OPEN ACCESS
Engineering Science & Technology Journal
P-ISSN: 2708-8944, E-ISSN: 2708-8952
Volume 4, Issue 2, P.No. 33-45, June 2023
DOI: 10.51594/estj/v4i2.1287
Fair East Publishers
Journal Homepage: www.fepbl.com/index.php/estj

THE INTEGRATION OF SMART GRID TECHNOLOGY WITH CARBON CREDIT TRADING SYSTEMS: BENEFITS, CHALLENGES, AND FUTURE DIRECTIONS

Afor Avwioroko[1]

[1]Consultant, PwC, Nigeria

*Corresponding Author: Afor Avwioroko
Corresponding Author Email: Aforavwioroko@yahoo.com

Article Received: 11-02-23 **Accepted:** 23-04-23 **Published:** 30-06-23

ABSTRACT

The integration of smart grid technology with carbon credit trading systems offers a promising path to improve the grid efficiency and stability and reduce greenhouse gas emissions. This paper examines the possible interoperability of smart grid technology and carbon credit trading systems. Smart grid technology, characterized by its advanced monitoring, control, and optimization capabilities, offers the foundation for real-time data collection and analysis. On the other hand, carbon credit trading systems create financial incentives for reducing emissions. By combining these two systems, Nigeria can improve grid stability and increase the adoption of renewable energy sources, accelerating the transition to cleaner energy. Additionally, this paper discusses challenges that could hamper the successful integration of smart grid and carbon credit systems such as data security, regulatory compliance, and technological infrastructure requirements. Using case studies and examples, this paper examines the successful implementation of an integrated smart grid and carbon credit trading system, sharing valuable lessons learned and best practices. The paper also highlights the potential for advancements in technology and policy frameworks to promote wider adoption of these integrated systems..

Keywords: Integration, Smart Grid Technology, Carbon, Credit, Trading Systems.

INTRODUCTION

Smart grid is an advanced grid system that integrates advanced digital communication and control systems with traditional power infrastructure (Gungor et al., 2011). Unlike conventional grids, which operate with limited real-time monitoring and control capabilities, smart grids leverage various technologies to enable bidirectional communication between utility providers and consumers. Key components of smart grids include Advanced Metering Infrastructure (AMI) which is a system smart meters that monitor energy consumption in real-time, allowing utilities to gather detailed data on usage patterns and optimize distribution. Another is the Distribution Automation which is the use of advanced technologies such as sensors, switches, and control systems to enable faster detection and response to outages, reducing downtime and improving reliability and operational efficiency. Thirdly, Demand Response Systems which are systems implemented by utility companies to manage electricity demand in response to supply constraints, price fluctuations, or grid reliability concerns. These systems empower consumers to adjust their electricity usage based on these factors, helping to balance supply and demand and avoid peak load periods. Also, the Energy Storage Systems are systems and technology used to store energy for later use. These solutions play a crucial role in enhancing grid stability, integrating renewable energy sources, and managing fluctuations in supply and demand. For example, in a renewable energy grid connected system, batteries store excess energy during periods of low demand for later use, improving overall grid flexibility and efficiency.

Carbon credit trading system, also referred to as emissions trading, is a market-driven mechanism aimed at reducing greenhouse gas (GHG) emissions. It incentivizes emission reductions and encourages innovation and investment in cleaner technologies while allowing for flexibility in compliance with GHG reduction goal. They achieve this by imposing a cap on the total volume of emissions permitted within a specific industry. Within these frameworks, participating entities are allocated or must purchase a finite number of emission allowances. Each allowance signifies the authorization to emit an allocated quantity of GHGs (Zhang, 1998). Allowances are usually distributed through auctions, free allocation, or a mix of both approaches. Over time, the total number of allowances decreases to meet emissions reduction goals. Participating entities can buy and sell allowances on secondary markets, allowing them to respond to changes in emissions levels, market prices, and regulatory requirements (Holt et al., 2007).

Integrating smart grid technology with carbon credit trading systems presents an opportunity to track and improve the effectiveness of carbon emissions reduction efforts (Hua et al., 2022). By leveraging the capabilities of smart grids to collect real-time data on energy consumption, generation, and grid operations, as well as integrating carbon accounting and trading mechanisms, it becomes possible to improve measurement and reporting, optimize emissions reduction strategies, improve market efficiency, and drive technological innovation (Zhao et al., 2016).

Smart Grid Technology

Smart grid is an advanced grid system that integrates advanced digital communication and control systems with traditional power infrastructure (Gungor et al., 2011). A smart grid facilitates bidirectional communication between utility providers and consumers, enabling real-time monitoring, analysis, and control of energy flows. This bidirectional communication requires an advanced metering infrastructure. Typically, smart meters are deployed at consumer premises to measure energy consumption in real-time and communicate data back to utility providers (Pitì et al., 2017). This enables more accurate billing, improved demand forecasting, and the implementation of dynamic pricing schemes. Other components of a smart grid include such as sensors, switches, and control systems integrated into distribution networks to detect and respond to faults, outages, and demand fluctuations. These devices improve reliability, reduce downtime, and enhance overall grid efficiency. Smart grid also makes it easier to implement demand response programs. Demand response programs help to balance supply and demand, reduce strain on the grid, and avoid the need for costly infrastructure upgrades. This empowers consumers with greater visibility and control over their energy usage, enabling informed decision-making, energy conservation, and participation in demand response programs (Gellings, 2020). Smart grids facilitate the integration of renewable energy sources into the grid by leveraging advanced forecasting tools, grid management capabilities, demand response mechanisms, and energy storage integration. By predicting renewable energy generation and dynamically balancing supply and demand, smart grids optimize the use of renewable resources and support the transition to a cleaner and more sustainable energy system. Battery storage systems and other energy storage technologies play a crucial role in smart grids by storing excess energy during low-demand periods for later use during peak demand or when renewable sources are unavailable. This also improves grid flexibility, stability, and enables easy integration of intermittent renewable energy sources (Tan et al., 2021) and (Hung et al., 2016). From the foregoing, it also implies that smart grids play a pivotal role in reducing carbon emissions by enabling the integration of renewable energy. This helps to reduce the dependence on conventional fossil fuel-based plants, thereby reducing carbon emissions. Moreover, by facilitating demand response, consumers adjust their electricity usage in response to changes in energy supply and demand. By shifting energy consumption to times when renewable energy sources are more abundant, demand response helps optimize renewable energy use and reduces the need to rely on fossil fuel-based power plants, thereby reducing carbon emissions. Smart grid can also support the decarbonization of the transportation sector. By synchronizing electric vehicles (EV) charging with periods of high renewable energy generation, the smart grid ensures that more EVs are powered by clean energy rather than fossil fuels (Arvesen et al., 2021). Smart grids also facilitate smart charging practices and use EV batteries as distributed energy storage, enhancing grid stability and further reducing the need for fossil fuel power plants.

Figure 1 shows the structure of distributed dispatch system for EVs participating in grid frequency regulation.

In summary, smart grid technology plays a crucial role in the transition to a low-carbon energy economy. It helps integrate renewable energy, enables increased grid efficiency, and allows consumers to actively reduce carbon emissions. By driving innovation, fostering collaboration, and implementing smart grid solutions, we can speed up our progress toward a more sustainable and decarbonized future.

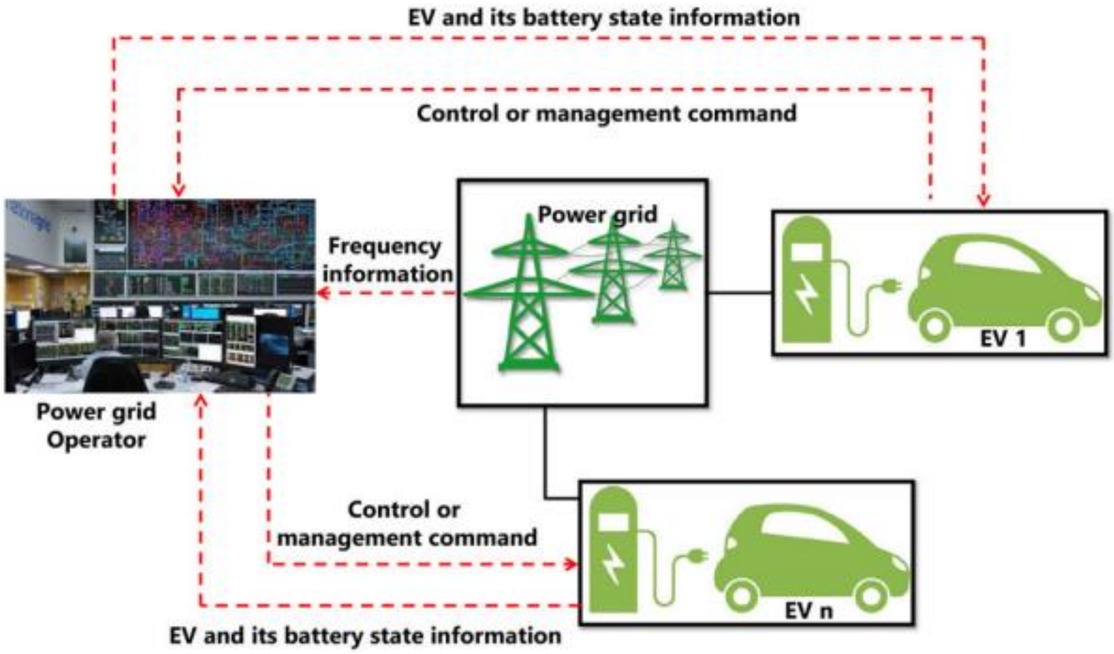

Figure 1. Structure of Distributed Dispatch System For EVs Participating in Grid Frequency Regulation (Peng et al., 2017)

Carbon Credit Trading Systems

Carbon credit trading system, also referred to as emissions trading, is a market-driven mechanism aimed at reducing greenhouse gas (GHG) emissions. It incentivizes emission reductions and encourages innovation and investment in cleaner technologies while allowing for flexibility in compliance with GHG reduction goal.

Regulatory authorities set an emissions cap that determines the total number of available allowances. This cap is gradually reduced over time to meet emissions reduction targets (Kollenberg and Taschini, 2016). The key objectives of carbon credit trading systems include; Emissions Reduction by placing a cap on total emissions and allowing for the trading of emission allowances, carbon credit trading systems provide economic incentives for entities to reduce their emissions below the allocated cap. Carbon credit trading systems enable emissions reductions to be achieved at the lowest possible cost. This implies that entities with lower abatement costs can sell surplus allowances to those facing higher abatement costs. Trading allows for flexibility in how emissions reductions are achieved. Entities can opt for the most cost-effective and efficient strategies while ensuring compliance with regulatory mandates.

At the core of carbon credit trading system is emission allowance allocation. This process distributes allowances through auctions or free allocation, or sometimes a mix of both. In auctions, allowances go to the highest bidder, while free allocation assigns them based on factors like past emissions or production levels (Löfgren et al., 2018). Participating entities, such as power plants, factories, and large industrial facilities, are required to surrender allowances to cover their actual emissions during a compliance period while entities that emit more than their allocated allowances must purchase additional allowances to comply with regulatory requirements (Hung et al., 2016). Participants can buy and sell allowances on secondary markets, allowing them to respond to changes in emissions levels, market prices, and regulatory requirements. Participating companies can engage in buying and selling allowances on secondary markets, enabling them to adapt to shifts in emissions levels, market prices, and regulatory demands. Trading platforms play a crucial role in facilitating this process by offering avenues for purchasing and selling allowances, thereby enhancing liquidity and establishing price benchmarks. Beyond trading allowances, some systems also permit the acquisition of carbon offsets. These offsets represent investments in projects aimed at decreasing or eliminating greenhouse gas emissions, such as reforestation endeavors or renewable energy initiatives (van der Gaast et al., 2018).

Carbon credit trading systems play a crucial role in climate change mitigation efforts by providing a market-based mechanism for reducing GHG emissions. These systems leverage market dynamics to achieve emission reductions, allowing entities to trade allowances and refine their emission reduction tactics by weighing relative costs and benefits (Dimos & Pugh, 2016). Carbon credit trading systems can be scaled up to different sectors, regions, or gases, thereby providing an adaptable framework for addressing diverse emission sources and achieving broader emission reduction goals. On a global level, carbon credit trading systems can provide a basis for international cooperation on climate change mitigation by establishing common rules, standards, and mechanisms for emissions reduction and facilitating cross-border trading of allowances and offsets (Mehling, 2016).

INTEGRATION FRAMEWORK BETWEEN SMART GRIDS AND TRADING PLATFORMS

Interoperability between smart grids and carbon credit trading platforms is essential for seamless integration and operation of both systems (Nafi et al., 2016). Establishing common data formats and protocols for exchanging information ensures compatibility and interoperability between the two systems. Integration necessitates real-time data exchange capabilities to enable prompt decision-making and responses to changes in energy consumption, generation, carbon pricing, and market conditions.

Application Programming Interfaces

Application Programming Interfaces (APIs) can play a crucial role in facilitating communication and data exchange between smart grid systems and trading platforms, ensuring seamless integration. Regulatory agencies would also be required to develop policies and frameworks that would enable the seamless exchange of information and compliance reporting (Woo et al., 2021).

Authentication and Authorization

Implementing robust authentication and authorization mechanisms to ensure that only authorized entities can access and exchange data between the two systems will be crucial while integrating both systems. This is crucial to ensure the security, integrity, and privacy of sensitive information such as energy consumption data and financial transactions. The authentication and authorization controls would help prevent unauthorized access, data breaches, and other security threats, thereby safeguarding the integrity and trustworthiness of the system.

Real-Time Data Sharing and Analysis

The effective integration between smart grids and carbon credit trading systems relies on real-time data processing, data sharing, and analysis capabilities to enable informed decision-making and optimize emissions reduction strategies (Jebaraj & Iniyan, 2006). Smart grid infrastructure collects vast amounts of data on energy consumption, generation, grid operations, and carbon emissions. Integrating this data with carbon credit trading platforms requires robust data collection and aggregation mechanisms (Schletz et al., 2020). Ensuring the quality and accuracy of our data is essential for reliable analysis and decision-making. Implementing data validation, verification, and quality control measures would help to minimize errors and inconsistencies. The systems must be designed to be scalable and robust to accommodate future growth in data and user demand. Cloud-based infrastructure and containerization, and microservices architecture are viable options that support flexibility and scalability.

Automated Decision-making Processes

Automation plays a vital role in integrating smart grids with carbon credit trading systems by enabling real-time decision-making, execution, and optimization of emissions reduction strategies. The implementation of algorithmic trading algorithms allows for automated buying and selling of emission allowances based on predefined rules, strategies, and market conditions (Durenard, 2013). By automating demand response programs, real-time adjustments to energy consumption can be made based on carbon pricing signals, grid conditions, and consumer preferences, thereby maximizing the effectiveness of emissions reduction efforts.

Dynamic pricing mechanisms based on carbon prices, energy supply, and demand can incentivize emissions reductions and optimize resource allocation across the grid. Additionally, the utilization of smart contracts and blockchain technology facilitates secure, transparent, and automated execution of emissions trading transactions, compliance reporting, and settlement processes (Lee & Khan, 2019).

By implementing an integration framework that emphasizes interoperability, data sharing and analysis, and automated decision-making processes, we can unlock the full potential of smart grids and carbon credit trading systems to drive emissions reductions, promote sustainable development, and mitigate the impacts of climate change.

ADVANTAGES OF INTEGRATING SMART GRID TECHNOLOGY WITH CARBON CREDIT TRADING SYSTEMS

The integration of smart grid technology with carbon credit trading systems offers a wide range of benefits, including increased efficiency in carbon emission reduction, optimization of energy consumption, and financial incentives for grid operators and participants. These advantages are evident in various dimensions (Ponnusamy et al., 2021).

Carbon Emission Reduction

The integration enables real-time monitoring of energy consumption, generation, and carbon emissions, offering utilities and regulators precise data on emissions levels and compliance status. Smart grid systems can dynamically respond to shifts in carbon prices and market conditions, optimizing energy dispatch, demand response programs, and emissions reduction strategies in real-time to maximize cost-effectiveness and achieve emissions reduction targets (Assad et al., 2022). Moreover, integration enables data-driven decision-making by delivering actionable insights and analytics on energy usage, carbon emissions, and trading opportunities to utilities, grid operators, and participants. This aids in identifying improvement areas, prioritizing investments, and optimizing resource allocation to achieve emissions reduction goals. Additionally, integration fosters enhanced coordination and collaboration among utilities, regulators, and market participants by providing a shared platform for information exchange, action coordination, and alignment of incentives toward common emissions reduction objectives (Lee et al., 2014).

Optimization of Energy Consumption

The integration enables the optimization of demand response programs by aligning energy consumption patterns with carbon pricing signals and market dynamics. Smart grids can automatically adjust energy usage in response to changes in carbon prices, grid conditions, and consumer preferences, thereby maximizing the effectiveness of demand response initiatives. Additionally, the integration could facilitate the implementation of energy efficiency measures by offering utilities and consumers insights into energy usage patterns, inefficiencies, and improvement opportunities (Lopes et al., 2012). Moreover, the integration would empower utilities to optimize grid operations, balance supply and demand, and minimize carbon emissions using real-time data on energy generation, consumption, and grid conditions. Furthermore, the integration would support the increased adoption of renewable energy sources like solar, wind, and hydroelectric power by providing mechanisms for efficient grid integration and management of variable generation (Zafar et al., 2013).

Financial Incentives for Grid Operators and Participants

The integration would create revenue opportunities for grid operators and participants through participation in carbon credit trading markets. Grid operators can sell excess allowances or offsets on carbon markets, leveraging emissions reductions from demand response, energy efficiency, and renewable energy integration. The integration can also optimize energy distribution, reduce losses, and improve resource utilization, leading to cost savings. Utilities can identify cost-effective emissions reduction strategies and optimize asset utilization using smart grid data and analytics. It also provides access to carbon credit trading markets, facilitating allowance or offset trading to meet compliance obligations or generate revenue (Zafar et al., 2013). It enhances market efficiency, incentivizes innovation in clean energy, and accelerates the transition to a low-carbon economy.

CHALLENGES TO THE INTEGRATION OF SMART GRID TECHNOLOGY WITH CARBON CREDIT TRADING SYSTEMS AND SOLUTIONS

The integration of smart grid technology and carbon credit trading systems comes with its own challenges. These challenges include technical hurdles, regulatory complexities, and privacy concerns. In this section, we examine some of the key challenges and propose solutions to overcome them.

Data Security and Privacy Concerns

Smart grid data is sensitive and requires protection to safeguard consumer privacy and prevent unauthorized access or misuse. Smart grid infrastructure is also vulnerable to cybersecurity threats, including hacking, data breaches, and malicious attacks, which could compromise the integrity, confidentiality, and availability of data (Pandey and Misra, 2016). Moreover, utility companies and grid operators would have to navigate and comply with data protection regulations, such as the General Data Protection Regulation (GDPR) in the European Union and the California Consumer Privacy Act (CCPA) in the United States to ensure privacy and prevent smart grid data breach.

To address these challenges, implementing robust encryption and authentication mechanisms is crucial. These measures help safeguard smart grid data from unauthorized access and tampering, ensuring its confidentiality and integrity (Just, 2003). Enforcing access control policies and permissions is another vital step, as it limits access to sensitive data to authorized users, thereby reducing the risk of data breaches and unauthorized disclosure. Deploying secure communication protocols, such as Transport Layer Security (TLS) and Secure Sockets Layer (SSL), is essential for ensuring the secure transmission of data between smart grid devices and trading platforms. This mitigates the risk of eavesdropping and interception by malicious actors (Hu, 2021). Furthermore, establishing robust regulatory compliance frameworks is essential. These frameworks help ensure that smart grid data handling practices adhere to relevant data protection regulations and privacy standards, thereby minimizing legal and reputational risks for utilities and grid operator

Regulatory and Policy Barriers

The lack of harmony and consistency in regulatory frameworks across jurisdictions presents challenges for integrating smart grids and carbon credit trading systems. This hinders interoperability and cross-border trading (Stewart, 1981). Uncertainty surrounding carbon pricing mechanisms, emissions reduction targets, and regulatory requirements further complicates matters, creating barriers to investment and innovation in smart grid technologies and carbon markets (Brown et al., 2018). Inadequate stakeholder alignment and coordination among policymakers, regulators, utilities, and market participants can hinder the development and implementation of integrated solutions for emissions reduction.

To address these challenges, promoting policy harmonization and alignment at regional, national, and international levels is crucial. This facilitates the integration of smart grid technology and carbon credit trading systems, enabling interoperability and cross-border trading (Cerulli, 2010). Providing clear and consistent regulatory guidance and frameworks for carbon pricing, emissions trading, and smart grid deployment enhances investor confidence and encourages innovation in clean energy technologies and emissions reduction strategies (Gielen et al., 2019). Moreover, engaging stakeholders from government, industry, academia, and civil society in collaborative dialogue and decision-making processes helps build consensus, identify common goals, and address regulatory and policy barriers to integration.

Technological Compatibility Issues

Incompatibility and lack of interoperability between smart grid systems, carbon credit trading platforms, and legacy infrastructure present significant challenges for data exchange, integration, and coordination (Abdmouleh et al., 2015). Integrating disparate systems and technologies, each with its own protocols, standards, and interfaces, demands substantial investment, expertise, and coordination, leading to increased complexity and integration costs. Furthermore, legacy infrastructure and outdated technologies may lack the necessary capabilities and functionality for seamless integration with smart grids and carbon credit trading systems, thereby limiting scalability and effectiveness.

To address these challenges, establishing common standards and protocols for data exchange, interoperability, and communication between smart grid systems and carbon credit trading platforms is essential (Cicilio et al., 2021). Deploying middleware solutions and integration platforms equipped with adapters, connectors, and APIs facilitates seamless integration and interoperability across diverse systems and technologies. Additionally, adopting a modular architecture for smart grid systems and carbon credit trading platforms supports integration, scalability, and flexibility, allowing for incremental upgrades and enhancements to legacy infrastructure. Investing in research and development (R&D) initiatives focused on overcoming technological compatibility issues, developing interoperable solutions, and advancing standards and protocols accelerates progress towards integration and interoperability.

SUCCESSFUL CASE STUDIES AND LEARNINGS

Case Studies

California's Cap-and-Trade Program and Smart Grid Integration:

California has emerged as a leader in integrating smart grid technology with its cap-and-trade program, one of the largest and most comprehensive carbon markets globally. Leveraging advanced metering infrastructure (AMI) and demand response programs, the state optimizes energy consumption and reduces emissions. Utilities like Pacific Gas and Electric (PG&E) and Southern California Edison (SCE) have implemented smart grid solutions enabling real-time energy monitoring and automated demand response. These systems effectively balance supply and demand, integrate renewable energy sources, and mitigate peak load, resulting in emission reductions.

European Union Emissions Trading System (EU ETS) and Smart Grid Projects:

In Europe, the EU ETS stands as the world's largest carbon market, encompassing numerous sectors and countries. Several European nations have pioneered the integration of smart grid technologies with carbon trading mechanisms. For example, Germany's Energiewende (Energy Transition) initiative focuses on integrating renewable energy sources and smart grid infrastructure. Initiatives like the "C/sells" project in Southern Germany utilize smart grid technology to manage decentralized energy production from solar, wind, and biomass, alongside carbon credit trading to incentivize low-carbon energy generation and consumption.

Japan's Smart Community Projects and Carbon Markets:

In Japan, Smart Community Projects such as the Yokohama Smart City Project aim to merge smart grid technologies with carbon markets to enhance energy efficiency and reduce emissions. These projects deploy smart meters, energy management systems, and renewable energy sources to establish a flexible and responsive grid. Integration with Japan's carbon markets enable real-time tracking of carbon emissions and trading of carbon credits, offering economic incentives for emission reductions.

Lessons Learned

Successful integration of smart grids with carbon credit trading systems requires strong regulatory support and clear policy frameworks. Regulatory clarity and consistency help build investor confidence and encourage the adoption of smart grid technologies and participation in carbon markets (Komor & Bazilian, 2005). The lack of common standards and protocols can hinder the integration process. Establishing interoperability standards for data exchange, communication, and system interfaces is crucial for seamless integration and effective coordination between smart grid systems and carbon trading platforms. Collaboration between government, industry, and academia is essential for the successful implementation of integrated solutions. Public-private partnerships can facilitate knowledge sharing, resource pooling, and coordinated efforts to overcome technical and regulatory challenges (Geels et al., 2020). Engaging consumers and providing them with the tools and incentives to participate in demand response programs and energy efficiency initiatives is critical. Educating consumers about the benefits of smart grid technologies and carbon markets can drive behavior change and enhance the effectiveness of integration efforts.

Future Directions

Advanced data analytics and artificial intelligence (AI) can enhance the integration of smart grids with carbon credit trading systems. AI-driven predictive models and machine learning algorithms can optimize energy consumption, forecast emissions, and identify trading opportunities, further improving efficiency and emissions reduction. Blockchain technology offers potential solutions for secure, transparent, and automated execution of carbon trading transactions (Lewis, 2016). Smart contracts on blockchain platforms can facilitate real-time trading, compliance reporting, and settlement processes, enhancing the efficiency and reliability of carbon markets. Harmonizing carbon markets at the international level can expand trading opportunities and improve market liquidity. Efforts to link regional and national carbon markets can create a more cohesive and efficient global carbon market, driving broader emissions reduction and investment in clean technologies. The growing deployment of distributed energy resources, such as rooftop solar panels, energy storage systems, and electric vehicles, presents new opportunities for integration (Ahmad, & Zhang, 2021). Smart grid technologies can manage and optimize the interaction between distributed energy resources and carbon markets, maximizing the potential for decentralized low-carbon energy production and consumption.

CONCLUSION

The integration of smart grid technology with carbon credit trading systems presents numerous benefits from reducing carbon emissions, optimizing energy consumption, and providing financial incentives for utilities and consumers. Successful case studies from California, the European Union, and Japan demonstrate the potential of this integration to drive sustainable development and combat climate change effectively. However, key challenges such as data security and privacy concerns, regulatory barriers, and technological compatibility issues must be addressed to realize the full potential of this synergy.

Collaboration among stakeholders, including government, industry, academia, and consumers, is crucial for overcoming these challenges and achieving successful integration. Regulatory support, public-private partnerships, consumer engagement, and the establishment of common standards and protocols are essential components of this collaborative effort. By working together, stakeholders can create a more efficient, resilient, and sustainable energy system.

The integration of smart grid technology with carbon credit trading systems has the potential to contribute to sustainable development by reducing carbon emissions, promoting clean energy adoption, and driving technological innovation. This integration supports the transition to a low-carbon economy, enhances energy security, and fosters economic growth through the creation of green jobs and investment opportunities.

By harnessing the synergies between smart grids and carbon markets, we can accelerate progress towards a more sustainable and resilient future, addressing the urgent challenges of climate change and environmental degradation.

References

Abdmouleh, Z., Alammari, R. A., & Gastli, A. (2015). Review of policies encouraging renewable energy integration & best practices. *Renewable and Sustainable Energy Reviews*, *45*, 249-262.

Ahmad, T., & Zhang, D. (2021). Renewable energy integration/techno-economic feasibility analysis, cost/benefit impact on islanded and grid-connected operations: A case study. *Renewable Energy*, *180*, 83-108.

Arvesen, A., Völler, S., Hung, C. R., Krey, V., Korpås, M., & Strømman, A. H. (2021). Emissions of electric vehicle charging in future scenarios: The effects of time of charging. *Journal of Industrial Ecology*, *25(5)*, 1250–1263

Assad, U., Hassan, M. A. S., Farooq, U., Kabir, A., Khan, M. Z., Bukhari, S. S. H., ... & Popp, J. (2022). Smart grid, demand response and optimization: a critical review of computational methods. *Energies*, *15*(6), 2003.

Brown, M. A., Zhou, S., & Ahmadi, M. (2018). Smart grid governance: An international review of evolving policy issues and innovations. *Wiley Interdisciplinary Reviews: Energy and Environment*, *7*(5), e290.

Cerulli, G. (2010). Modelling and measuring the effect of public subsidies on business R&D: A critical review of the econometric literature. *Economic Record*, *86*(274), 421-449.

Cicilio, P., Glennon, D., Mate, A., Barnes, A., Chalishazar, V., Cotilla-Sanchez, E., ... & Kapourchali, M. H. (2021). Resilience in an evolving electrical grid. *Energies*, *14*(3), 694.

Dimos, C., & Pugh, G. (2016). The effectiveness of R&D subsidies: A meta-regression analysis of the evaluation literature. *Research Policy*, *45*(4), 797-815.

Durenard, E. A. (2013). *Professional Automated Trading: Theory and Practice*. John Wiley & Sons.

Geels, F. W., McMeekin, A., & Pfluger, B. (2020). Socio-technical scenarios as a methodological tool to explore social and political feasibility in low-carbon transitions: Bridging computer models and the multi-level perspective in UK electricity generation (2010–2050). *Technological Forecasting and Social Change*, *151*, 119258.

Gellings, C. W. (2020). *The smart grid: enabling energy efficiency and demand response*. River Publishers.

Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., & Gorini, R. (2019). The role of renewable energy in the global energy transformation. *Energy Strategy Reviews*, *24*, 38-50.

Gungor, V. C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C., & Hancke, G. P. (2011). Smart grid technologies: Communication technologies and standards. *IEEE Transactions on Industrial Informatics*, *7*(4), 529-539.

Holt, C. A., Shobe, W., Burtraw, D., Palmer, K. L., & Goeree, J. K. (2007). Auction design for selling CO 2 emission allowances under the regional greenhouse gas initiative. *Available at SSRN 2459462*.

Hu, Z. (2021). Layered Network Protocols for Secure Communications in the Internet of Things. *University of Oregon: Eugene, OR, USA.*

Hua, W., Chen, Y., Qadrdan, M., Jiang, J., Sun, H., & Wu, J. (2022). Applications of blockchain and artificial intelligence technologies for enabling prosumers in smart grids: A review. *Renewable and Sustainable Energy Reviews*, *161*, 112308.

Hung, D. Q., Shah, M. R., & Mithulananthan, N. (2016). Technical challenges, security and risk in grid integration of renewable energy. *Smart Power Systems and Renewable Energy System Integration*, 99-118.

Jebaraj, S., & Iniyan, S. (2006). A review of energy models. *Renewable and Sustainable Energy Reviews*, *10*(4), 281-311.

Just, R. E. (2003). Risk research in agricultural economics: opportunities and challenges for the next twenty-five years. *Agricultural Systems*, *75*(2-3), 123-159.

Kollenberg, S., & Taschini, L. (2016). Emissions trading systems with cap adjustments. *Journal of Environmental Economics and Management*, *80*, 20-36.

Komor, P., & Bazilian, M. (2005). Renewable energy policy goals, programs, and technologies. *Energy Policy*, *33*(14), 1873-1881.

Lee, J. H., Hancock, M. G., & Hu, M. C. (2014). Towards an effective framework for building smart cities: Lessons from Seoul and San Francisco. *Technological Forecasting and Social Change*, *89*, 80-99.

Lee, J., & Khan, V. M. (2019). Blockchain and smart contract for peer-to-peer energy trading platform: Legal obstacles and regulatory solutions.

Lewis, J., Ritchie, J., Ormston, R., & Morrell, G. (2003). Generalising from qualitative research. *Qualitative research practice: A guide for social science students and researchers*, *2*(347-362).

Lewis, N. S. (2016). Research opportunities to advance solar energy utilization. *Science*, *351*(6271), aad1920.

Löfgren, Å., Burtraw, D., Wråke, M., & Malinovskaya, A. (2018). Distribution of emissions allowances and the use of auction revenues in the European Union emissions trading system. *Review of Environmental Economics and Policy*.

Lopes, M. A., Antunes, C. H., & Martins, N. (2012). Energy behaviours as promoters of energy efficiency: A 21st century review. *Renewable and Sustainable Energy Reviews*, *16*(6), 4095-4104.

Mehling, M. A. (2016). Legal frameworks for linking national emissions trading systems. *The Oxford handbook of international climate change law*, 257-85.

Nafi, N. S., Ahmed, K., Gregory, M. A., & Datta, M. (2016). A survey of smart grid architectures, applications, benefits and standardization. *Journal of Network and Computer Applications*, *76*, 23-36.

Pandey, R. K., & Misra, M. (2016, December). Cyber security threats—Smart grid infrastructure. In *2016 National power systems conference (NPSC)* (pp. 1-6). IEEE.

Papaefthymiou, G., & Dragoon, K. (2016). Towards 100% renewable energy systems: Uncapping power system flexibility. *Energy Policy*, *92*, 69-82.

Peng, C., Zou, J., & Lian, L. (2017). Dispatching strategies of electric vehicles participating in frequency regulation on power grid: A review. *Renewable and Sustainable Energy Reviews*, *68*, 147-152.

Pitì, A., Verticale, G., Rottondi, C., Capone, A., & Lo Schiavo, L. (2017). The role of smart meters in enabling real-time energy services for households: The Italian case. *Energies*, *10*(2), 199.

Ponnusamy, V. K., Kasinathan, P., Madurai Elavarasan, R., Ramanathan, V., Anandan, R. K., Subramaniam, U., ... & Hossain, E. (2021). A comprehensive review on sustainable aspects of big data analytics for the smart grid. *Sustainability*, *13*(23), 13322.

Schletz, M., Franke, L. A., & Salomo, S. (2020). Blockchain application for the paris agreement carbon market mechanism—a decision framework and architecture. *Sustainability*, *12*(12), 5069.

Stewart, R. B. (1981). Regulation, innovation, and administrative law: A conceptual framework. .

Tan, K. M., Babu, T. S., Ramachandaramurthy, V. K., Kasinathan, P., Solanki, S. G., & Raveendran, S. K. (2021). Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration. *Journal of Energy Storage*, *39*, 102591.

van der Gaast, W., Sikkema, R., & Vohrer, M. (2018). The contribution of forest carbon credit projects to addressing the climate change challenge. *Climate Policy*, *18*(1), 42-48.

Woo, J., Fatima, R., Kibert, C. J., Newman, R. E., Tian, Y., & Srinivasan, R. S. (2021). Applying blockchain technology for building energy performance measurement, reporting, and verification (MRV) and the carbon credit market: A review of the literature. *Building and Environment*, *205*, 108199.

Zafar, S., Nawaz, K., Naqvi, S. A. R., & Malik, T. N. (2013). Integration of renewable energy sources in smart grid: A review. *The Nucleus*, *50*(4), 311-327.

Zhang, Z. X. (1998). Greenhouse gas emission trading and the world trading system.

Zhao, X. G., Jiang, G. W., Nie, D., & Chen, H. (2016). How to improve the market efficiency of carbon trading: A perspective of China. *Renewable and Sustainable Energy Reviews*, *59*, 1229-1245.