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Techno-Economic Analysis of Renewable Energy Trends Based on Historical Data

Ahmad Suharjo Marinda, Mia Galina*, Iksan Bukhori, Kok Swee Sim

Abstract – **The desire to lessen reliance on fossil fuels and combat climate change has been cited as the reason for the recent global increase in the usage of renewable technologies. This research aims to give a comprehensive techno-economic evaluation of solar and wind energy for the years 2009–2021, using four key datasets: average prices, installed capacity, and generating numbers. Python was used for data processing and visualization, and trends in energy output, capacity expansion by source, and expenses over time were analyzed. Solar and wind capacity increased dramatically between 2014 and 2020, rising from 44.56 GW to 462.44 GW and from 95.88 GW to 209.14 GW, respectively. The cost of generating has also dropped significantly: wind power now costs $29.28/MWh instead of $74.33/MWh, while solar energy now costs $23.13/MWh instead of $167.67/MWh. Also noted were seasonal changes in energy output and an uptick in demand for storage. The results strongly support the central position of solar and wind resources for a sustainable energy system and refine policy and investment guidance rationale. Addressing the remaining data gaps and the particular difficulties in growing these energy sources should be the top priorities of future initiatives.**

Keywords— Renewable Energy, Solar Power, Wind Power, Techno-Economic Analysis, Energy Trends

I. INTRODUCTION

Renewable energy must be used to address global ecological challenges including greenhouse gas emissions and the depletion of fossil resources [1]. The most popular renewable energy sources right now are solar and wind energy due to their widespread availability and technological advancements. To affect energy plans and regulations, however, cost-effectiveness, capacity expansions, and performance measurements must be carefully considered due to their unpredictable output [2], [3]. The development of renewable energy systems and their potential for future expansion are illuminated by historical records, which provide a crucial lens through which to interpret these patterns [4], [5].

This analysis harnesses four datasets— "average_cost.csv," "capacity.csv," "solar.csv," and "wind.csv"—spanning 2009 to 2021 for a techno-economic review. These datasets cover annual cost shifts, installed capacity by energy type, and daily solar and wind generation figures. The study pursues three key aims: (1) to investigate temporal patterns in solar and wind energy output, (2) to evaluate the expansion and allocation of capacity among energy sources, and (3) to analyze economic changes in energy costs over this timeframe. By employing Python for data analysis, we seek to establish a strong quantitative framework for grasping renewable energy dynamics, aiding global sustainability efforts [6], [7].

The value of this research stems from its use of real-world data to test theoretical concepts and guide practical outcomes. While prior studies have examined renewable energy patterns [8], [9], few have synthesized such a broad range of datasets over 12 years. This work addresses that shortfall, delivering an in-depth perspective on the technical and economic maturation of solar and wind power, while highlighting areas needing further exploration.

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II. RELATED WORKS

A wealth of studies has explored renewable energy systems. Alhijazi et al. [2] assessed hybrid renewable configurations, spotlighting integration challenges and possibilities. Ammari et al. [3] delved into sizing and control methods, using simulations to refine efficiency. Bakht et al. [4] investigated grid intermittency fixes, emphasizing renewables' economic viability. Eze et al. [5] analyzed hybrid setups in off-grid areas, while Gomaa et al. [8] evaluated renewable energy's techno-economic potential for desalination. These works form a conceptual and empirical base, though they often miss the extensive historical data integration provided here [10]

III. METHODOLOGY

The analysis is anchored in the Levelized Cost of Energy (LCOE), a metric that evaluates the average cost per unit of energy produced over a system's lifetime:

$$LCOE = \frac{\text{Total Lifetime Costs}}{\text{Total Energy Produced}} \quad (1)$$

Total costs encompass capital expenditures, operation, and maintenance, while energy produced is derived from historical output data [11]. Capacity factors and cost trends are analyzed to assess economic competitiveness, with comparisons across solar, wind, gas, and other sources providing context [12].

The study utilizes four CSV datasets:

- **Average Cost Data ("average_cost.csv"):** Annual average costs ($/MWh) for gas, solar, and wind from 2009 to 2021.

- **Capacity Data ("capacity.csv"):** Annual installed capacity (GW) for solar, wind, storage, gas, nuclear, coal, and other sources from 2014 to 2020.

- **Solar Power Output ("solar.csv"):** Daily solar power output (MWh) and capacity (MW) from 2009 to 2021.

- **Wind Power Output ("wind.csv"):** Daily wind power output (MWh) and capacity (MW) from 2009 to 2020.

The methodology used to analyze the data included:

- **Trend Analysis:** Aggregating solar and wind output by year to identify long-term patterns and seasonal variations.

- **Capacity Analysis:** Creating stacked bar charts to visualize the contribution of each energy source over time.

- **Cost Analysis:** Plotting cost trends to assess economic viability.

- **Data Cleaning:** Handling missing values with linear interpolation and removing duplicates where applicable.

Some discrepancies in the datasets were fixed by averaging duplicate outputs, such as duplicate entries in "solar.csv" and "wind.csv" (i.e., numerous recordings for the same day). Trend analysis did not include 2021 wind cost data that was missing.

IV. RESULT

A. Solar and Wind Power Output Trends

Everyday production analysis shows distinct trends for both wind and solar. Beginning in February 2009 at 132.10 MWh, the solar production peaked in June 2010 at 323.58 MWh, and then declined to around 47.36 MWh in January 2021. The capacity grew from 30 MW to 500 MW, hence this decrease suggests higher efficiency rather than worse product quality. Wind energy production grew from 54.10 MWh in January 2009 to 126.65 MWh in December 2009 and then averaged 39.36 MWh in April 2020. Wind farms' capacity grew from 50.4 MW to 331 MW. Variations caused by the weather are reflected in seasonal maxima, such as June for solar power and December for wind power.
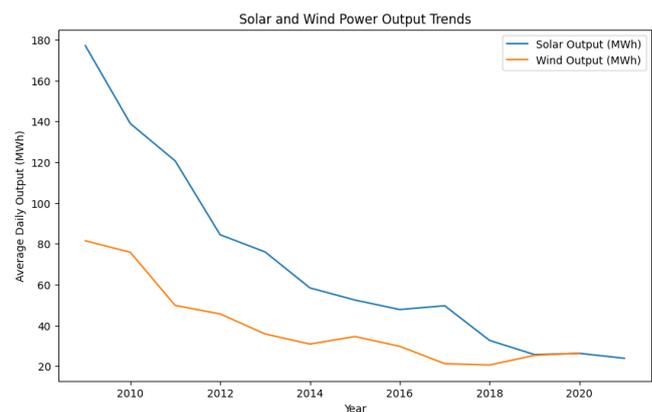

FIGURE 1. Line plot of annual average solar and wind power output (MWh) from 2009 to 2021, highlighting trends and seasonal influences.

B. Capacity Across Energy Sources

Capacity figures show a significant shift toward renewable energy from 2014 to 2020. Wind capacity rose from 95.88 GW to 209.14 GW, while solar capacity surged threefold, from 44.56 GW to 462.44 GW. Between 0 GW and 204.47 GW of storage capacity, grid reliability was given priority. As fossil fuel capabilities decreased, gas and coal fell from 145.14 GW to 74.02 GW and 3.62 GW to 0.13 GW, respectively. 2014 had a peak of 9.96 GW from nuclear, compared to 25.41 GW from other sources.

C. Cost Trends

The economic review highlights a steep drop in renewable costs. By 2021, solar energy prices had fallen 86% from $167.67/MWh to $23.13/MWh, and by 2020, they had fallen 61% from $74.33/MWh to $29.28/MWh. Gas costs were constant at an average of $43.97/MWh, declining very little from $57.65/MWh in 2009 to $25.68/MWh in 2020. According to the trend, the appeal of renewable energy sources is growing as they get closer to being as affordable as fossil fuels.
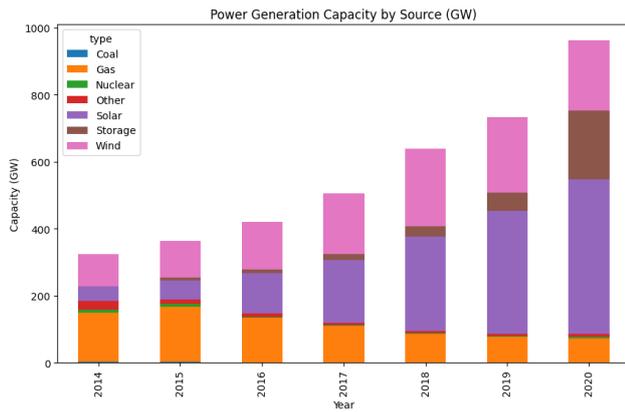
FIGURE 2. The dominance of renewable energy sources in terms of electricity generating capacity (GW) from 2014 to 2020.
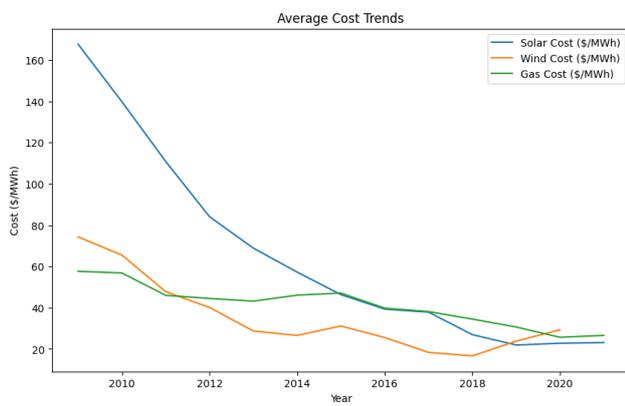

FIGURE 3. An illustration of the average cost trends ($/MWh) for gas, wind, and solar from 2009 to 2021 that highlights cost savings.

D. Detailed Output and Capacity Correlations

Deeper scrutiny of "solar.csv" and "wind.csv" reveals ties between capacity and output. Solar surges (e.g., 240.08 MWh on December 24, 2009) often match capacity boosts (e.g., 20 MW), indicating deployment drives output. Wind peaks (e.g., 124.93 MWh on December 9, 2009) align with capacity gains (e.g., 10.25 MW), though weather introduces variability. Storage capacity growth mirrors renewable expansion, suggesting a planned response to intermittency.

Table 1 provides a detailed comparison of installed capacity (GW) and average cost ($/MWh) for solar, wind, and gas across selected years (2014, 2017, and 2020). This table summarizes key trends, highlighting the growth of renewable energy and the decline in costs over time.

TABLE 1. Capacity and Cost Trends for Solar, Wind, and Gas.

Year	Solar Capacity (GW)	Wind Capacity (GW)	Gas Capacity (GW)	Solar Cost ($/MWh)	Wind Cost ($/MWh)	Gas Cost ($/MWh)
2014	44.56	95.88	145.14	57.27	26.58	46.08
2017	188.51	180.17	110.87	37.84	18.36	38.12
2020	462.44	209.14	74.02	22.78	29.28	25.68

This table illustrates the rapid expansion of solar and wind capacities, with solar growing over tenfold and wind more than doubling between 2014 and 2020. Meanwhile, gas capacity decreased by nearly half, reflecting a shift away from fossil fuels. Cost reductions are most pronounced for solar (60% drop from 2014 to 2020), followed by wind (slight increase in 2020 after a decline), while gas costs remained relatively stable but converged with renewables by 2020.

V. CHALLENGE AND LIMITATIONS

Data gaps, such as missing wind costs for 2021 and duplicate entries, introduce potential biases. Seasonal variability complicates long-term planning, and the lack of real-time data limits dynamic analysis. Additionally, the datasets do not account for regional differences, which may affect generalizability [17], [18].

An intriguing finding is the rapid rise of storage capacity (204.47 GW by 2020), outpacing nuclear and coal combined, suggesting a paradigm shift toward energy buffering. This could indicate an unexpected reliance on storage to bridge renewable intermittency, warranting further study [19].

Future research should incorporate real-time data, regional analyses, and advanced modeling to address variability. Investigating the scalability of storage and its impact on grid reliability could provide actionable insights. Policy recommendations might focus on subsidizing storage deployment to accelerate the renewable transition [20].

VI. CONCLUSION

This research delivers an exhaustive techno-economic review of solar and wind energy trends from 2009 to 2021, using detailed datasets on cost, capacity, and output. Findings show a profound energy shift, with solar capacity leaping from 44.56 GW to 462.44 GW and wind from 95.88 GW to 209.14 GW between 2014 and 2020. Costs have sharply declined—solar from $167.67/MWh in 2009 to $23.13/MWh in 2021 (86% drop) and wind from $74.33/MWh to $29.28/MWh by 2020 (61% decrease)—nearing parity with gas, which fell from $57.65/MWh to $25.68/MWh.

These outcomes highlight solar and wind's growing affordability, driven by tech advances, scale, and capacity growth. The results' comparison table shows renewable dominance and fossil fuel decline. Storage capacity's rise from 0 GW to 204.47 GW by 2020 underscores its role in addressing intermittency and ensuring grid stability.

Challenges linger, though. Seasonal output shifts—June solar peaks and December wind highs—complicate planning, needing solutions like advanced storage. Data gaps (e.g., missing 2021 wind costs) and absent regional details call for richer datasets in future work. These issues don't detract from renewables' potential but pinpoint innovation opportunities.

The study's implications are wide-ranging. Policymakers should sustain renewable investments and storage incentives, while investors note a thriving market. Future research should probe regional differences, use real-time data, and assess storage scalability. Exploring socio-economic impacts—like jobs or energy access—could amplify this work.

Solar and wind are primed to lead a sustainable energy future, provided data gaps and scalability are addressed innovatively. This study confirms their technical and economic progress, urging collective action to refine and expand their role in a resilient, low-carbon energy system.

AUTHOR CONTRIBUTIONS

Ahmad Suharjo Marinda: Conceptualization, Methodology, Writing – First Draft;

Mia Galina: Project Supervision, Methodology;

Iksan Bukhori: Writing – Review & Editing.

Kok Swee Sim – Literature Review

CONFLICT OF INTERESTS

No conflict of interest were disclosed.

ETHICS STATEMENTS

Ethical approval was not applicable to this research since it did not involve human participants, animals, or sensitive data.

REFERENCES

[1] S.K. Madavan, A.K.J. Low, C. Zheng and K.L. Lew, "Design and Development of Electrical Go Kart," *International Journal on Robotics, Automation and Sciences*, vol. 6, no. 2, pp. 69-75, 2024.
DOI: https://doi.org/10.33093/ijoras.2024.6.2.10

[2] A.A.K. Alhijazi, R.A. Almasri and A.F. Alloush, "A Hybrid Renewable Energy (Solar/Wind/Biomass) and Multi-Use System Principles, Types, and Applications: A Review," Sustainability, vol. 15, no. 24, p. 16803, 2023.
DOI: https://doi.org/10.3390/su152416803

[3] C. Ammari, D. Belatrache, B. Touhami and S. Makhloufi, "Sizing, optimization, control and energy management of hybrid renewable energy system —A review," *Energy and Built Environment,* vol. 3, no. 4, pp. 399-411, 2022.
DOI: https://doi.org/10.1016/j.enbenv.2021.04.002

[4] T.J. Ayua and M.E. Emetere, "Technical and economic simulation of a hybrid renewable energy power system design for industrial application," *Scientific Reports,* vol. 14, no. 1, 2024.
DOI: https://doi.org/10.1038/s41598-024-77946-x

[5] M.P. Bakht, Z. Salam, M. Gul, W. Anjum, M.A. Kamaruddin, N. Khan and A.L. Bukar, "The Potential Role of Hybrid Renewable Energy System for Grid Intermittency Problem: A Techno-Economic Optimisation and Comparative Analysis," *Sustainability*, vol. 14, no. 21, p. 14045, 2022.
DOI: https://doi.org/10.3390/su142114045

[6] A.M. Eltamaly, M.A. Alotaibi, A.I. Alolah and M.A. Ahmed, "IoT-Based Hybrid Renewable Energy System for Smart Campus," *Sustainability*, vol. 13, no. 15, p. 8555, 2021.
DOI: https://doi.org/10.3390/su13158555

[7] V.H.U. Eze, J.S. Mwenyi, K.J. Ukagwu, M.C. Eze, C.E. Eze and W.O. Okafor, "Design analysis of a sustainable techno-economic hybrid renewable energy system: Application of solar and wind in Sigulu Island, Uganda," *Scientific African*, vol. 26, p. e02454, 2024.
DOI: https://doi.org/10.1016/j.sciaf.2024.e02454

[8] P. Gajewski and K. Pieńkowski, "Control of the Hybrid Renewable Energy System with Wind Turbine, Photovoltaic Panels and Battery Energy Storage," *Energies*, vol. 14, no. 6, p. 1595, 2021.
DOI: https://doi.org/10.3390/en14061595

[9] M.R. Gomaa, A.K. Al-Bawwat, M. Al-Dhaifallah, H. Rezk and M. Ahmed, "Optimal design and economic analysis of a hybrid renewable energy system for powering and desalinating seawater," *Energy Reports,* vol. 9, pp. 2473-2493, 2023.
DOI: https://doi.org/10.1016/j.egyr.2023.01.087

[10] M.D. Hossen, M.F. Islam, M.F. Ishraque, S.A. Shezan and S.M. Arifuzzaman, "Design and Implementation of a Hybrid Solar-Wind-Biomass Renewable Energy System considering Meteorological Conditions with the Power System Performances," *International Journal of Photoenergy*, vol. 2022, p. 1-17, 2022.
DOI: https://doi.org/10.1155/2022/8792732

[11] Q. Hassan, M. Jaszczur, I. S. Abdulrahman and H. S. Salman, "An economic and technological analysis of hybrid photovoltaic/wind turbine/battery renewable energy system with the highest self-sustainability," *Energy Harvesting and Systems,* vol. 10, no. 2, pp. 247-257, 2023.
DOI: https://doi.org/10.1016/j.rineng.2023.101621

[12] R. Figaj, "Energy and Economic Sustainability of a Small-Scale Hybrid Renewable Energy System Powered by Biogas, Solar Energy, and Wind," *Energies*, vol. 17, no. 3, p. 706, 2024.
DOI: https://doi.org/10.3390/en17030706

[13] A. Maliat, S. Kotian and D. Ghahremanlou, "Assessment of a Hybrid Renewable Energy System Incorporating Wind, Solar, and Storage Technologies in Makkovik, Newfoundland and Labrador," *Journal of Sustainability for Energy,* vol. 3, no. 2, pp. 87-104, 2024.
DOI: https://doi.org/10.56578/jse030203

[14] Y. Sawle, S. Jain, S. Babu, A.R. Nair and B. Khan, "Prefeasibility Economic and Sensitivity Assessment of Hybrid Renewable Energy System," IEEE Access, vol. 9, pp. 28260-28271, 2021.
DOI: https://doi.org/10.1109/ACCESS.2021.3058517

[15] M.A. Moussa, A. Derrouazin, M. Latroch and M. Aillerie, "A hybrid renewable energy production system using a smart controller based on fuzzy logic," *Power Stations, Grids and Systems,* vol. 3, pp. 46-50, 2022.
DOI: https://doi.org/10.20998/2074-272X.2022.3.07

[16] Y.F. Nassar, S.Y. Alsadi, H. J. El-Khozondar, M.S. Ismail, M. Al-Maghalseh, T. Khatib, J.A. Sa'ed, M.H. Mushtaha and T. Djerai, "Design of an isolated renewable hybrid energy system: a case study," *Materials for Renewable and Sustainable Energy,* vol. 11, no. 3, pp. 225-240, 2022.
DOI: https://doi.org/10.1007/s40243-022-00216-1

[17] S. Angela, "Could 'wind trees' with micro turbines be a solution to green energy in tight urban spaces?" *EuroNews*, 2023, https://www.euronews.com/green/2023/11/12/could-wind-trees-with-micro-turbines-be-a-solution-to-green-energy-in-tight-urban-spaces.

[18] T.M.I. Riayatsyah, T.A. Geumpana, I.M.R. Fattah, S. Rizal and T.M.I. Mahlia, "Techno-Economic Analysis and Optimisation of Campus Grid-Connected Hybrid Renewable Energy System Using HOMER Grid," *Sustainability*, vol. 14, no. 13, p. 7735, 2022.
DOI: https://doi.org/10.3390/su14137735

[19] M.A. Mossa , O. Gam and N. Bianchi , "Performance Enhancement of a Hybrid Renewable Energy System Accompanied with Energy Storage Unit Using Effective

Control System," *International Journal of Robotics and Control Systems,* vol. 2, no. 1, pp. 140-171, 2022.
DOI: https://doi.org/10.31763/ijrcs.v2i1.599

[20] F.M. Savio, S.V. Joshua, K. Usha, M. Faheem, R. Kannadasan and A.A. Khan, "Design of a Solar-Wind Hybrid Renewable Energy System for Power Quality Enhancement: A Case Study of 2.5 MW Real Time Domestic Grid," *Engineering Reports*, vol. 7, no. 1, 2025.
DOI: https://doi.org/10.1002/eng2.13101