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Fundamental Studies of Smart Distributed Energy Resources along with Energy Blockchain

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Abstract: This article studies the broad methodology and major application of smart distributed energy resources (DER) in terms of energy generation, consumption, transaction, and power scheduling. This article simplifies a general DER system into a generic type of integrated DER model. This model is used to investigate a smart DER system that transforms three input parameters, (3I parameters) into three critical output functions(3O functions); hence, the model is also called the 3I3O model. The power at a common connection joint can be enabled by a computer that makes computerized decisions to utilize smart DER. Therefore, the computer algorithm collects various data fed into a computer for deep learning and artificial intelligence (AI) decision making. The authors demonstrate important results and the best solutions to meet power demand, offer an economic advantage and have a low carbon footprint for consumers. Moreover, several network blockchain options are discussed. EBC and DER represent an ideal combination with advantages in managing exergy through so-called intelligent power technology. This technology is discussed in detail and includes special hardware, software, and a broad set of computerized intelligence. Finally, the exergy that can possibly be achieved for smart DER systems is discussed.

Keywords: distributed energy resources; decarbonized power; power utility matrix; renewable energy; energy blockchain; keyless blockchain-as-a-service; exergy

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1. Introduction

In accordance with the Paris Agreement [1,2], multiple sectors have been making great efforts to find efficient and effective solutions to mitigate climate change. Intending to address an increasing trend of carbon emissions and climate change, the world has made an important agreement to curb this trend [1–3]. The field of distributed energy resources (DER) has become extremely interesting, and has attracted considerable attention from researchers [4–6]. Carbon emissions produce greenhouse gases (GHGs) during energy generation. GHGs play a vital role in climate change, and there is an urgent need to reduce carbon emissions. A climate emergency has been declared due to GHGs, which enhance solar irradiance absorption on Earth and lead to rapid melting of glaciers and destruction of fragile ecosystems [2,7]. Energy generation is a significant contributor to GHGs; therefore, it is extremely important to advance renewable energy technologies to reduce carbon emissions [8,9]. In the transition from less environmentally friendly to more renewable energy sources, substantial carbon pricing strategies are necessary to drive carbon emissions to below the 1.5 °C limit [10,11].

In the past several decades, clean technologies have rapidly developed and are commercially implemented, including energy storage (ES) technology, wind power, solar photovoltaics, marine energy, hydrogen fuel cells, and biofuel energy [12–20]. The recent exponential growth in energy consumption has led to an emergent need to identify renewable energy sources that can operate economically on a large scale.

For example, scaling up renewable energy operations is challenging for many reasons. Electricity generation can be unstable on a daily basis: solar energy cannot generate power at night and wind may not generate power under certain daily and seasonal weather conditions. Despite these challenges, many countries have developed advanced technologies that enable them to use renewable energy sources [8,9,21].

Carbon pricing includes a variety of low-cost and/or cost-saving operations related to energy efficiency, schedule optimization, alternative energy sources, energy storage and fuel conversion.

Our literature research shows that there are many exciting works published on the topic of DER and on EBC. Masood et al. produced an interesting report about managing the valuable transactive energy and managing energy storage for optimization of both power in different times and carbon reduction during the overall power utilization [22–24]. The EBC promotes transitive energy from all participants safely. Unlike the central power operation, the EBC mode has a distributed architecture that allows the storage and validation of shared energy transaction to all participants. This mode offers superior advantages against grid failures or external attacks [25–29]. Many exciting studies report the related models, design and impacts, and energy transaction of DER systems [23,30–36].

For businesses that cannot operate on a large scale of renewable energy, renewable energy can be collected using microgrids or systems that integrate a variety of complementary power generation and energy storage processes [37–40]. The energy generated by microgrids can be monitored and distributed using sophisticated algorithms that match the energy producer's supply to the needs of consumers, ensuring that power stability and quality are maintained. The Internet of Things (IoT) facilitates information sharing and collaboration among all parties in the energy production and consumption process. In addition to energy producers and consumers, prosumers are becoming common. Prosumers produce and consume energy daily; they can exchange surplus energy with other users or profit from energy-related transactions [41]. Recently, blockchain technology has enabled buyers and sellers to conduct energy transactions easily and transparently [42].

For a wide range of renewable energy systems, there are several characteristic factors of the system in energy function. A discussion of the impact of renewable energy on load forecasting and the carbon economy has recently been reported in the literature [43–45].

Among various system options of hardware and software configuration, the DER system design can have a significant impact on key output functions. The optimal solution of each output function may be coupled to the other functions. Previous studies are incomplete because they handled each key output function separately. Therefore, more research must be done to resolve this relationship.

The power utility matrix (PUM) method [43] provides a typical type of PUM design based on an intelligent energy approach that considers subsystems and critical components. In recent years, exciting progress and discoveries have been made in the field of renewable energy [44–46]. This article studies smart microgrid generation with energy blockchains.

2. Materials and Methods

2.1. Analysis of Microgrid System Architecture

The DER, microgrid, and simplified PUM model used to address the power, cost, and carbon emissions of energy are illustrated in Figure 1. The left side shows the power generation (PG), energy storage (ES), and grid power (GP), which is a large energy source. The right side may include the power output, the user's financials of power, and the carbon-emitted data. Because a microgrid operates more stably and reliably in the grid-connected mode, energy scheduling with optimization mainly focuses on achieving economic and environmental goals. The working scenarios and caveats may be extended to a variety of applications. In other words, the PUM system may have extensions or caveats for every input hardware. For instance, authors have designed an improvement in utilizing dual-energy storage (DES) as one type of energy storage. Researchers have also concluded [13,14] that energy storage batteries have an optimal charge-discharge cycle depth. The ES is one of the critical components in DER. In the following, the important parameter for the depth of the discharge of batteries (DoDb) is investigated.

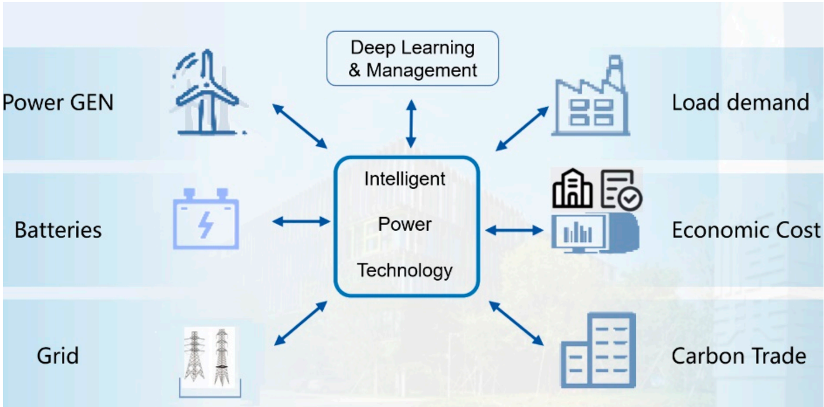

Figure 1. Optimal energy management systems: (1) the left-hand side shows three inputs; (2) the middle column illustrates a high technology with an intelligent interface; (3) the right-hand side shows three output functions for users.

DES technology is proposed to improve the ES life cycle. The new energy management system (EMS) is highly beneficial for maximizing the throughput benefits in the lifecycle. For different types of batteries, their DoDb values may differ, and the corresponding values must be obtained through experiment and curve fitting of the DoDb. According to the above analysis, energy storage batteries have different optimal charge-discharge cycle depths DoDb, which must be determined to maximize the throughput in the life cycle.

The DES module is used in this study. This separates charge and discharge tasks and performs them independently to ensure that the energy storage battery can work optimally as much as possible [47–49]. The specific working modes are as follows. The charged-state energy storage battery performs only the charging task, and starts charging from the initial charging value until a critical condition that is to be defined later such that the state of charge transitions from the discharged state to the charged state. The discharged-energy storage battery performs only the discharge task and discharges from the initial charge value until reaching a critical condition that is to be defined. The above state transition is reiterated throughout the lifecycle. The critical condition for the battery is either the charging level when the energy storage battery increases to SOC, max, or the discharging level when the energy storage battery decreases to SOC, min. The working schematic diagram is shown in in Figure 2 of Section 2.2.

The smart DER system can be implemented as intelligent power technology (IPT) via a computerized processor that optimally schedules power utilization in the DER system.

2.2. Microgrid System Architecture Based on DES Mode

According to the analysis above, we propose a microgrid system architecture based on the dual-ES (DES) mode, as shown in Figure 2. In this system, DES is mainly used to overcome the prediction error and track the microgrid system's day-ahead trading plan in real time. The specific working mode and process are described in the following sections.

The working schematic is shown in Figure 2.

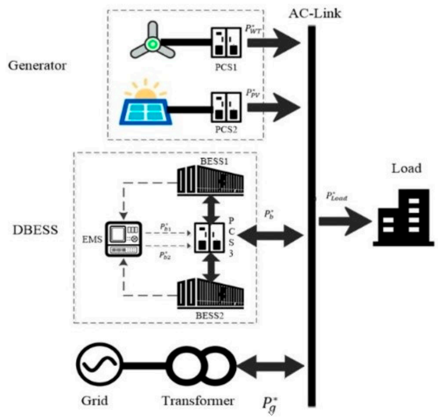

Figure 2. Microgrid architecture with a dual battery energy storage system mode.

3. Results

3.1. Case Study of an Optimized Hybrid System with Distributed Energy Resources

In a decentralized energy system, energy supply contracts can be directly constructed between producers and consumers. Enabling an energy blockchain can result in a considerable number of transactions between producers and consumers, which can decrease the overall transaction cost. Blockchains facilitate direct interactions and transactions between local energy producers and consumers by eliminating the necessity for a third-party monitoring platform.

Comparison of Economic Cost and Carbon Emissions.

Employing the power utility model to resolve the smart PUM system, we computed the 3I3O smart PUM for three critical outputs of the system. In a typical system with wind and solar power generation, along with ES and grid power, the grid power has a specific pricing schedule that differentiates peak, valley, and average hours. Moreover, the inputs involve wind power and solar power specified at slightly above or below 500 kW. The ES is set at 300 kWh. The computer simulation resulted in favorable outputs, as shown in Tables 1 and 2. Table 1 shows that the cost results favor the case of wind-solar light with an ES complementary microgrid and that the peak load in this case demands significantly less of the grid. The load at valley time for traditional wind-solar-without ES has a negative value, where the microgrid outputs power to the grid. The configuration with wind-solar-and-ES demonstrates economic income, as shown by negative value(s). It has net power output during the peak hours leading to financial gains, and it has net power input during the valley hours for overall financial benefit. Moreover, Figure 3 demonstrates the following: (1) that the typical state of battery charges or discharges; (2) that PCC shows the typical energy in-out flow as a function of time during a day.

Table 1. Simulation results cost (conversion of money is approximately $1 USD = 7 yuan).

Methods	Base Load	Traditional Wind-Light Complementary Microgrid	Wind-Light Complementary Microgrid (with ES)
Cost (yuan)	9125	78	−510
Peak load (KWh)	6908	40	−1289
Valley load (KWh)	2608	−398	22

Table 2. Simulation results-carbon emissions (t: tons).

Methods	Base Load	Traditional Wind-Light Complementary Microgrid	Wind-Light Complementary Microgrid (with ES)
Carbon emission (t)	8.5	1.2	0.9
Proportion of RES local consumption	/	87%	94%

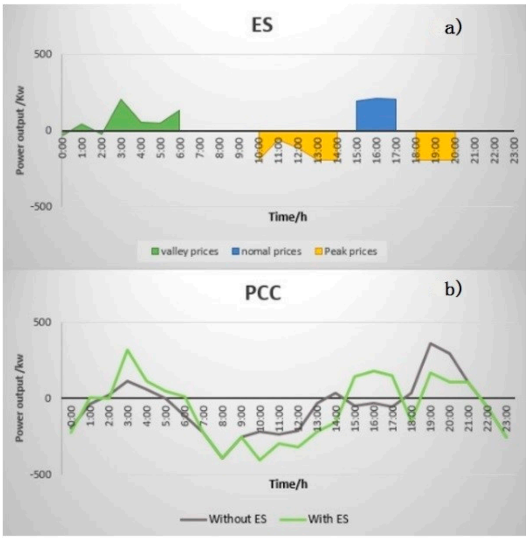

Figure 3. (**a**) Battery state and scheduling of an ES/DER system's energy storage. (**b**) PCC showing a typical energy in-out flowchart.

The carbon emission scenario is demonstrated in Table 2, with the carbon emission unit in tons. The computer simulation resulted in the best carbon emission data for the case of wind-solar light with an ES complementary microgrid.

The renewable energy system (RES) takes the local energy generation, as shown in RES for local consumption, which meets most of the energy demand and that has much lower carbon emissions in comparison to the grid. As expected, the highest proportion of RES that is up and running to meet local demand favors the case of wind-solar light with an ES complementary microgrid with its local power consumption at 94%. Based on Table 2, the carbon emissions are significantly reduced, and the lowest emissions occur for a system with wind-solar-and-ES combination.

It is in general more complex and/or challenging to balance a smart DER system with all the loads than it is with the traditional grid power. These loads have many inputs and outputs. The smart DER system with EBC features requires significant characterization of both the hardware system and software with significant AI. In addition, the big data of smart DER system with deep learning capability should be powerful enough such that the data analytics can provide transparent, accessible, trusted and secure account of the trade ledger of the DER and EBC.

We discovered the 3I3O model on the top level. Furthermore, the management of ES of the smart DER system may embed certain levels of the intelligent power technology (IPT) so that this technology can be more valuable for the extension to the above model. For example, Figure 3 illustrates the advantages to empower the ES by employing DES in detail as follows. The IPT enables the energy storage full cycle that each DES may have sufficient full charge and discharge processes. The battery cycle life is usually very important, and the DES model can be configured optimally when the cycle depth of charge-discharge of Figure 4 is fully utilized.

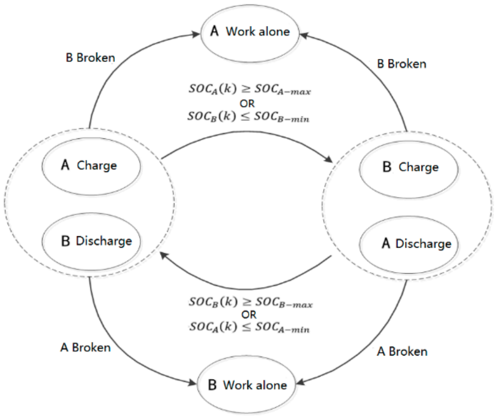

Figure 4. Dual-energy storage charge-discharge cooperative working mode.

A schematic diagram of advantages is shown in Figure 4, where it can be seen that dual energy storage increases both the storage capacity and lifetime.

3.2. DER Transaction Network and Blockchain Options

In a decentralized energy system, energy supply contracts can be directly constructed between producers and consumers. Enabling an energy blockchain can result in a considerable number of transactions between producers and consumers, which can decrease the overall transaction cost. Blockchains facilitate direct interactions and transactions between local energy producers and consumers by eliminating the necessity for a third-party monitoring platform.

There have been several network blockchain options for industrial energy applications. Many researchers have discovered EBC phenomena with attractive transaction features, and much research has been done in this field [50–52]. Researchers have studied, demonstrated and improved knowledge about the recent use of renewable energies and distributed energy technologies.

3.2.1. Private Blockchain Networks

Unlike public blockchain networks, a private blockchain network can be permission-based and centralized. Usually, a private blockchain network is set up within one organization that controls who is permitted to join the network. In terms of energy consumption and efficiency, the newer proof-of-stake systems (PoS) are far superior to the proof-of-work top dogs, such as the Bitcoin blockchain. Any particular private blockchain network can be operated completely behind a corporate firewall and can even reside entirely on the premises.

3.2.2. Permissioned Blockchain Networks

Companies can set up private blockchain networks, which are a type of permissioned blockchain network, which differ from a general setup. A consortium blockchain represents an ideal solution for companies where membership of the network is permission-based so that business transactions with associated rights and responsibilities can be executed.

3.2.3. Blockchain Security and Key Options

When building an enterprise blockchain network, it is critical to have a comprehensive and holistic view for security. A proper security strategy should adopt fitting cybersecurity frameworks, assurance services, and best practices to reduce attacks and fraud risks.

PoS: During the blockchain boom, most players in the industry opted for the promised PoS mechanisms that offer high energy efficiency. The proof-of-stake system has been recommended for the ledger in EBC applications. Power transactions can include many elements, such as mobile batteries. For instance, an important type of mobile battery available in large quantities is present in electric vehicles. Electric vehicle usage will increase steadily in the future. For instance, 199,826 EVs were sold in 2017 in China alone, which surpassed the previous expectations established in 2016. This number is expected to increase to 11 million by 2025 and 30 million by 2030. EVs are increasingly sold in developed countries as well.

Power transaction may be enabled and performed with value units known as tokens. Additionally, these tokens can be exchanged into legal tender (currency) or traded on other platforms as a digital asset. For example, to access the trading platform for power utilities, a smart contract can be created and paid in the form of issued tokens. The trading platform acts as an exchange that can attract more potential users to install battery systems that can stabilize the grid and make the grid user community more active. From previous market efforts, consumers have invested in batteries that are self-sustained and less dependent on the grid. The cost reduction for components such as solar panels and batteries makes usage economically viable without government subsidies. Thus, with a power trading platform, consumers with sunk costs can provide surplus power to other users and receive income in return.

The exchange platform needs to establish an appropriate mechanism to make the distributed electric ecosystem stable, clean, and low-cost. The infrastructure for self-generating renewable energy enables consumers to become self-sustained on power and with possible surplus "off-grid."

3.3. Operator Administered in the EBC Process

While the centralized management of large energy grids is effective, these energy grids are expensive to operate because maintenance and security are extremely important for both the physical and digital assets. If any sensitive data are lost, or equipment is damaged, severe financial and social consequences will occur. Furthermore, over centralization can lead to information asymmetry, and it can be difficult to protect the privacy of consumers. In contrast, distributed energy networks can adopt supply-side point-to-point transaction models. The main challenge energy producers face is to create safe, efficient, and transparent distribution networks that allow symmetric information sharing between energy buyers and sellers. However, there are three major issues when implementing this type of point-to-point system. First, many power producers and consumers compete for a single transaction. Second, there is uncertainty and volatility inherent in every producer's ability to generate energy at a given point in time. Finally, producers may wish to increase their financial gain at the cost of an efficient pricing strategy.

Blockchain technology [50–54] has led to new transaction frameworks that are decentralized and allow users to track data in decentralized markets. By using blockchain methods in both distributed and decentralized energy networks, it is possible to ensure secure, reliable, and transparent transactions. These transactions are controlled by distributed and in-house cost-effective centers rather than outside third-party centers.

Because blockchain transactions are encrypted and not stored in a central location, and it is difficult to tamper with blockchain data. By utilizing blockchain technology in a smart microgrid, users can return unused electricity directly to the grid. In addition, in a microgrid, the balance between supply and demand can be maintained by storing excess power when the demand unexpectedly increases. This type of energy storage approach ensures that the amount of power stays within the predetermined power limits.

After considering network constraints, Tai et al. [55] proposed setting up a central station that can block, modify, or accept transactions based on how much power is available at the current moment; the transaction history is then recorded in the blockchain.

All power producers and consumers must report account numbers and the corresponding entity identities to the power grid before conducting transactions. A complete trading cycle consists of the trading and delivery stages, where the delivery stage of the current trading cycle represents the trading stage of the next trading cycle. These two stages are further subdivided into the free quotation stage, prepayment stage, power delivery stage, and automatic cost settlement stage. Ideally, in a transaction credit score of the system, the number of defaults that occur in distributed energy transactions should be minimized.

A flowchart of the proposed control algorithm is presented in Figure 5, where it can be seen that this algorithm includes power management procedures. The proposed energy blockchain is shown in Figure 4 for energy transactions.

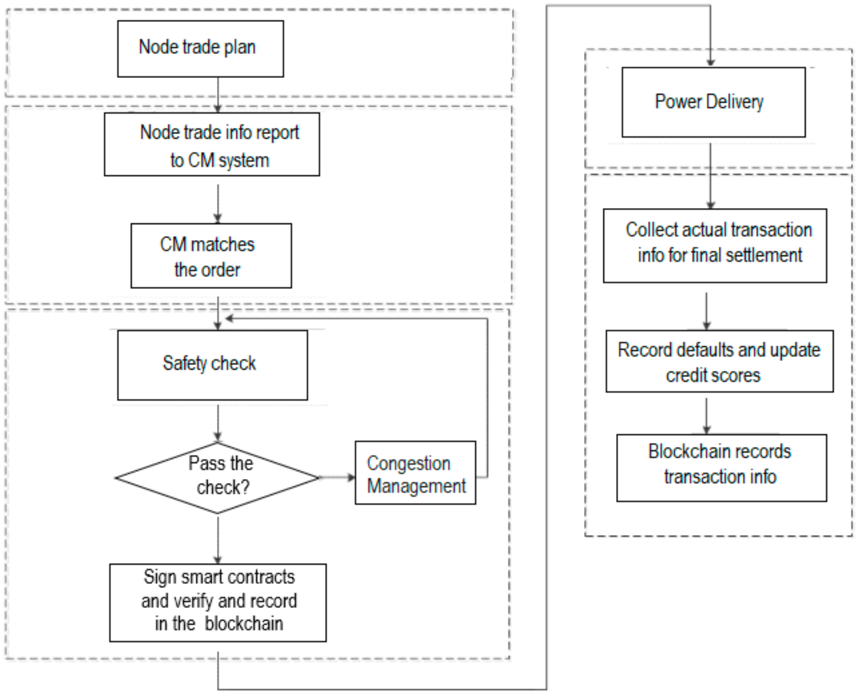

Figure 5. Flowchart of the control algorithm proposed for energy blockchain where CM indicates the central matching server.

The PMU unit monitors its energy values and sends data about them to the POS-Stake or a permission-based network to meet the power needs of prosumers, users, and consumers. The EBC function is to resolve the power supply and demand ecosystem.

3.4. Transaction Data Proven Based on Keyless Signatures

While the centralized station is efficient in matching supply and demand, interested parties face security and trust issues. First, prosumers and centralized management may not trust, but may challenge, each other over transaction information during the trading stage or delivery stage. Second, meters of prosumers can be hijacked by prosumers to present false data. Third, microgrid and central management can be attacked or affected by a virus, and transactional data could be systematically tampered with before being recorded in the blockchain ledgers. The transactional data provenance must be protected across prosumers and central management during each complete trading cycle, i.e., in both the trading and delivery stages.

Previous works have successfully presented keyless signature-based solutions to provide data provenance on power grids [55–57]. This article provides microgrid-management data provenance based on a lightweight, keyless blockchain-as-a-service (KBaaS). The KBaaS is presented in Figure 6.

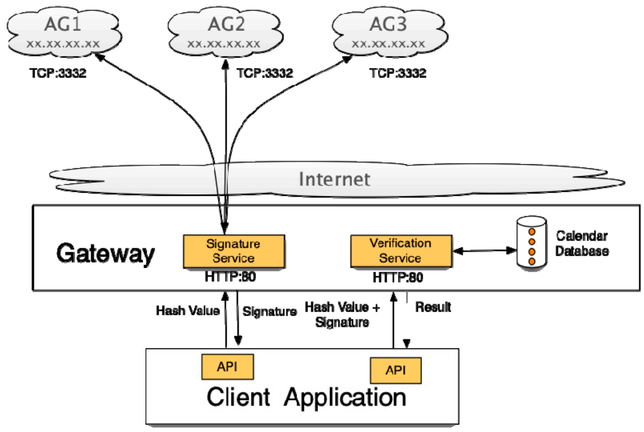

Figure 6. Flowchart of keyless blockchain-as-a-service interfaces.

The KBaaS API can be called upon whenever trading information is sent between prosumers to gateways, and energy records are received by the grid admin in both trading and delivery stages so that both prosumers and management can have nonrepudiation proof for each transaction. Verification services can then be called whenever data integrity must be checked in the full life-cycle of these data.

4. Discussion

In this article, we focus on carbon emission reduction in a smart DER system. First, a carbon reduction method is investigated in light of smart DER systems. The smart DER is optimized according to the 3I3O method of renewable energy management that has facilitated EBC for energy trades. Based on the studies presented in prior sections, both the optimized smart DER and EBC constitute a set of powerful tools during transition to a low-carbon economy. Carbon trade and renewable energies are employed to reduce the carbon emission level to the maximal level possible. The critical output functions are derived from the input parameters through a set of simplified 3I3O power utility matrix models. Based on this model, we have demonstrated benefits through the simulation results.

Second, the computer algorithm collects data that are fed into the computer for deep learning. The computer makes artificially intelligent decisions in delivering power with the optimal schedule of power resources. Moreover, the results favor the hybrid use of complementary wind power and solar PV power with energy storage over individual power sources. The authors recommend that the common connection of electricity offer various intelligent power technologies and that smart DERs accommodate computerized decision making.

Third, several network EBC options are discussed in Section 3. Among these options, for example, a permission-based blockchain and KBaaS interface are studied. Many researchers have previously reported work on EBC that has covered the following four types: public, private, consortium, and hybrid blockchain [19–21,23]. EBCs have many advantages in exploiting valuable renewable power. Smart DER solution can resolve the modern industry pain by fully utilizing renewable energy resources. Moreover, both smart DER and EBC are used to economically implement commercial solutions for net zero goals. Renewable energies and carbon trading are employed to reduce carbon emissions to the maximal level possible.

Fourth, we studied a typical case to approach the exergy of the DER system through the aforementioned intelligent power technology. Moreover, with recent technological advancements, smart DER systems can be implemented with hybrid renewable energies to quickly attain the carbon peak and achieve carbon neutrality in the future.

Finally, determining the exergy of a system is among the top goals of thermodynamics in physics. Smart DER and EBC enable one to extract maximal useful work to achieve the exergy of the smart DER system.

5. Conclusions

This article presents a theoretical study on the power utility matrix (PUM) model that can solve the key outputs from distributed energy resources (DER). The PUM is specified by a 3I3O matrix, and the PUM may deliver the functions or orthogonal variables. The study aims to provide measures for the design and planning of carbon peaking and carbon neutrality. The above PUM model is complete in scope, and it is predictive of DER operation with renewable energies for DER-system designs. There are many aspects of benefits with the outcome of the above predictive designs. First, by accurately predicting the energy output, the optimal use of available energy resources can be achieved. Second, algorithms of energy management optimization can consider both expected and unexpected demands for power to be provided in a stable, safe, and cost-efficient fashion. Third, the key outputs, such as the power, cost, and carbon emission footprint, may be optimized and decoupled from each other when each output is modeled in its eigenspace. Finally, further research is necessary to obtain applicable values of elements of the aforementioned PUM square matrix and the K-coefficients. The trade-off of lower K3j values can be an important marketing tool to leverage K2j for renewable energy drives.

At the microgrid energy transaction level, a peer-to-peer transaction mode based on a blockchain approach can promote transactions with low marginal costs characterized by immutability and high transparency. The proposed approach provides important guidance for smart DER design, construction, and operation.

Author Contributions: Conceived the plan: A.J.J.; Investigation: A.J.J., C.L., J.S. and J.T.; Data analysis: A.J.J., C.L., J.S. and J.T.; Wrote the paper: A.J.J., C.L., J.S. and J.T. All authors have read and agreed to the published version of the manuscript.

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