Enhancing Understanding of Project Valuation of Energy Transition through Hybrid Power Plants

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Abstract. Hybrid power plants, which combine renewable energy sources such as photovoltaic solar and wind power with storage systems, offer a promising solution for improving energy reliability, reducing emissions, and accelerating the energy transition. However, their development is complex due to the integration of multiple energy sources, grid parity challenges, and the variety of potential risks involved. Therefore, this type of power plant requires a project valuation approach that addresses beyond techno-economic aspects such as risks and uncertainties due to intermittent conditions. This study explores and examines best practices and current insights into project valuation approaches for hybrid power plants, while also highlighting gaps in existing research and future research direction. The analysis reveals that most research primarily focuses on deterministic approaches of economic analyses, which have been predominantly used in the field. A deterministic approach provides a single specific value of economic estimation. However, we found that recent studies have highlighted the limitation of such approach in incorporating uncertainties and risks. Therefore, our findings suggest the need for further research to incorporate uncertainties and to adopt models such as stochastic approaches that better reflect the spectrum of potential outcomes.

Keywords: *hybrid power plant; reducing emission; energy transition; uncertainty; stochastic approach.*

1 Introduction

Climate change, has negatively impacted the environment, health, food production, and water access as discussed by Tao et.al. in [1]. In response, countries committed to reducing emissions through Nationally Determined Contributions (NDCs) and the Net Zero Emission (NZE) initiative, which focuses on decarbonization, low-carbon development, and transition as discussed in UNFCCC [2], Azevedo et.al. in [3], Wimbadi & Djalante in [4]. This transition is also driven by a global trend toward environmentally friendly practices that comply with emission standards, making future energy dependent on renewable energy as discussed by Farhat et.al. in [5]. Renewable energy, especially wind and solar, plays a critical role in replacing fossil fuels, major contributors to CO2 emissions as written by Bogdanov et.al. in [6]. In Indonesia, energy consumption

Received ________, Revised ________, Accepted for publication __________

has shifted toward the industrial sector, with coal, petroleum, and biodiesel dominating the energy mix, though renewable energy still falls short of the 17.87% target as reported by DEN [7]. Lei et.al. in [8] stated that the increasing renewable energy is key to sustainable development, and decarbonizing power generation through hybrid systems.

Moreover, Indonesia has ambitious goals to shifting from fossil dominance to renewable energy sources. This plan cannot be done spontaneously by simply replacing fossil-based power generation, a gradual approach is necessary to ensure the transition steadily as discussed by Hersaputri et.al. in [9]. The decarbonization program in the power sector, as outlined in the RUPTL 2021-2030, has focuses on integrating renewable energy both in on-grid systems and off-grid, to reduce reliance on diesel power plants. This program is crucial as it has a significant impact on the nation's electricity demand and environmental quality, with approximately 5,200 diesel generators across 2,130 locations being potential candidates for involvement.

Generally, the development of hybrid power plants faces significant complexity, requiring a project valuation approach that considers techno-economic aspects and uncertainty as discussed by Berrada in [10]. This complexity includes determining the optimal design based on load profiles, taking into account various factors such as subcomponents, sizing, control systems, and response time as written by Ramirez-Meyers et.al. in [11] Moreover, hybrid technology integrates both fossil and non-fossil energy sources, which must optimize energy efficiency while managing the uncertainties associated with the variability of renewable energy sources influenced by weather and location [12]. In addition, the development of electricity infrastructure that supports energy transition, digitalization, decentralization, and decarbonization requires significant investment [13]. The primary goal of this energy transition is to reduce fossil fuel consumption, decarbonize power generation, and electrify various sectors [14]. Although this process takes time, its benefits will be widely harvested at the future as discussed by Yudiartono et.al. in [15].

Furthermore, NREL also highlights that integrating technology into hybrid systems requires revising financial planning models to enable a more comprehensive and accurate investment evaluation [16]. Given the distinct complexities of hybrid systems compared to conventional power generation, there is a need for a re-analysis of financial models to ensure investment decisions are based on a more varied set of valuation methods as written by Dobrowolski & Drozdowski in [17]. Traditionally, the traditional valuation has been unable to reflect elements of risk and uncertainty [18], as it produces a deterministic value, limiting its ability to provide comprehensive information about investment risks [19]. In this context, risk is associated with the probability of success, while uncertainty refers to the inability to precisely define something as discussed by Witter et.al. in [20].

Our reviews show that there is growing research on the hybrid renewable energy systems, which can be categorized into several streams: (1) studies focusing on the calculation of optimize the configuration of hybrid systems, (2) studies that focus on explore the combination of several energy sources and (3) research focused on calculation cost of energy. Then we found there is opportunity at research focused in emerging studies applying stochastic models to better capture the variability and operational complexities of renewable energy systems. There is a significant opportunity for future research to incorporate more uncertainty factors, such as weather, policy changes, and price fluctuations, as well as applying stochastic models to provide an accurate and comprehensive analysis.

2 Literature Review

The deterministic approach, offers several advantages in terms of simplicity, ease of application, and reliance on fixed data. This method facilitates swift and consistent decision-making, as the weight of each criterion is predetermined, eliminating the need to account for variability or uncertainty as discussed by Ari & Gencer in [21]. In the context of hybrid systems, this approach simplifies the optimization of reliability and cost into a single cost-optimization problem. The design is based on worst-case scenarios, using average values for load and power production, without accounting for random variations in renewable resources or demand, provides simplicity and speed, making it easier to implement and understand as written by Maheri in [22].

On the other hand, stochastic methods offer distinct advantages in managing uncertainties inherent in renewable energy systems. In the context of microgrid energy management, stochastic approaches effectively handle the variability of renewable sources like wind and solar power, as well as energy demand as discussed by Eghbali, et.al. in [23]. In addition, the stochastic optimization of hybrid systems allows for more precise system sizing and cost optimization by considering the randomness in energy resources and demand. This leads to more reliable system performance and better economic outcomes compared to deterministic methods [24]. For large-scale wind energy integration, stochastic approach enhance system stability by smoothing power fluctuations and reducing the strain on energy storage systems, highlighting the effectiveness of stochastic methods in managing complex and unpredictable energy systems were given by Barelli, et.al. in [25].

In terms of renewable energy development risks, research highlights various risks that must be identified and managed effectively for projects to succeed. Technical, economic, social, and environmental risks must all be considered in renewable energy projects [26]. Chebotareva et al. in [27] and Shimbar & Ebrahimi in [28] also pointed out that political uncertainty and ineffective governmental support are key risk factors in renewable energy projects, particularly in developing countries. In its development, quantitative risk assessment is often conducted by rerunning models to calculate economic feasibility metrics, including IRR and LCOE, within a range of uncertain input parameters as discussed by Guindon & Wright in [29]. Another study by Wu et al. in [26] identified four key risks in the development of renewable energy projects: technical risks related to technology, investment costs, social risks from the lack of policy support, and environmental risks. Similarly, research by Kul et al. in [30] highlighted investment risks in renewable energy, with findings showing that economic and business risks are the most dominant, followed by market, policy, technical, environmental, and social. Furthermore, with proper risk identification, effective mitigation strategies can be implemented, increasing the likelihood of successful renewable energy project investments as discussed by Abba et al. in [31] and Aquila, Coelho et al., in [32]

3 Material and method

The systematic literature review (SLR) is used in this research to determine how research about techno-economic perspective conducted in hybrid power plant topics. SLR is a highly rigorous and methodical approach that offers several advantages for synthesizing research in a scientific field. SLR is a valuable tool for assessing trends, gaps, and the state of knowledge within a field [33]. This approach allows researchers to uncover knowledge gaps, evaluate current trends, and provide a robust foundation for further research. The process concludes with a detailed analysis and reporting of findings, ensuring that others can replicate the review and build upon its conclusions as discussed by Carrera-Rivera et.al in [34].

SLR is widely recognized as a standard in review methodologies, providing comprehensive answers to specific research questions, involves clearly defining research questions, selecting databases, and using a systematic search strategy. SLR contributes reliable conclusions that inform policy, practice, and future research directions were given by Snyder in [35]. In line with prior research, SLR is a methodology that ensures comprehensive and unbiased coverage of literature by following a structured and transparent approach with strict inclusion and exclusion criteria. It strengthens the validity of research by synthesizing findings from multiple studies and helps identify knowledge gaps for future research as discussed by Xiao & Watson in [36].

The current study referred to Scopus database for analysis and used Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) for SLR. Before conducting any PRISMA analysis, the keywords are regarded as the foundation on which the analysis is based. For this purpose, more than 100 articles in five years back published were obtained from the Scopus Database to conduct important author keywords considered central to the theme. The authors saved the final search string and list of the documents as below:

Table 1 Summary of Searching

Parameters	Value
Data Source	Scopus-indexed database
Keyword	Hybrid renewable energy*, hybrid power plant, decarbonization, decarbonisation, techno economy
Time Publication	2019 to 2024
Publication Stage	Final: 140
Source Type	Journal: 131 Conference: 9
Language	English: 140
Number Article-year	2024: 2 2023: 33 2022: 47 2021: 30 2020: 19 2019: 9

Table 2 Ranking the Top Publisher

Rank	Publisher	Articles	Citations
1	Journal Of Cleaner Production	63	1182
2	Frontiers In Energy Research	16	99
3	Iscience	7	52
4	Heliyon	5	2
5	Electricity Journal	3	25

The systematic review process started identifying 140 records from the years 2019 to 2024, focusing on topics such as hybrid renewable energy, hybrid power plants, decarbonization, techno-economy, business, and economy across multidisciplinary fields. After screening, 110 records were retained, limited to those published in Q1 and Q2 journals. In the eligibility assessment, 94 papers were excluded as they did not specifically discuss hybrid power plants, leaving 19 studies included in the review. The results of PRISMA analysis is presented below:

Table 3 PRISMA analysis

Identification	Records identified from*: (n = 140)	Limit to: 2019-2024 Hybrid renewable energy*; hybrid power plant; decarbonization; decarbonization; techno economy; Business; Economy; Multidisciplinary.
Screening	Records screened (n = 110)	Limit to: Q1 & Q2 Journal Publisher
	Records screened (n = 94)	Limit to: Specific discussing techno-economy approach
	Records screened (n = 55)	Limit to: Specific related to all categories of hybrid system
Eligibility	Reports assessed for eligibility (n = 19)	Reports excluded: 36 papers are not specifically related to electricity field esp. hybrid power plant
Included	Studies included in review (n = 19)	19 papers studied

4 Results

Previous studies have emphasized the importance of diversifying energy sources and incorporating energy storage in hybrid systems. Research by Baseer et al. in [37], Thirunavukkarasu & Sawle in [38], and Babatunde et al. in [39] demonstrated that hybrid systems can enhance system reliability and reduce dependence on a single energy source. Similar findings were highlighted by Rinaldi et al. in [40] and Nyeche & Diemuodeke in [41], who emphasized that energy diversification helps mitigate the variability of renewable resources. Jahangir et al. in [42] stated that further reinforced this by underlining the importance of multi-year sensitivity analysis in optimizing hybrid renewable energy systems.

Other research has shown that integrating various renewable energy sources into hybrid configurations, such as PV, wind turbines, biogas, and biomass, can reduce emissions and improve the reliability of the electrical grid as discussed by Thirunavukkarasu & Sawle in [43], Kumar & Channi in [44], Vendoti et al. in [45], and Arif et al. in [46]. Studies by Aykut et al. in [47] at Turkey, Icaza &

Borge-Diez in [48] at Ecuador, and Odetoye et al. in [49] at Nigeria revealed that hybrid renewable energy systems are more economical and have lower emissions compared to conventional diesel-based systems. Additionally, Aquila et al. in [32] highlighted the importance of the stochastic CVaR-LCOE approach in analyzing financial risks in renewable energy investments. While deterministic approaches are still predominantly used in hybrid system analyses, stochastic approaches, which better account for uncertainty and risk, have not been widely explored, leaving a gap in comprehensive risk understanding.

Table below are 19 research related to hybrid power plants that show different approaches to techno-economic analysis and how they put risks analysis in study:

Table 4 Research of Hybrid Systems

No	Research	Risk Analysis	Hybrid Type	Tech-Eco Approach	
				Det	Stc
1	Baseer et. al. in [37]	Identified 3 risk factors: fuel price fluctuations, changes in government regulations, and technical uncertainties.	PV, WT, Batt, DG	✓	✗
2	Yong et al. in [50]	Discusses the risk of capacity shortages in the system. It highlights that the hybrid system faces a 6% annual capacity shortage, but acceptable range.	PV, BM, DG	✓	✗
3	Babatunde et.al. in [39]	Considered the impact of annual real interest rate changes.	PV, WT, Batt, DG	✓	✗
4	Nyeche & Diemuodeke in [41]	None.	PV, WT, PHES	✗	✓
5	Jahangir et.al. in [51]	The assessed risk relates to the variability of renewable energy sources and economic uncertainty.	PV, WT, Batt, DG	✓	✗
6	Neves et.al. in [52]	Risks include difficulties in securing funding, operational challenges in integrating renewable systems and the uncertainty surrounding long-term investment.	PV, WT, BG	✓	✗
7	Rinaldi et.al. in [40]	Considered the variability of renewable energy sources and economic uncertainty in system performance.	PV, WT, DG	✓	✗

No	Research	Risk Analysis	Hybrid Type	Tech-Eco Approach	
				Det	Stc
8	Thirunavukkasrasu & Sawle in [43]	Risk analysis related to renewable energy variability, system reliability, and cost uncertainty.	PV, WT, Batt, DG	✓	✗
9	Vendoti et. al. in [45]	Evaluated risks related to the variability of renewable energy sources, technology costs, and load estimation.	PV, WT, Batt, FC, BG, BM	✓	✗
10	Jaganath et. al. in [53]	The key risks: intermittent of sources, power fluctuations during peak load, and maintain consistent performance.	PV, WT, CHP, Batt	✓	✗
11	Kumar & Channi in [44]	The risks were analyzed through system sensitivity to discount rate and inflation levels.	PV, BM	✓	✗
12	Thirunavukkasrasu & Sawle in [38]	Variability of renewable energy sources and the reliability of system configurations under various conditions.	PV/BM/Hydro/Batt	✓	✗
13	Al Shetwi et. al. in [54]	Operational challenges associated configurations considering their intermittency and variability.	PV, WT, Batt	✓	✗
14	Arif et al. (2023) Arif et. al. in [46]	None.	PV, Batt	✓	✗
15	Aykut et. al. in [47]	The assessed risks include solar radiation variability and biomass availability.	BM, DG	✓	✗
16	Icaza & Borde-Diez in [48]	Identified financial risks associated with initial investment and operational costs.	PV, WT, Batt, HKT	✓	✗
17	Odetoye et. al. [49]	None.	PV, WT, Batt, CSP, Small hydro, DG	✓	✗
18	Kariuki et. al. in [55]	Key risks are energy variability, high costs, design complexity, environmental impacts, and limited practical validation.	Geothermal, PV	✓	✗

No	Research	Risk Analysis	Hybrid Type	Tech-Eco Approach	
				Det	Stc
19	Ngouleu et. al. in [56]	Risks in renewable energy variability, system reliability, and high investment costs.	PV, WT, DG, Batt, Thermal Energy Storage	✓	×

Note: Tech-eco: Technology-Economy; Det: Deterministic; Stc: Stochastic; PHES: Pump Hydro Energy Storage; BG: Biogas; FC: Fuel Cell; BM: Biomass; CHP: Combined Heat and Power Microturbine; HKT: Hydro Kinetic Turbine; PV: Photovoltaic; WT: Wind Turbine; Batt: Battery; DG: Diesel generator

5 Discussion

Hybrid power plants have made significant progress in contributing to the global energy transition. However, there remain critical research gaps, particularly in the evaluation of these systems which most studies rely on deterministic approaches. The method provides useful application, but fail to capture the uncertainties and variability inherent in renewable energy sources. This gap highlights the need for broader exploration of stochastic models that more comprehensive in understanding of the uncertainty.

Our review suggest that it is still insufficient attention to risk and uncertainty elements in investment valuation models. The current dominance of deterministic approaches, limits the ability to account for variability in real-world conditions. Therefore, stochastic approaches need to be further explored to provide a more accurate understanding of risks and uncertainties. Besides that, future research also shall discusses alternative energy sources and storage technologies. Incorporating these underutilized resources will enable the design of robust, regionally adaptable hybrid systems that enhance resilience and maximize the utilization of locally available resources. Such diversification is critical to meeting the complex demands of a decarbonized global energy landscape.

In addition to expanding technical capabilities, future studies should focus on the development of hybrid systems. These systems can replace polluting diesel generators, providing affordable, clean energy to remote communities while fostering economic growth. Furthermore, an interdisciplinary approach integrating policy and regulatory analysis is essential. Effective policies, streamlined regulations, and institutional support can incentivize investments and remove barriers to deployment, particularly in developing countries with limited infrastructure.

Finally, future research can focus on further developing and refining stochastic approaches to better address the uncertainties associated with hybrid renewable energy systems, even more approach that incorporated with the risks analysis. These models will not only enhance the accuracy of investment decisions but also help optimize system performance in real-world conditions. By integrating these advanced methods into energy planning, policymakers and investors can make more informed decisions that support the long-term viability and sustainability of the energy transition.

6 Conclusion

This research highlight the critical role of hybrid power plants in the global shift towards sustainable energy systems. Hybrid systems offer significant advantages in terms of energy reliability and emission reduction. However, the current literature still relies mostly on deterministic approaches to evaluate the techno-economic feasibility. While deterministic methods provide simplicity and ease of implementation, they are insufficient in capturing the inherent risks due to variability and uncertainty present in renewable energy sources, particularly under conditions of intermittency and fluctuating demand.

As renewable energy systems grow more complex, the need for more advanced analytical approaches becomes indispensable. Stochastic methods, which consider the probabilistic nature of both energy generation and consumption, offer a more comprehensive and accurate assessment of hybrid systems. By incorporating uncertainties into the valuation process, these methods can provide a range of possible outcomes rather than a single deterministic value, thus improving the reliability and robustness of project evaluations. This transition towards stochastic modeling is essential for capturing the true economic and operational dynamics of hybrid power plants.

Acknowledgement

The authors would like to thank Fakultas Teknologi Industri, Institut Teknologi Bandung for supporting this study.

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