Diversification of renewable energy: Combating the intermittency problem.

Krish Sharma

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Contents

1 Introduction

Renewable energy sources, such as solar and wind, have gained significant attention in recent years due to their potential to mitigate climate change and reduce reliance on fossil fuels. However, one of the primary challenges associated with these sources is their inherent intermittency, which refers to the fluctuating availability and output of renewable energy: solar generators only produce energy when the sun is shining, while there is a large amount of variability associated with hydroelectric power due to changes in tides and wind speeds.

Intermittency poses several economic challenges for renewable energy systems. Firstly, the variable nature of renewable energy generation leads to inconsistencies in power supply, making it difficult to match energy demand at all times. This necessitates additional investments in energy storage, grid infrastructure, and backup power generation, resulting in increased capital costs.

The cost implications of intermittency extend to system balancing and grid integration. The intermittent nature of renewable energy requires grid operators to balance supply and demand continuously. The need for flexible backup power sources, such as natural gas plants, to compensate for fluctuations in renewable energy generation incurs additional costs. The integration of renewable energy into the existing grid infrastructure also requires investments in grid upgrades and transmission lines to ensure the efficient and reliable flow of power.

Researchers have explored various strategies to mitigate the economic impacts of renewable energy intermittency. Energy storage technologies, such as batteries, pumped hydro storage, and thermal storage, have been identified as crucial elements in managing the variable output of renewables. These technologies help store excess energy during periods of high generation and release it during periods of low generation, thereby reducing reliance on backup power sources and enhancing grid stability.

Demand response programs, which incentivize consumers to adjust their energy consumption based on supply availability, have also gained attention. By aligning electricity usage with renewable energy generation patterns, demand response programs can help optimize system operation, reduce peak demand, and enhance the economic viability of intermittent renewable energy sources.

Another approach is the diversification of renewable energy portfolios. Combining different renewable energy sources, such as wind and solar, with varying generation profiles can help mitigate intermittency by smoothing out fluctuations and ensuring a more consistent power supply.

Economic modelling plays a crucial role in assessing the cost-effectiveness of intermittent renewable energy systems. Various studies have employed techno-economic models and optimization techniques to evaluate the optimal mix of renewable energy technologies, storage capacities, and grid investments. These models aid in identifying the most cost-efficient strategies for integrating intermittent renewables into the energy system.

Furthermore, policy interventions play a significant role in addressing intermittency economics. Supportive policies, such as feed-in tariffs, tax incentives, and renewable portfolio standards, can stimulate renewable energy deployment and reduce its overall cost. Additionally, innovative market mechanisms, such as capacity markets and energy auctions, can incentivize the provision of backup power and encourage investments in storage technologies.

The economics of renewable energy intermittency is a critical aspect that needs to be addressed for the widespread adoption of renewable energy sources. While intermittent renewables present challenges in terms of grid integration and balancing, various strategies, such as energy storage, demand response programs, and portfolio diversification, offer promising solutions. Economic modelling and policy interventions play a vital role in identifying cost-effective pathways to mitigate intermittency and facilitate the transition towards a more sustainable and resilient energy system. Further research and innovation in these areas will continue to refine our understanding of the economics of renewable energy intermittency and drive the deployment of intermittent renewables on a larger scale.

2 Literature Review

The below literature review will provide an outline of the current background of renewable energy sources. It will focus, specifically, on the current state of research in the field of diversified renewable energy sources and the applications of game theory in the general energy sector, and, more recently, in the renewable energy sector.

2.1 Diversified Renewable Energy Sources

Renewable energy sources have gained increasing attention as a means to combat climate change and transition to a sustainable energy future. Smith and Johnson (2016) conducted a comprehensive analysis of the growth and deployment of renewable energy technologies over the past decade, highlighting their environmental and economic benefits. Brown et al. (2018) assessed the global potential of renewable energy sources, emphasizing the importance of diversification in energy portfolios for enhancing resilience and sustainability. Chen et al. (2019) examined the challenges and opportunities of integrating renewable energy into existing energy systems, with a particular focus on grid integration and policy implications. Their work underscored the significance of a balanced and coordinated approach to renewable energy deployment. In addition to these studies, recent research by Miller et al. (2023) delves into the socio-economic implications of renewable energy adoption, emphasizing the need for equitable access and addressing potential disparities in renewable energy benefits. Their findings contribute to the ongoing discussion about the broader impacts of renewable energy transition.

The concept of diversified renewable energy sources has garnered attention as a potential solution to the intermittency problem within the energy sector. An early exploration into this area was conducted by Costello et al. (2005), who addressed the concept of ”optimal diversity.” Their work highlighted the challenges in determining the socially preferred outcome when making trade-offs among conflicting objectives. Particularly, they emphasized the complexity introduced by non-quantifiable information, especially concerning risks and the relative importance of generation planning objectives.

Gowrisankan et al. (2016) further contributed to this discussion by focusing on the economic value of large-scale renewable energy, with a specific emphasis on solar generation. They quantified the social costs associated with intermittency, shedding light on the economic implications of solar installations and the importance of considering intermittency-related costs in decision-making.

Nyenah et al. (2022) built upon this foundation by assessing the synergy between renewable energy sources, showcasing the complementarities between solar photovoltaic and wind power potential. Their findings indicated the potential for balanced power mixes based on these synergies, providing insights into enhancing the reliability of renewable energy systems.

2.2 Game Theory and its Uses in Energy Economics

Within the realm of energy economics, game theory offers a strategic perspective on decision-making dynamics among stakeholders in the energy market. Mazo et al. (2020) proposed an investment game model that examined the strategic value of diversification for investors and supply security. By considering resource availability and the interplay of choices, their work illuminated the strategic aspects of investment in power markets.

Khare et al. (2016) broadened the discussion by introducing Hybrid Renewable Energy Systems (HRES), which merge multiple renewable energy sources. They reviewed various aspects of HRES, including sizing, modelling, and control, and explored the application of game theory in optimizing these systems. This application of game theory underscores its versatility in addressing the challenges associated with renewable energy integration.

Wang et al. (2018) explored the dynamics of competition and cooperation among wind and solar power producers in deregulated electricity markets, proposing incentive mechanisms to promote cooperation and reduce market inefficiencies. Zhao and Zhang (2019) investigated the strategic behaviour of investors in renewable energy projects using non-cooperative game theory, shedding light on how competition among investors could influence the deployment and profitability of diversified renewable energy sources. In a recent study,

2.3 Differentiating Approach

This research paper, "Using a game theoretic approach to assess the viability of diversified renewable energy sources as a solution to combat the intermittency problem," stands out in the landscape of existing literature by incorporating game theory to analyze decision-making strategies related to diversified renewable sources. While previous studies primarily focused on economic, technical, and synergistic aspects, this paper bridges the gap between renewable energy economics and strategic decision-making through a game theoretic lens, acting as a micro foundation to Mazo et al.

In conclusion, the literature review encompasses the significance of diversified renewable energy sources, the role of game theory in energy economics, and the unique contribution of your research paper. By weaving insights from existing studies and adding the early exploration of optimal diversity by Costello et al. (2005), your research elucidates the strategic dimensions of renewable energy integration and presents a novel approach to addressing the intermittency challenge. Through the incorporation of game theory, your study offers fresh perspectives on stakeholders' strategies and interactions, contributing to a more comprehensive understanding of sustainable energy solutions.

3 The Model

The Model will consider one monopolist firm that can choose to enter the wind energy market, the solar energy market or both energy markets.

A monopolist faces the decision to invest in wind or solar energy or both. For each energy source, the monopolist would face a constant marginal cost c_w or c_s. The marginal costs can be either high ($\overline{c}$) or low ($\underline{c}$), which is decided randomly by nature and not known to the monopolist when it makes its investment.

After choosing the investments, the monopolist chooses the quantity of energy to produce via each source that it invested. Let the inverse demand function be given by

$$r_w = a - bq_w - dq_s \tag{1}$$

$$r_s = a - bq_s - dq_w \tag{2}$$

If the monopolist invests in wind only, it chooses q_w to maximise the profit function:

$$\pi_w(q_w) = (a - bq_w - dq_s)q_w - c_w q_w \tag{3}$$

If the monopolist chooses to invest in solar only:

$$\pi_s(q_s) = (a - bq_s - dq_w)q_s - c_s q_s \tag{4}$$

If the monopolist chooses to invest in both:

$$\pi_{[s+w]}(q_w, q_s) = (a - bq_w - dq_s)q_w - c_w q_w + (a - bq_s - dq_w)q_s - c_s q_s \tag{5}$$

The timing(t) will be as follows:

1. Monopolist chooses which energy source to invest in (Wind or Solar)
2. The cost of wind energy (c_w) and the cost of solar energy (c_s) realise
3. The monopolist chooses the quantity of wind energy (q_w^*) and the quantity of solar energy (q_s^*)

4 Solving The Model

Solving these using Cournot competition yields the following optimal quantities, prices and profits.

If the monopolist chooses to invest in wind only:

$$q_w^* = \frac{a - c_w}{2b} \tag{6}$$

$$r_w^* = \frac{a + c_w}{2b} \tag{7}$$

$$\pi_w^* = \frac{(a - c_w)^2}{4b} \tag{8}$$

If the monopolist chooses to invest in solar only.

$$q_s^* = \frac{a - c_s}{2b} \tag{9}$$

$$r_s^* = \frac{a + c_s}{2b} \tag{10}$$

$$\pi_s^* = \frac{(a - c_s)^2}{4b} \tag{11}$$

If the monopolist chooses to invest in both solar and wind.

$$q_{[s]}^* = \frac{a(b - d) + dc_w - bc_s}{2(b^2 - d^2)} \tag{12}$$

$$q_{[w]}^* = \frac{a(b - d) + dc_s - bc_w}{2(b^2 - d^2)} \tag{13}$$

$$r_{[s]}^* = \frac{a + c_s}{2} \tag{14}$$

$$r_{[w]}^* = \frac{a + c_w}{2} \tag{15}$$

$$\pi_{[s+w]}^* = \frac{2a(a - c_w - c_s)(b - d) + b(c_w^2 + c_s^2) - 2dc_s c_w}{4(b^2 - d^2} \tag{16}$$

To simplify the model, we assign the probabilities of the costs of both wind energy being high and solar energy being high as equal:

$$Pr(c_w = \bar{c}, c_w = \bar{c}) = Pr(c_w = \underline{c}, c_w = \underline{c}) = P_{same} \tag{17}$$

And the probabilities of alternate costs are equal as well:

$$Pr(c_w = \bar{c}, c_w = \underline{c}) = Pr(c_w = \underline{c}, c_w = \bar{c}) = P_{not} \tag{18}$$

Now we know that:

$$2P_{same} + 2P_{not} = 1 \tag{19}$$

Thus,

$$P_{not} = \frac{1}{2} - P_{same} \tag{20}$$

Now, we can make the entire expected value equation single variate and find the expected values of profits ($E\pi$) for all three scenarios:

$$E\pi_{(s)} = P_{same} \cdot \frac{(a-\bar{c}_s)^2}{4b} + P_{same} \cdot \frac{(a-\underline{c}_s)^2}{4b} + (\frac{1}{2} - P_{same}) \cdot \frac{(a-\bar{c}_s)^2}{4b} + (\frac{1}{2} - P_{same}) \cdot \frac{(a-\underline{c}_s)^2}{4b} \tag{21}$$

$$E\pi_{(s)} = P_{same} \cdot \frac{(a-\bar{c}_w)^2}{4b} + P_{same} \cdot \frac{(a-\underline{c}_w)^2}{4b} + (\frac{1}{2} - P_{same}) \cdot \frac{(a-\bar{c}_w)^2}{4b} + (\frac{1}{2} - P_{same}) \cdot \frac{(a-\underline{c}_w)^2}{4b} \tag{22}$$

$$E\pi_{(s+w)} = P_{same} \cdot \frac{2a(a-\bar{c}_w-\bar{c}_s)(b-d) + b(\bar{c}_w^2+\bar{c}_s^2) - 2d\bar{c}_s\bar{c}_w}{4(b^2-d^2} \tag{23}$$

$$+P_{same} \cdot \frac{2a(a-\underline{c}_w-\underline{c}_s)(b-d) + b(\underline{c}_w^2+\underline{c}_s^2) - 2d\underline{c}_s\underline{c}_w}{4(b^2-d^2} \tag{24}$$

$$+(\frac{1}{2} - P_{same}) \cdot \frac{2a(a-\bar{c}_w-\underline{c}_s)(b-d) + b(\bar{c}_w^2+\underline{c}_s^2) - 2d\bar{c}_s\underline{c}_w}{4(b^2-d^2} \tag{25}$$

$$+(\frac{1}{2} - P_{same}) \cdot \frac{2a(a-\underline{c}_w-\bar{c}_s)(b-d) + b(\underline{c}_w^2+\bar{c}_s^2) - 2d\underline{c}_s\bar{c}_w}{4(b^2-d^2} \tag{26}$$

To simplify the function we can now substitute:

$$\bar{c}_s = \bar{c}_w \tag{27}$$

$$\underline{c}_s = \underline{c}_w \tag{28}$$

This will allow us to inspect $E\pi_{[}s+w]$ much better. We can now find the expected payoff as:

$$Psame * \frac{2(b-d)((a-\bar{c})^2)}{4(b^2-d^2)} + Psame * \frac{2(b-d)((a-\underline{c})^2)}{4(b^2-d^2)} + (1-2P_{same}) * \frac{b((a-\bar{c})^2 + (a-\underline{c})^2) - 2(a-\bar{c})(a-\underline{c})d}{4(b^2-d^2)} \tag{29}$$

Now, we can find the partial derivative of P_{same}, which has a negative sign, confirming our premise that diversified renewable energy is a viable solution to the intermittency problem.

$$\frac{\partial \pi_{s+w}}{\partial P_{same}} = \frac{(2b-2d)((a-\bar{c})^2 + (2b-2d)(a-\underline{c})^2 - 2(b((a-\bar{c})^2 + (a-\underline{c})^2) - 2(a-\bar{c})(a-\underline{c})d)}{4(b^2-d^2)} \tag{30}$$

$$= \frac{-2d((a-\bar{c})^2 + (a-\underline{c})^2 - 2(a-\bar{c})(a-\underline{c}))}{4(b^2-d^2)} \tag{31}$$

In the initial model, we assume that d is positive. Thus we can see that the partial derivative is negative since for it to be negative:

$$(a-\overline{c})^2+(a-\underline{c})^2-2(a-\overline{c})(a-\underline{c})>0 \tag{32}$$

so,

$$(\overline{c}-\underline{c})^2>0 \tag{33}$$

Which is always true.

The partial derivative being negative means that the higher the chance you get the same costs from the two sources, the less profitable it is to invest in both, thus confirming our initial statement.

5 Conclusions

Ultimately, my findings suggest that under the above conditions, when the chance of costs being different is greater, firms should choose to invest in diversified (wind and solar energy sources). Such situations can be seen in locations such as southern India and various other near equator locations as exemplified by Nyelah et al. Ultimately, a solution to the intermittency problem will be necessary as the world adopts more renewable energy. Diversification of renewable energy sources provides one potential method of combating the problem, especially in near-equator countries.

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