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PRIMARY RESEARCH

Transformative approach to renewable energy generation and management - integrating microgrids and virtual power plants, with an internal blockchain and artificial intelligence system

Siyeong Park *
Shanghai American School Puxi Campus

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Abstract
The growing employment of renewable energies brought positive impact to the environment, however, is facing efficiency issues, for instance, intermittency, limited store capacity, and integration problems with traditional grids, due to different supplies and demands in different regional dynamics. Today, the primary problem is not about how energy can be generated in a sustainable manner, but instead, how renewable energy storage and distribution can be optimized. This study proposes this integration as a solution of renewable energy sources in their issues regarding interactions with the main grid, limited store capacity, and intermittency issues. This study's objective is to show the feasibility and efficiency of such integration. In pursuit of substantiating this study, energy grid models from the National Renewable Energy Lab were utilized. Numerous data, such as energy consumption levels, greenhouse gas emissions, cost, efficiency, and other data involved in energy production, storage, and transaction were input into the module where there were some assumptions in the performance of the technology (AI and blockchain) and the average values in emissions and energy usage. To prevent complication and distortion from data overload, the only renewables implemented in this module were solar PVs and hydropower. Still, to achieve diverse results under different circumstances, 2 simulation models were established for the experiment. The module output graph displayed a match in demand and production, minimal involvement of the central grid, peak shaving, and peer-to-peer trading systems, directly manifesting that the involvement of AI and blockchain technology in the integration of microgrids and VPPs lead to anticipated outcomes. In conclusion, the findings indicated from this study have shown that the following integration enhanced the usage of renewable energy. Further research could explore development of AI and blockchain technology, also executing physical integrations then eventually pilot projects of this model, as well as exploring options to optimize this idea to become universally adaptable to diverse environments. The implementation of developing regulatory frameworks in this field will bring positive outcomes such as expansion of higher efficiency usage accessibility to cheap and sustainable energy for the public.

I. INTRODUCTION

Today, the energy sector and energy consumption are the largest emitters by far responsible for 73.2% of global greenhouse gas emissions [1]. The primary factor behind this statistic is fossil fuels, and it is critical for society to realize that it is a finite resource and is being depleted in a rapid manner [2]. Thus, it is crucial to transition into sustainable energy production and distribution methods that can mitigate negative environmental impact; the increase in use of renewable energies can reduce climate risk. Yet, technological role has not played a significant role in the employment of renewable energies [3]. The employment of renewable energies is not only beneficial for the environment - in fact, they can provide economic and social benefits as well. Fig-

*Corresponding author: Siyeong Park
†email: siyeong0318@gmail.com

ure 1 directly manifests how the trend in the cost of renewable energies is plummeting, rendering them economically viable compared to fossil fuels. Specifically, regarding the installation of solar photovoltaics (PV), the curve of best fit on figure 2 demonstrates the exponential decay of the cost trends of PV installations in certain countries.

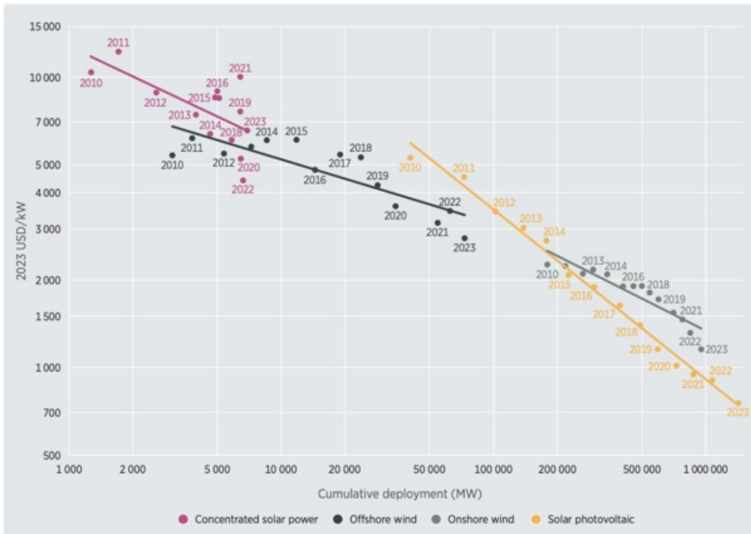

Fig. 1. Global-weighted-average total installed cost learning curve trends for solar PV, CSP and onshore and offshore wind, 2010-2023. Source: [4].

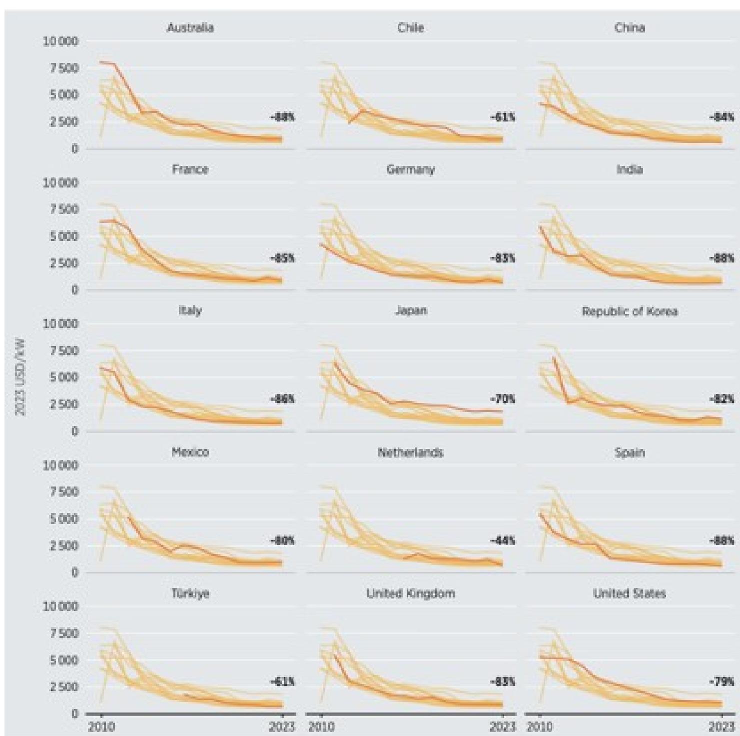

Fig. 2. Figure 2 Utility-scale solar PV total installed cost trends in selected countries, 2010-2023 Source: [4]

Additionally, the price fluctuation of renewable energy is less susceptible to international and diplomatic affairs compared to fossil fuels. Fossil fuel prices often fluctuate due to geopolitical tensions, supply chain disruptions, oil embargoes, gas pipeline failures, or political conflicts. In fact, its prices are responsible for 75 percent of energy inflation over 2022 [5]. Consequently, countries that do not have domestic access to fossil fuels (South Korea, Japan, Sin-

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gapore, etc.) inevitably must trade with other countries, which makes them susceptible to be affected by these factors. In contrast, renewable energies can eliminate such factors since all countries can initiate domestic production if they have sufficient infrastructure [6]. Even if certain LEDCs (Less Economically Developed Countries) might not have access to adequate infrastructure or budget to initiate renewable energy production, there are numerous opportunities from green funds, climate funds, and incentives provided from NDC (Nationally Determined Contributions).

Yet, renewable energy sources have three primary shortcomings: intermittency-related issues, limited store capacity, and integration issues with traditional grids [7, 8, 9]. To address this problem, this research paper aims to manifest the employment of integration of microgrids and virtual power plants (VPP) as a grid system, along with advanced technologies such as Artificial Intelligence (AI) and blockchain technology for information technology to optimize renewable energy systems.

A microgrid is a localized energy system that consists of Distributed Energy Resources (DER), such as renewable energy generation systems, energy storage systems, generators, utility providers, and critical load [10]. Microgrid is distinct from traditional grids because it can operate in two modes: Grid-connected mode, where it mutually transfers energy with the main grid; and Island mode, where it is isolated from the main grid, operating independently [11]. Virtual Power Plant (VPP) is a cloud-based system that aggregates and optimizes a set of DERs, including renewable energy generation systems, energy storages, energy distribution systems to different domains including commercial, residential, and industrial areas [12]. Despite the limited range of Microgrids, VPP can span multiple locations, dynamically managing energy flows [13]. In simple terms, microgrid is an energy system, whereas VPP is a network of energy systems.

Notwithstanding microgrid's and VPP's advantages in giving rise to sustainability and efficiency, there are losses among electricity generated from sources in Microgrids and VPPs, often due to Microgrid's scalability issues, intermittency of renewables, and complex management system of VPPs. However, the characteristics of Microgrids and VPPs can compensate for each other [14, 15, 16]. For instance, VPPs can help microgrids in their limitation in scalability. Also, Microgrids can reduce VPP's dependency on the main grid, through its independence and functions like island mode. This unique compensation makes the integration of Microgrids and VPPs desirable, since this integration will boost resilience and scalability, expanding the range of usage. Furthermore, to address operation and energy management, an AI model will be interconnected with microgrids and VPPs to effectively manage energy. Additionally, blockchain technology will enable efficient energy transactions between DERs and factors of this integration model, by employing peer to peer (P2P) energy transfers. Integrating Microgrids with VPPs is tantamount to neighborhoods sharing extra energy to an energy center, which provides it to houses that are in need to ensure that all houses have enough energy. Overall, integration will contribute significantly to giving rise to the proficiency of renewable energy standardization, storage, and distribution.

Preliminary studies indicate that AI-integrated microgrids can reduce energy consumption by up to 20% by optimizing energy generation, distribution, and demand response management [17]. AI will forecast energy demands, optimize energy storage and production, and make efficacious decisions. There was also execution of pilot projects where blockchain was employed in energy transfers, and with a 27 GW total installed capacity, the P2P price was 43% lower than the retail electricity price for the same quantity [18]. Moreover, integration of Microgrids and VPPs can mutually enhance each other's capabilities, due to their flexible capacity in conjunction with localized resilience [19]. Research also indicates the advantages of the integration of blockchain and AI in the realms of energy sector, such as facilitation of energy management decentralization, enhanced decision making, and fortified security for energy data and transactions, which aligns adequately with this research's purpose.

This research does include several methodological gaps. Primarily, this research is based on an online simulation, with various assumed data based on average data points. This includes values such as the efficiency of AI and blockchain technology involved in this integration, data of total greenhouse gas emissions, and the net electricity that can be generated per renewable energy system. Despite this research theoretically proving the integration aligns with the objective of this research, it is important to highlight that this research was run under theoretical basis, and the practicality of this study may vary on different conditions where this integration is operated. For instance, each location varies in their altitude, climate, and available technological infrastructure. Numerous factors are involved, and even a single factor may cause significant differences since renewable energy systems are more sensitive towards their surroundings. These methodological gaps involved in this research may impact the result and future applications. Thus, the potential area of future research lies in several di-

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mensions: software development, grid-tied infrastructure, and pilot projects. Software development for developing a system where these technologies and grids are virtually connected; grid-tied infrastructure for the energy grid to be set physically with other renewable energy systems; and pilot projects for analyzing the effectiveness of such technology in diverse geographic and climate conditions, with different sustainable power generation technologies.

II. METHODS

This study utilized an online energy modelling tool to analyze the impact of integration of microgrids, VPPs, AI, and blockchain technology. Engage Energy Modelling Tool from the National Renewable Energy Lab (NREL) was employed to conduct the research. Data regarding greenhouse gas emissions, energy costs, and production capacities were calculated as average value and inputted into the model. There were two simulation models, where model A involved only solar panels and simple grid connections and a dwindling number of consumers, whereas model B involved solar power, wind power, hydropower, and geothermal power with more complex grid connections and various consumers. Both models underwent linear programming and simulation within the period to acquire the results. The duration of simulation A was from 2005-01-01 to 2005-01-07 at United Kingdom, Streatham. This simulation only involved solar photovoltaic power and simple electrical grid connections with a small number of energy consumers involved in the system.

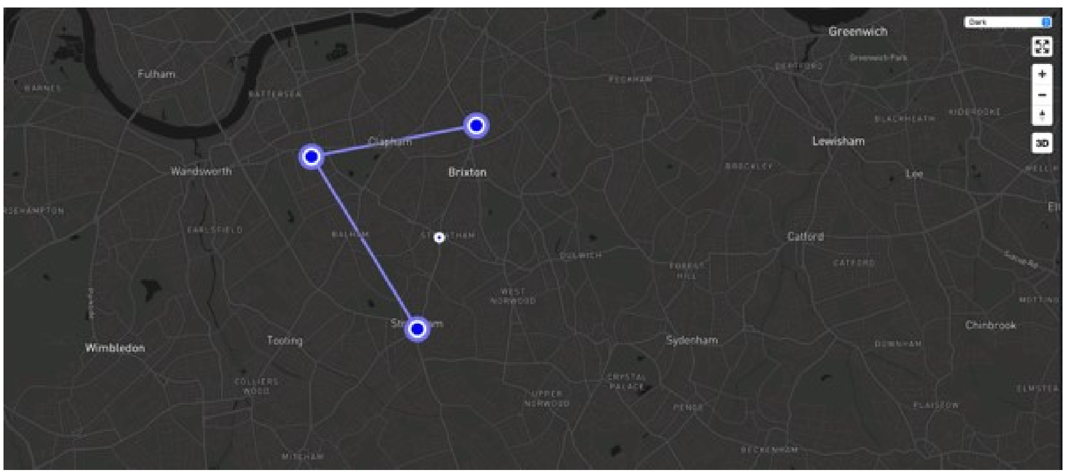

Fig. 3. Electrical grid connection diagram from simulation A

The duration of simulation B was from 2018-05-01 to 2018-05-08 at United States of America, Denver Golden. This simulation involved solar power, wind power, hydropower, and geothermal power with more complex grid connections involving more energy consumers in the system.

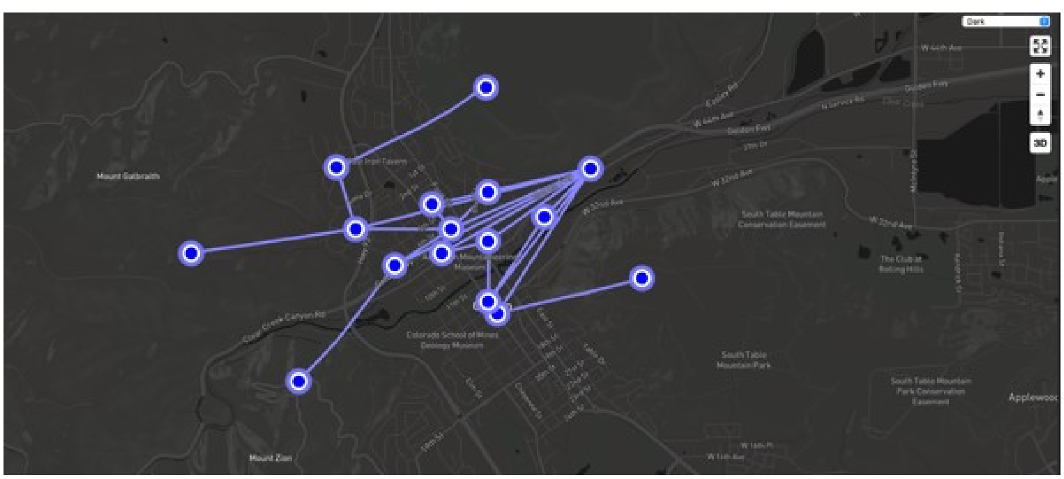

Fig. 4. Electrical grid connection diagram from simulation B

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While simulation model A focused more on generalized system capacity, simulation model B deconstructs sectoral aspects, demonstrating operational details.

III. RESULTS

These figures were the outcome after inputting necessary value to the energy model provided by the NREL.

Figure 5 portrays periodic variations in energy production and consumption. The peaks correspond to time periods of high demand on energy: a period which would be probable for VPPs to import energy from external energy sources and grids. The line of demand (dotted white line) nearly aligned with the lines on energy production (pink lines), although there were some parts when energy production exceeded it (The surplus energy will be either wasted or stored, which will not bring significant harm to the grid). Despite this, the alignment shows that energy production was able to align with demand regularly. Still, AI was able to predict consumption spikes and adequately shifted them to off-peak to reduce grid reliance and improve efficiency. Findings from this graph overall indicate a significant correlation between efficiency and integration.

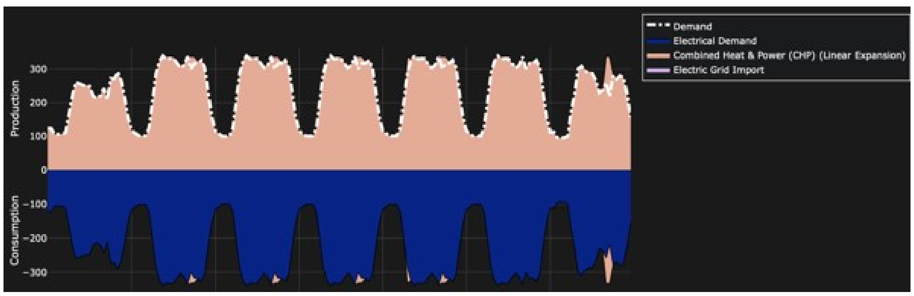

Fig. 5. Electricity production and consumption over time (Simulation model A)

Figure 6 illustrates the alterations in cost of energy production over time. Acute peaks correspond to occasions where energy cost is amplified due to high demand, and by the fact that they are sharp, this demonstrates that the AI made decisions accordingly to lower the prices to prevent the energy cost from being excessively expensive. In general, this means that when a peak energy cost is held at approximately $2.5, while the normal price is at $1, AI's real–time decision making can reduce expenses by 60%. Figure 6 shows financial benefits of the integration and operational benefits of peak shaving of costs within dynamic energy production and consumption. Figure 6 directly manifests operational and financial benefits of the integration.

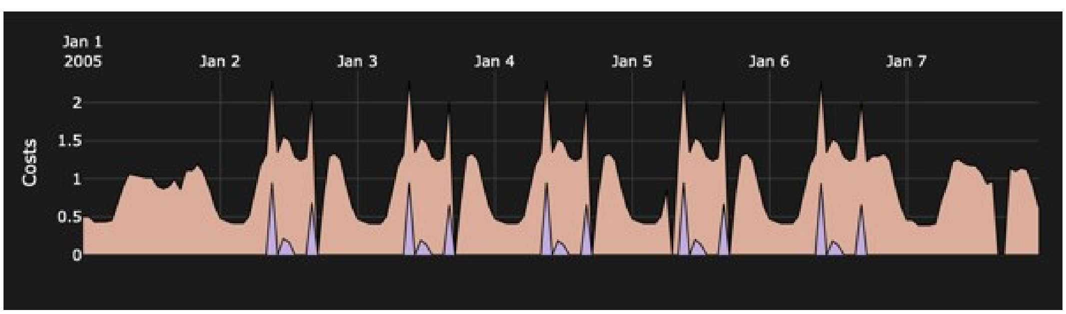

Fig. 6. Cost of energy production and electric grid import over time (Simulation model A)

Figure 7 portrays production capacity of energy production and electric grid import. The bold lavender represents an electric grid import of 9.496873kW, while the lavender shaded part represents the maximum capacity of electric grid import of 2000kW. The bold pink represents combined heat & power (CHP) production capacity of 336.3592kW, while the shaded part represents its maximum constraint of production capacity of 1500kW. The low electric grid import implies that most of the energy is produced locally, therefore there is less reliance on external energy supply. This suggests that proper operation is occurring, and solar PVs are generating sufficient energy. On the other hand, the high use of CHP implies that it is compensating for the intermittency of solar PVs and meeting heat demands; since occasionally, it might not receive enough solar power to generate sufficient energy. Figure 7 represents that this integration will be sufficient due to effective localization, reducing system vulnerability, while facing challenges due to high heat demands, as shown from the CHP bar.

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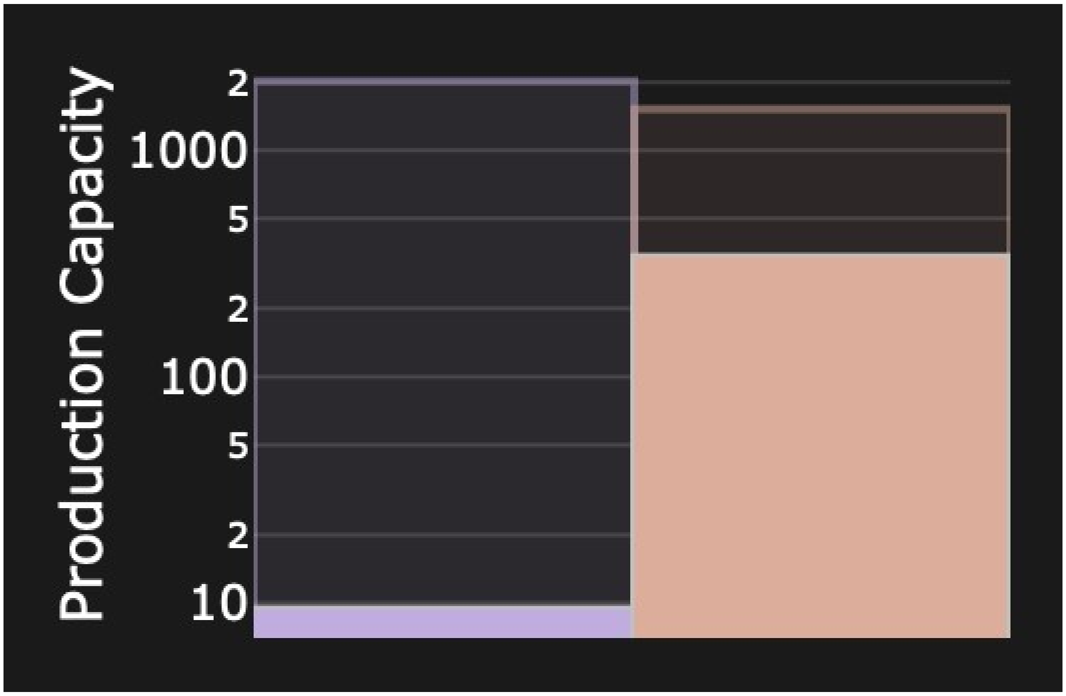

Fig. 7. Production capacity of energy production and electric grid import (Simulation model A)

Figure 8 illustrates the fixed cost from electric grid import and energy production. The lavender bar represents the fixed cost from electric grid import of $11.7201, while the pink bar represents the fixed cost of CHP of $680.3855. This figure represents the drastic advantages and disadvantages in terms of cost, where it is advantageous in electric grid import while it is not in CHP. The low fixed cost from electric grid import shows how this integration is performing properly in a localized manner. On the other hand, the extremely prohibitive costs from the CHP stress that quite a lot of money would be required to address heat demands. Figure 8 portrays the financial benefits and flaws of the integration.

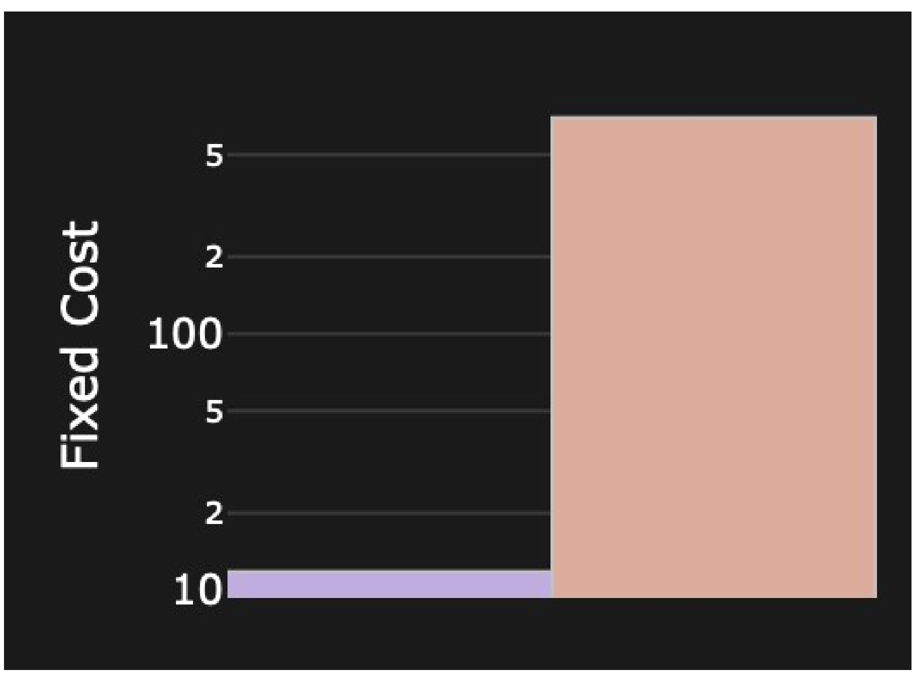

Fig. 8. Fixed costs from electric grid import and energy production (Simulation model A)

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Figure 9 represents changes of electricity production and consumption over time. As represented from numerous grey lines, simulation model B involved various components of a city, enabling realistic evaluation through the results. Additionally, simulation model B incorporated solar PVs and hydropower, expanding the level of complexity and energy sources. This provided an opportunity for the AI and blockchain model to demonstrate their abilities to handle production and consumption among these complex conditions.

Through this figure and other figures below, it can be inferred that the involvement of solar PVs in this model was consistent but limited. However, hydropower demonstrated a significant contribution, especially in managing energy production during high demand time periods. Furthermore, there was a significant contribution of the electric grid in both production and consumption sectors. Like figure 6, the electric grid from figure 9 portrays peak shaving, demonstrating active responses from AI to align production and consumption on a similar/identical level.

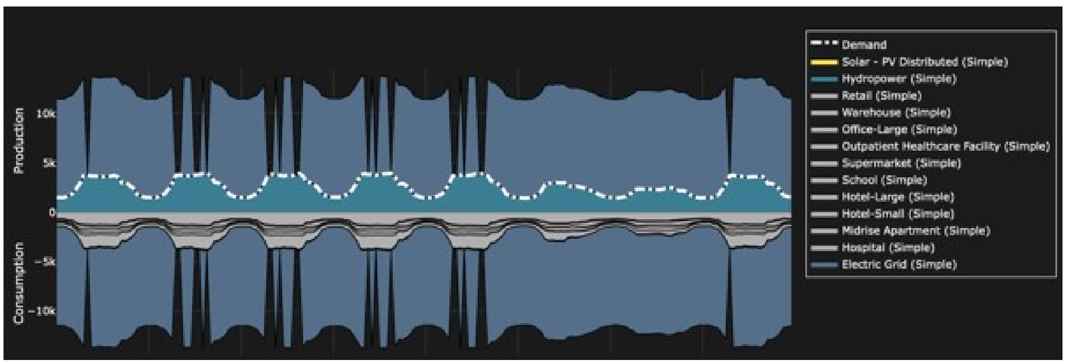

Fig. 9. Electricity production and consumption over time (Simulation model B)

Figure 10 demonstrates an extreme scenario compared to figure 6 from simulation model A. While figure 6 from simulation model A has more stubby curves and peaks, figure 10 represents acute peaks, while having a lot of time periods having $0 cost for energy. However, simulation model B is more extreme since its maximum cost reaches $20, while figure 6's maximum energy cost is $2. The optimistic case would be having a fusion of figure 6 and 10, where there are occasions when the cost of energy is $0, and the maximum cost is lower while fluctuation happens in a less extreme manner. The significance of figure 10 is that it implies the possibility of a society where the price of energy can be $0, in localized energy systems via the integration proposed in this research. Moreover, the role of AI is prominent as represented in the graph since it shows a negative trend of cost over time, indicating that AI is accommodating to the energy production and consumption conditions, in conjunction with making adequate decisions.

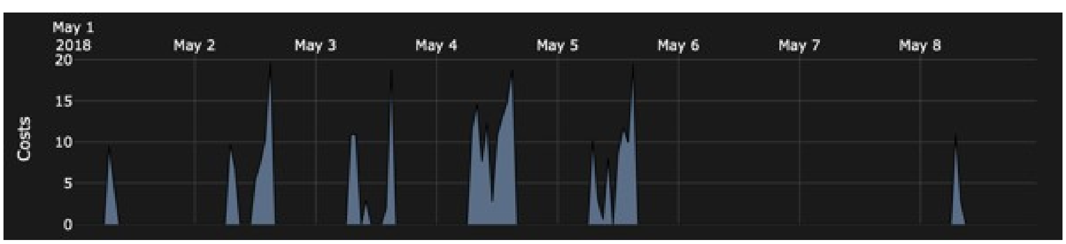

Fig. 10. Cost of energy production and electric grid import over time (Simulation model B)

Figure 11 demonstrates the production capacity of different energy sources. The yellow bar represents solar PVs' production capacity and maximum production capacity of 100kW, the lighter blue bar represents hydropower's production capacity of 3734.227kW, while its maximum capacity being 100,000 kW. The darker blue bar represents the electric grid's production capacity and maximum capacity of 10,000kW. Considering that solar PVs have low production capacity and maximum production capacity, it can be inferred that solar PVs were not productive enough due to intermittency-related issues, or an inappropriate decision making from the AI. However, since solar PVs reached their maximum production capacity, it can be inferred that inappropriate decisions made from AI's end are less responsible for this result. In contrast, hydropower represents higher production capacity, while not reaching its maximum.

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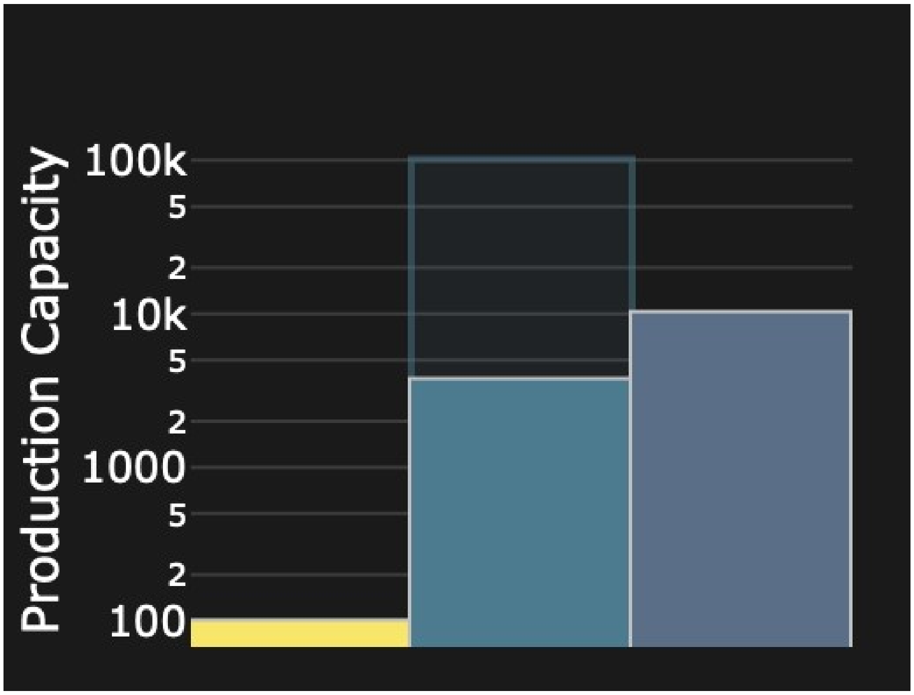

Fig. 11. Production capacity of energy production and electric grid import (Simulation model A)

Figure 12 portrays fixed costs from energy production and electric grid import. The yellow bar represents solar PV's fixed cost of $175.1233, the dark blue bar represents electric grid import cost of $310.0618, and the light blue bar represents fixed cost of hydropower of $10409.18. While these fixed costs are expensive compared to fixed costs from simulation model A on the facade, referring to figure 10, the overall cost of electricity is less expensive, contributing to compensation and even economic benefits in the long term.

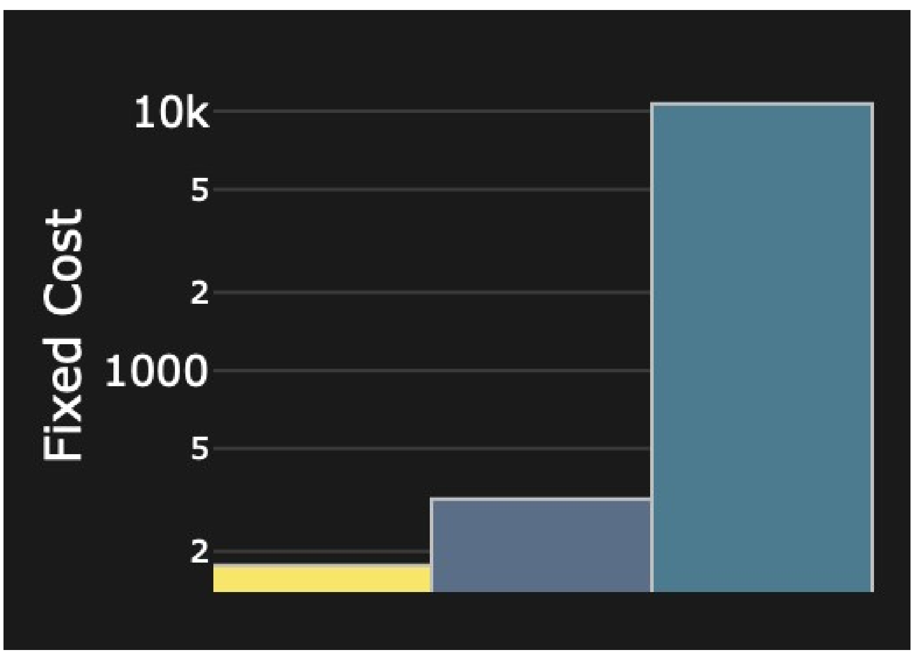

Fig. 12. Fixed costs from energy production and electric grid import (Simulation model B)

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Overall, these figures from simulation model A and B actively manifest the efficiency, management, and effective real-time response of this integration.
Results from simulation model A and B are both opposite extremes of each other. While model A has only one renewable energy source and limited consumers, model B has several renewable energy sources as well as various consumers. This impacted their electricity costs, production capacities, and their fixed costs.

IV. DISCUSSION

In conclusion, this study aimed to explore the theoretical feasibility of the integration of microgrid, VPP, AI, and blockchain technology. Results from simulation model A and B imply points toward the idea that the integration is economically and technologically feasible. Specifically, findings from this research suggest that energy can be efficiently managed through real-time responses and decision making by the AI to minimize waste of energy, costs of energy will diminish significantly and even have occasions which the cost for energy production and energy grid import will be free, and balance between renewable energy production systems show the feasibility of real-life applications of this integration. This aligns well with findings from prior research, despite their fragmented nature. The result from this research patches the concept that the integration of the four (microgrid, VPP, AI, blockchain) is feasible.
Some unexpected results from the experiment arose from production capacity, especially from simulation model A. Prior to this experiment, while it was assumed that efficiency of AI would look like employing all the energy systems to their maximum capacities in the grid in pursuit of optimization, there was a paradigm shift at the end where the efficiency of AI looked like energy optimized while energy sources were not yet utilized with their maximum capacity. This would mean that the leftover capacity can be used for unexpected situations, when there might be grid failures or resilience issues, which would mean microgrid will have to go island mode to prevent energy losses and inefficiency. Another unexpected result was from the energy costs of simulation model B. While prior studies have shown that there would be losses in energy caused by transmission and distribution systems, in conjunction with congestion during energy transfers [20, 21]. In contrast, results from simulation model B show that although there is energy transmission involved in this system, the cost of energy production and import was often $0, while there were acute fluctuations. Through this result, it can be inferred that the decision making of AI and the effectiveness of blockchain technology was able to overcome such loss.

Yet, several potential shortcomings must be considered. This study has only investigated this integration via the means of online simulation, while the input values were mostly based on average and assumed values. Realistically, the cost of this integration would be more expensive due to AI training and developing a P2P system aligning perfectly under the conditions of this integration. Another factor to recognize is that energy production and transfer costs itself would be nearly impossible to be free of cost practically - multiple previous research consider even detailed factors which were not a factor involved in the simulation [22, 4]. If this paper's purpose were to prove the possibility of acquiring and transferring energy free-of-cost, physical grid creation and pilot projects must be executed to prove the idea practically. Moreover, since microgrids and VPPs are DERs that are highly specialized in localization, outcomes from actually implementing this integration in various regions might vary and not always be positive.
Further work needs to be carried out through physical pilot projects, along with specialized AI connected with the P2P system, in conjunction with integrated microgrids and VPPs through electrical grid engineering. Moreover, research also must determine if AI's machine learning is capable of localizing to different regions with various energy production, geographical conditions, and consumption dynamics, along with intermittency issues that can undermine the capabilities of renewable energy sources within the energy system. Through further explorations in these fields, it will be able to elucidate this integration and facilitate implementations in the real world. After this integration reaches the level of being practically feasible, it will enter the stage of further developing the AI to exploit data collected from real life projects and infrastructures to create an optimization system for various regions with different renewable energy production infrastructure.
Ultimately, the goal is to actualize a coalescence of simulation model A and B from this simulation, for energy consumption in society. This would mean that energy will be free or extremely cheap of cost unless it is during a high demand hour, while energy consumption and production nearly matches so that there will be barely any waste of energy, as well as low fixed costs but high production capacities in our energy production and distribution facilities. This study has elaborated some way towards enhancing the understanding of how the integration of microgrids, VPPs, AI, and blockchain technology will look in economic and theoretical aspects. Through this integration proposed in this paper, this will be a possible stepstone for sustainable energy production and consumption to arrive soon.

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REFERENCES

[1] H. Ritchie, P. Rosado, and M. Roser, ``Breakdown of carbon dioxide, methane and nitrous oxide emissions by sector,'' 2020.

[2] IEA. (2023) The energy world is set to change significantly by 2030, based on today's policy settings alone. [Online]. Available: https://shorturl.at/L1eI0

[3] Y. Shang, S. Sang, A. K. Tiwari, S. Khan, and X. Zhao, ``Impacts of renewable energy on climate risk: A global perspective for energy transition in a climate adaptation framework,'' *Applied Energy*, vol. 362, p. 122994, 2024.

[4] International Renewable Energy Agency. (2023) Renewable power generation costs in. [Online]. Available: https://shorturl.at/ibeoA

[5] L. Melodia and K. Karlsson, ``Energy price stability: The Peril of fossil fuels and the promise of renewables,'' *Roosevelt Institute*, vol. 11, p. 15, 2022.

[6] M. Wei, S. Patadia, and D. M. Kammen, ``Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US?'' *Energy policy*, vol. 38, no. 2, pp. 919-931, 2010.

[7] . K. I. o. P. E. UNC Energy Center. (2018) Meeting the renewables intermittency challenge. [Online]. Available: https://shorturl.at/rOSaX

[8] S. Emporium. (2025) What are the challenges of renewable energy storage? [Online]. Available: https: //shorturl.at/7ww9V

[9] P. Discovery. (2023) Using renewables in energy grids–challenges & solutions. [Online]. Available: https: //shorturl.at/Hp5TB

[10] NREL. (2025) Grid modernization. [Online]. Available: https://shorturl.at/VVDH4

[11] AusNet. (2024) Grid-connected microgrids. [Online]. Available: https://shorturl.at/8z6gO

[12] Next. (2017) Virtual power plant: How to network distributed energy resources. [Online]. Available: https: //shorturl.at/oZ0CI

[13] A. Larson. (2025) How virtual power plants enhance grid operations and resilience. [Online]. Available: https: //shorturl.at/AzJwZ

[14] R. Walton. (2024) Virtual reality: Microgrids, vpps mutually boost each other's case. [Online]. Available: https://shorturl.at/b7fRn

[15] W. Zhang, Y. Shen, X. Wang, M. Li, W. Ren, X. Xu, and Y. Zhang, ``Research on multi-market strategies for virtual power plants with hydrogen energy storage,'' *Frontiers in Energy Research*, vol. 11, p. 1260251, 2023.

[16] J. Amissah, O. Abdel-Rahim, D.-E. A. Mansour, M. Bajaj, I. Zaitsev, and S. Abdelkader, ``Developing a three stage coordinated approach to enhance efficiency and reliability of virtual power plants,'' *Scientific Reports*, vol. 14, no. 1, p. 13105, 2024.

[17] Datategy. (2024) Empowering grids: AI-driven microgrid management solutions. [Online]. Available: https: //shorturl.at/aSkLJ

[18] G. Bhavana, R. Anand, J. Ramprabhakar, V. Meena, V. K. Jadoun, and F. Benedetto, ``Applications of blockchain technology in peer-to-peer energy markets and green hydrogen supply chains: A topical review,'' *Scientific Reports*, vol. 14, no. 1, p. 21954, 2024.

[19] L. L. Glória, S. B. Righetto, D. B. S. de Oliveira, M. A. I. Martins, R. A. S. Kraemer, and M. A. Ludwig, ``Microgrids and virtual power plants: Integration possibilities,'' in *2022 2nd Asian Conference on Innovation in Technology (ASIANCON)*. IEEE, 2022.

[20] A. M. Al Shareef, S. Seçkiner, B. Eid, and H. Abumeteir, ``Integration of blockchain with artificial intelligence technologies in the energy sector: A systematic review,'' *Frontiers in Energy Research*, vol. 12, p. 1377950, 2024.

[21] J. H. Eto, ``Electricity transmission congestion costs: A review of recent reports,'' 2003.

[22] IEA. (2020) Projected costs of generating electricity 2020. [Online]. Available: https://shorturl.at/iP4d7

ISSN: 2414-4592
DOI: 10.20474/jater-10.2.2