau Microgrid	- Incentive to invest in rooftop solar - Greater share of renewables in the grid	- Lower electricity rates - Reliance on energy storage systems for winter energy
Water Lilies project	- Lower electricity rates - Incorporation of solar into living community - Completely renewable energy portfolio	- Community-centered neighborhoods - Self-build housing option - Reliance on energy storage systems for winter energy

Table 2. Landscape features present for three microgrids

Research Question	Brooklyn Microgrid	Landau Microgrid	Water Lilies project
What landscape features are present with microgrid projects?	- Grid failure during natural disaster - Statewide energy plan	- Germany's *Energiewende*: national push towards renewable energy - LO3 energy input (inspiration from Brooklyn Microgrid) - Belief that small-scale projects like microgrids are easier than sweeping energy system changes - Existing rooftop solar from prior ease-of-access	- History of environmental progressivism - Citizen funding via share offer - Declaration of climate crisis - Renewable energy goals

Discussion

Table 1 provides a summary of the findings about environmental and non-environmental outcomes associated with the three microgrid projects, filling in gaps identified by Research Questions 1 and 2. Table 2 similarly reports findings about the landscape features found associated with each microgrid, the chief concern of Research Question 3.

There were numerous beneficial environmental outcomes seen for each microgrid analyzed in the case study, with overlap between the three cases (see Table 1). All three projects were able to incorporate more renewable energy sources into the energy mix for the area serviced by each respective microgrid, primarily by incentivizing prosumers by making rooftop solar more cost-effective via peer-to-peer energy trading. In two cases, the ability to leverage a peer-to-peer trading platform lowered renewable energy costs for consumers, lowering *all* energy costs for residents of the Water Lilies project.

The localized nature of microgrids also was found to be associated with some environmental benefits. First, consuming locally-produced energy through microgrids reduced energy transmission requirements and thus energy transmission losses. Consequently, the microgrid increased the energy consumption efficiency of the grid as a whole. Second, the small scale of microgrids is what enables the islanding ability discussed previously. Allowing microgrids to function autonomously when the connected traditional grid fails increases grid uptime and system resilience.

Microgrids also were found to have several social and economic benefits to their areas as well. As mentioned earlier, the Water Lilies project reduced electricity rates for residents in that community, regardless of whether they were previously buying renewable or nonrenewable energy. Additionally, social and economic benefits were found to be intertwined with some of the environmental outcomes above. The incorporation of EV charging stations in the grid brought ease of access to EV owners (a social benefit). This ease-of-access may eliminate barriers to EV ownership, increasing the proportion of EVs on the road and reducing the emissions of transportation overall. Electrical grid resilience brought about by microgrid islanding allows communities to better respond to energy and natural disasters and provide social and health services to citizens.

Table 2 shows a key finding of this analysis: that all three microgrids studied had a significant landscape feature that may have been responsible for the inception of each project (Hurricane Sandy, *Energiewende*, and local environmentalist culture). All three of these landscape features likely increased local public support for developing these three microgrid projects.

There are several patterns in the analysis above worth discussing. First, blockchain-supported microgrids synergize well with other green energy technologies like renewable energy sources (especially solar photovoltaic energy) and electric vehicles. Second, environmental and social/economic outcomes were often intertwined, as in the case of grid resilience via islanding and electric vehicle synergy. Lastly, the study finds the presence of an atypical landscape feature with each project.

Currently, there are not many blockchain-supported microgrids that exist or are in development. This analysis suggests that is because the necessary public support for a microgrid project requires some unusual impetus.

In future study of the ideas and questions presented in this analysis, more extensive investigative research would be beneficial, specifically, trying to interview parties associated with each project and its development. Another interesting research subtopic would be the existence and outcomes of a blockchain-based microgrid that does not primarily use renewable energy sources. That kind of study may be able to distinguish which benefits from renewables and which come from microgrids themselves.

Conclusion

The micro-scale, localized nature of microgrids is in stark contrast to the size of most traditional energy grids today. Investigating some of the few instances of microgrids with peer-to-peer trading yields interesting insights into some of the drawbacks of traditional grids. Prosumer incentivization, disaster resilience, and transmission efficiency are all benefits that are not present in larger traditional grids. These are all directly related to the localization and open-market nature of blockchain-based trading platforms. Blockchain technology may bring about additional benefits to other systems associated with energy transitions, such as vehicle-to-vehicle communication between EVs. Additionally, as the review of smart grid management applications of blockchain suggests, the benefits of blockchain extend beyond just localization and open trading.

The investigation of blockchain-related benefits in other types of energy projects (including the ones discussed in the literature review) is a further study that would be valuable to energy policymakers. It is possible that the benefits seen in this study associated with blockchain technology may only apply to microgrids, so investigating its application in other energy projects would give clarification on this issue. Also, the impact of social, political, and economic landscape features was not deeply investigated in this study. An analysis of the landscape features that shape the funding and development of cutting-edge energy projects (including but not limited to peer-to-peer microgrids) would provide insight to lobbyists, policymakers, and other parties advocating for energy system innovation. Lastly, this study finds numerous benefits associated with blockchain-supported microgrids and suggests that blockchain technology could improve other energy projects as well. A difficult but worthwhile follow-up study would be quantifying the benefits to perform a precise cost-benefit analysis and see if the costs of microgrid projects outweigh the benefits.

This study found that the development of blockchain-supported microgrids is not widespread; in each case, there was an uncommon, compelling landscape feature that supported the development of the experiment. However, the study and advance of knowledge about the benefits of these projects will increase policymakers' consideration of these projects. Studies that bring light to the benefit of blockchain-supported energy projects can be utilized by energy innovation advocates to increase the funding and development of cutting-edge energy projects. In a broader lens, the areas of Brooklyn, Landau, and Bristol that were reviewed in this paper enjoy both the benefits of traditional grids and peer-to-peer microgrids. Diversifying the kinds of subsystems in the greater energy sphere may also be an inherent way to increase the energy-related benefits, whether environmental, social, or economic. Although this paper does not do a cost-benefit analysis, investing in more peer-to-peer microgrids, at least in areas seeking the benefits that this study found associated with this kind of project, may be a worthwhile investment. Governments that are engaging in transition policies that support digitization, decarbonization, and decentralization would benefit from including experimentation with blockchain-based peer-to-peer trading systems to develop a better understanding of their costs and benefits.

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