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Techno-economic Analysis of a Solid Fuel Testing Facility for Thermal Power Plants in Peninsular Malaysia: A Monte Carlo Approach

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ABSTRACT

Coal-fired thermal power plants in Peninsular Malaysia are expected to remain operational for at least another 20 years, highlighting the need for clean coal technology adoption. The introduction of new coal types necessitates the verification of their technical viability prior to adoption into power plants, which is addressed by the proposed Solid Fuel Testing Facility (SFTF) system. Hence, this study developed a Monte Carlo-based model to examine the economic factors influencing the profitability of the SFTF system as a solid fuel pre-qualification assessment tool. Three critical factors have been identified as contributors to the SFTF system's economic viability uncertainty: the Test Number, Power Purchase Agreements (PPA) Reduction, and Test Cost. In terms of Net Present Value (NPV) valuation, the Test Number has the highest sensitivity. The projected increase in coal demand necessitating the inclusion of a broader spectrum of new coal variants in power plant operations. As a result, the possibility of an expanded Test Number for the SFTF system exists until the PPA's tenure expires. Therefore, the possibility of favourable NPV outcomes remains prominent throughout the term of the PPA. In contrast, the PPA Reduction has the lowest susceptibility to NPV sensitivity. This demonstrates the SFTF system's ability to navigate policy shifts related to PPA tenure reductions, albeit within a range of 3 to 4 years of reduction. It is suggested that a broader range of parameters be considered in order to gain a more holistic understanding of the economic viability of the proposed SFTF system.

1. Utilisation of Solid Fuels in Thermal Power Plants (Peninsular Malaysia): An Overview

Solid fuels, such as coal, play an important role as energy sources in many countries, most notably China and India, due to their abundant availability and low cost [1-2]. This is also true in Malaysia, where coal accounts for approximately 20% of total energy supply [1]. Malaysia's reliance on this fuel has grown significantly over the last few decades, with its contribution to the energy mix quadrupling between 1996 and 2016 [1]. The rising demand for affordable electricity, a driving force behind Malaysia's power generation expansion [1], has resulted in a heavy reliance on thermal power plants, which account for a significant portion of the energy matrix [1].

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Malaysia, a developing country in Southeast Asia, is geographically located around the South China Sea, encompassing regions of the Malay Peninsula and the island of Borneo [1]. The country is made up of 13 states, 11 of which are in Peninsular Malaysia, as well as Sabah and Sarawak on Borneo, which are known as East Malaysia [1]. Peninsular Malaysia borders Thailand on the land and Singapore, Vietnam, and Indonesia on the sea. East Malaysia on Borneo has land borders with Brunei and Indonesia, as well as maritime borders with the Philippines and Vietnam. Peninsular Malaysia has benefited primarily from electrification improvements as it has been the focal point of the country's notable economic progress, with a plethora of thermal power plants facilitating its socioeconomic endeavours.

As of August 2023, the Peninsular Malaysian power sector had a total of 12.2 GW of power generated by coal-fired thermal power plants, all of which were linked to Power Purchase Agreements (PPAs). These PPAs ensure that generation capacity is available to meet electricity demand [3]. Table 1 provides an overview of the aforementioned power plants (GF is an abbreviation for Generating Facilities).

Table 1
Coal-fired thermal power plants in Peninsular Malaysia [4-15]

Thermal power plant	Technology	Total MW	Commissioning year	PPA tenure end year
Kapar Energy Ventures (KEV) - GF2, GF3	Sub-critical	1600	1989	2029
Janamanjung - GF1	Sub-critical	2100	2003	2030
Tanjung Bin	Sub-critical	2100	2006	2031
Jimah Energy Ventures (JEV)	Sub-critical	1400	2009	2034
Janamanjung M4 - GF2	Ultra-super critical	1000	2015	2040
Tanjung Bin Energy	Ultra-super critical	1000	2016	2041
Janamanjung M5 - GF3	Ultra-super critical	1000	2017	2042
Jimah East Power (JEP)	Ultra-super critical	2000	2019	2044

The JEP power plant, commissioned in 2019, will be the last coal-fired power plants by Tenaga Nasional Berhad (TNB), Malaysia's utility giant [16-17]. According to the TNB Sustainability Pathway 2050, they have stated that they have no plans to build such power plants in the future in order to focus on greener energy sources [16-17]. The PPA tenure end year for the JEP power plant, as shown in Table 1, is 2044, which is another 20 years (as of 2023). Therefore, in the future of sustainability, coal-fired thermal power plants in Peninsular Malaysia will have at least 20 years of operation left, demonstrating the need for clean coal technology to be implemented.

2. Pre-qualification of Solid Fuels for Thermal Power Plants in Peninsular Malaysia

Solid fuel is a heterogeneous substance that varies in rank, maceral content, and related impurities [18]. The combustion of solid fuels, such as coal, will cause significant ash-related issues such as erosion, corrosion, slagging, and fouling, which will eventually lead to a loss in the efficiency of the coal-fired utility boiler, potentially resulting in an unplanned shutdown [19]. Despite changes in coal-fired boiler design to increase boiler capacity and the use of routine soot blowing systems to mitigate the effects of slagging and fouling, unforeseen issues still occur at various locations where the cleaning system is inaccessible or the bonding between the deposits and the walls is too strong for the cleaning system to be effective [19]. In addition, ash deposition complicates combustion tuning processes in coal-fired power plants [19].

Furthermore, stricter environmental regulations and a decreasing supply of high-quality solid fuels will jeopardise the operating assets of thermal power plants. To improve fuel flexibility and reduce emissions, a variety of combustion solutions have been proposed or implemented in coal-fired thermal power plants. The two most common combustion solutions are solid fuel blending and, more recently, co-firing with green fuels (hydrogen, ammonia, biomass) [20-21].

Nonetheless, there are numerous unknowns about the fundamentals of suggested combustion solutions due to confidentiality and adaptability to local designs and operation characteristics. In order to assess guarantees and contractual responsibilities, it will also be necessary to develop agreed-upon measurement parameters. As a result, before implementing any of these combustion solutions in any thermal power plant, the risks to the utility boiler and its associated downstream systems must be assessed.

Furthermore, the power utility will receive several new coal brands each year to be burned in Peninsular Malaysia's thermal power plants. Because of the numerous coal mines as its sources and the complex coal supply chain globally, it is extremely difficult to obtain the desired coal brand. To ensure a profitable and sustainable coal power generation business, the technical and financial risks of these new coal brands will also need to be proven and qualified prior to adoption in actual coal-fired thermal power plants.

The well-tailored Solid Fuel Testing Facility (SFTF) system is one of the best strategies for determining the performance of various solid fuel types such as sub-bituminous coal, bituminous coal, and biomass-coal blends prior to adoption in actual coal-fired thermal power plants in Peninsular Malaysia. The SFTF system will be the primary pre-qualification tool for assessing solid fuels prior to their use in power generation. TNB Research and TNB Fuel, both renowned Malaysian entities specialising in fuel and combustion domains, have consistently delivered assessments for the pre-qualification of solid fuels through meticulous analytical fuel testing. The proposed SFTF system was created with the goal of improving the pre-qualification process for a wide range of solid fuels intended for adoption in thermal power plants.

3. Importance of Techno-economic Analysis for the Proposed SFTF

While the SFTF system is critical in evaluating solid fuels prior to their adoption, there are several factors that could negate the proposed SFTF system's benefits. The potential reduction in annual testing of new solid fuels, which is influenced by economic and geographical factors, is one such factor. For example, due to domestic energy priorities, Indonesia has banned coal exports in 2022 [22]. This ban, which is significant given Indonesia's status as a major coal supplier, has had far-reaching consequences across the coal supply chain. Traditional trade routes have been disrupted, prices have risen, and demand is expected to rise in the near future. Furthermore, in 2022, a series of international incidents profoundly reshaped the coal commerce landscape, affecting pricing dynamics as well as supply and demand patterns [2, 22].

The following factor to consider is Malaysia's renewable energy policies and movements. Leading energy companies in the country, such as TNB and PETRONAS, play an important role in driving the energy transition. Both companies are committed to achieving a net-zero carbon target by 2050 [16, 23]. Numerous reports have emerged as of August 2023 regarding the potential reduction of PPA tenure for existing coal-fired power plants [6]. This initiative aims to accelerate the achievement of the 2050 sustainability targets. However, the potential reduction in PPA tenure for these plants raises the risk of rendering the SFTF system uncompetitive in terms of cost, jeopardising its payback period. This risk is especially significant given the system's heavy reliance on solid fuel testing, specifically coal.

As a result, conducting a techno-economic analysis (TEA) for the proposed SFTF becomes critical in order to assess its economic viability. The Monte Carlo method is an effective method for carrying out the TEA, providing a relatively simple and well-established approach for incorporating uncertainty and risk into quantitative models. Numerous calculations are performed in a Monte Carlo model, with each calculation randomly selecting input parameters from predefined distributions for individual estimations [24]. This methodology, however, has limitations, most notably the sensitivity of output distribution tails to input distributions. Extensive calculation trials are sometimes required to achieve convergence [24].

Over the years, the Monte Carlo method has been widely used in the fields of TEA. Dufo-López *et al.* [24], for example, used Monte Carlo simulation to optimise energy supply for off-grid healthcare facilities that used PV-diesel-battery systems. Their method included probabilistic optimisation via Monte Carlo simulation, which took into account uncertainties in renewable sources and load profiles. This enabled stochastic optimisation of complex hybrid systems with high modelling accuracy.

Benalcazar *et al.* [25] created a Monte Carlo-based model to investigate the complex economic and technical variables that could affect the effectiveness of Poland's green hydrogen strategy. This research also looks at the economics of renewable hydrogen at different stages of technological advancement and market adoption. The study's findings successfully predicted the geographic areas where the implementation of large-scale hydrogen production facilities would yield the best cost-effectiveness.

Rezvani *et al.* [24] used Monte Carlo analysis to conduct a comprehensive techno-economic and reliability assessment of solar water heaters in Australia. Their research concluded that solar water heaters have significantly better long-term economic feasibility than conventional systems, particularly under moderate auxiliary energy consumption scenarios.

Heck *et al.* [24] went beyond conventional point values in their Monte Carlo analysis of the probability distributions of Levelized Cost of Electricity (LCOE) for major generation technologies such as PV and solar thermal. Their findings highlighted that, while the Monte Carlo approach increases complexity slightly more than point value analyses, it provides more realistic insights into risk and uncertainty. As a result, it allows for more insightful assessments of potential investments in electricity generation.

Meschede *et al.* [24] used Monte Carlo methods to assess the probabilistic impact of distributed factors on renewable energy supply, specifically photovoltaics, for hotel applications. Their investigation revealed that both weather fluctuations and economic parameters have a comparable impact on results. Monte Carlo techniques aided in the refinement of annuity means and the effective evaluation of risks associated with variable weather and occupancy rates.

Therefore, a Monte Carlo-based model is introduced and developed in this study to delve into the intricate economic variables that may influence the efficacy of the proposed SFTF system. This analysis focuses on the probability of achieving a positive Net Present Value (NPV) profit across a variety of scenarios. The NPV is a financial metric that attempts to capture the total value of an investment potential. The fundamental concept underlying NPV entails forecasting all future cash inflows and outflows associated with an investment, discounting these projected future cash flows back to the present time, and finally aggregating them [26].

4. Methodology

This section describes the specially designed methodology for examining the economic risks associated with the proposed SFTF system. Unlike the majority of studies, which rely on simplistic sensitivity analyses (using deterministic methods with point or expected values) to assess the economic feasibility of planned or ongoing systems, this study takes a probabilistic approach to assess the impact of economic uncertainties on the adoption of the SFTF system for Peninsular Malaysia's thermal power plants. The techno-economic model proposed in this study incorporates the Monte Carlo methodology to evaluate the uncertainty caused by various inputs, determining the probability of achieving a positive NPV profit throughout the operation of the SFTF system. Figure 1 depicts a schematic representation of the approach developed in this study.

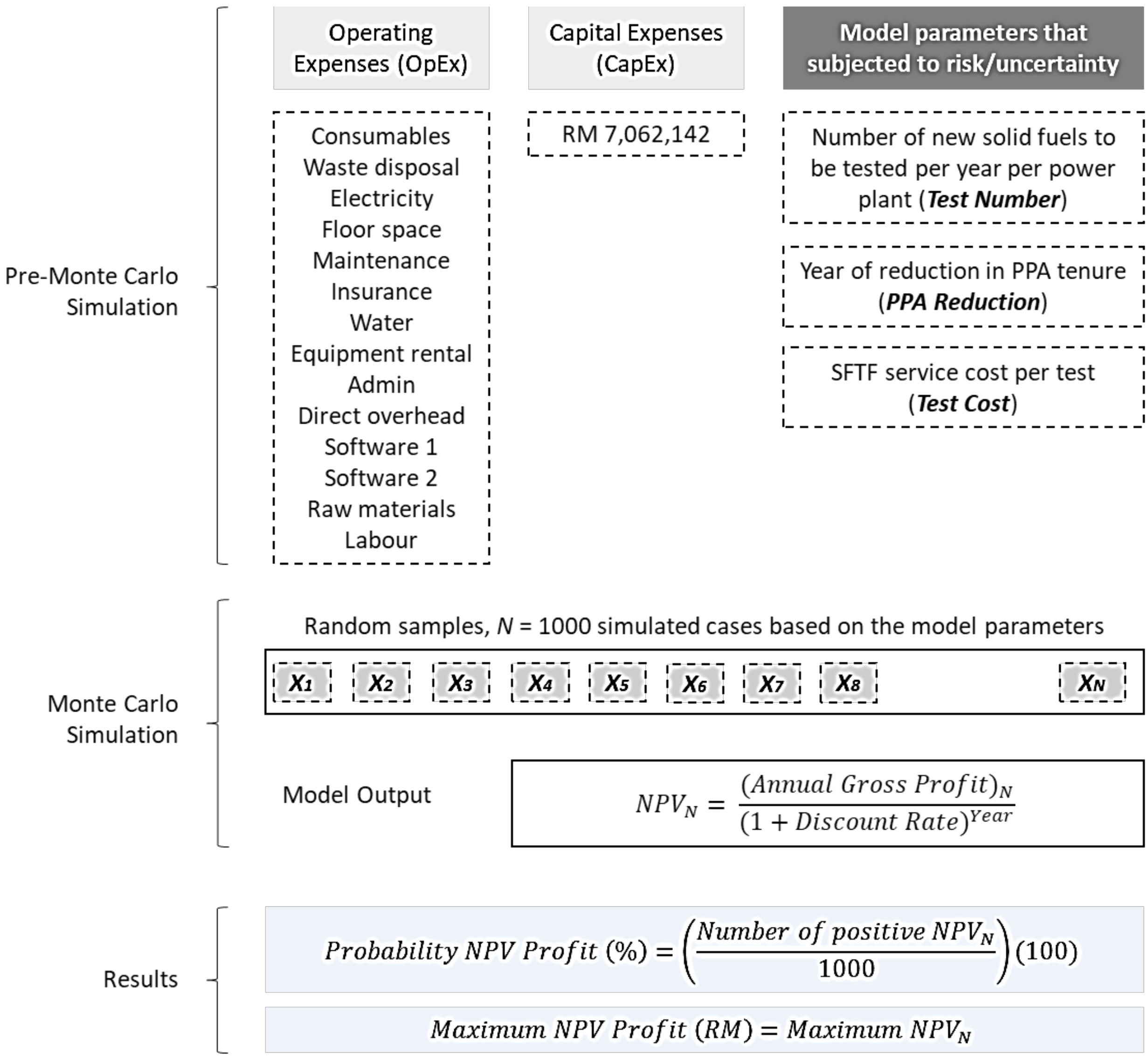

Fig. 1. Overview of the Monte Carlo approach applied in the current study

Monte Carlo simulation is a computer-based technique for estimating the expected value of an output function or deterministic model by using a set of inputs drawn at random from probability distributions [25]. Furthermore, this methodological approach is frequently used to examine hypothetical scenarios and perform what-if analyses in systems or processes where experimental testing is prohibitively expensive or impossible [25]. The Monte Carlo model in this study was created using the Microsoft Excel platform.

The incurred CapEx for establishing the SFTF system, as well as the OpEx associated with its operation, are depicted in Figure 1. A sensitivity analysis was performed using the Monte Carlo method to assess the impact of uncertainty parameters on the likelihood of achieving a positive NPV profit. Figure 1 depicts the anticipated factors contributing to the SFTF system's economic viability uncertainty, which include the Test Number, PPA Reduction, and Test Cost. This sensitivity analysis was carried out methodically by changing the values of individual parameters within the predefined ranges used to define the probability distributions (detailed in Table 2). Table 3 contains details on OpEx. The term "internal references" in Table 3 refers to confidential sources within the organisation in charge of building the SFTF system. As a result, these references cannot be disclosed in the context of the current study.

Table 2
Scenarios for the Monte Carlo assessment

Scenario	Test Number	PPA Reduction	Test Cost (RM)	Remarks
A	0 to 1	0 to 1	80,000 to 220,000	PPA reduction from 0 to 1 year is ideal. Even with the move to sustainability, reducing the PPA will hurt the power plant's ability to recover capital costs and earn a return on equity [27].
B	1 to 2	0 to 1	80,000 to 220,000	
C	2 to 3	0 to 1	80,000 to 220,000	
D	3 to 4	0 to 1	80,000 to 220,000	
E	1 to 2	0 to 1	80,000 to 220,000	According to historical pre-qualification evaluations conducted by TNB Research and TNB Fuel, 1 to 2 solid fuels were tested annually on average.
F	1 to 2	1 to 2	80,000 to 220,000	
G	1 to 2	2 to 3	80,000 to 220,000	
H	1 to 2	3 to 4	80,000 to 220,000	
I	1 to 2	0 to 1	80,000 to 120,000	The Test Cost varies in price depending on the work packages/deliverables requested by clients.
J	1 to 2	0 to 1	120,000 to 160,000	
K	1 to 2	0 to 1	160,000 to 200,000	
L	1 to 2	0 to 1	200,000 to 220,000	

Table 3
OpEx details

Operating Parameters	Unit Cost	Unit	References/Remarks
Consumables	400.00	RM/test	Personal protective equipment (internal references)
Waste disposal	62.50	RM/test	Internal references
Electricity	0.52	RM/kWh	[28]
Floor space	789.00	RM/year	Quit rent and rental (internal references)
Maintenance	20,000.00	RM/year	Internal references
Insurance	3,180.00	RM/year	Internal references
Water	0.08	RM/hour	[29]
Equipment rental	750.00	RM/hour	Internal references
Admin	15.00	RM/hour	Internal references
Direct overhead	292.50	RM/hour	Internal references
Software 1	72,000.00	RM/year	Internal references
Software 2	60,000.00	RM/year	Internal references
Raw material – fuels	0.07	RM/kg	Coal and Liquefied Petroleum Gas (LPG) [30]
Labour	20,163.00	RM/month	Internal references

The current TEA is based on several assumptions. To begin, the operational duration of the SFTF for each test has been estimated at 8 hours. Second, it is assumed in the TEA that all thermal power plants listed in Table 1 actively participate in providing solid fuel samples for testing within the SFTF system over the course of their PPA tenures. Furthermore, the OpEx details presented in Table 3 remain consistent throughout the designated years. Next, the TEA considers coal to be the sole solid fuel subject to testing, with LPG, as shown in Table 3, serving as a supplementary fuel solely for the SFTF system's startup procedure. The number of years employed in the TEA is based on the PPA tenure, with PPA tenure reduced in some cases. Finally, the discount and tax rates considered in this TEA are 10% and 21%, respectively.

5. Results and Discussion

5.1 NPV Distribution

This section summarises the findings and discusses the SFTF system's potential economic viability. To begin, Figure 2 depicts the predicted NPV results across various scenarios.

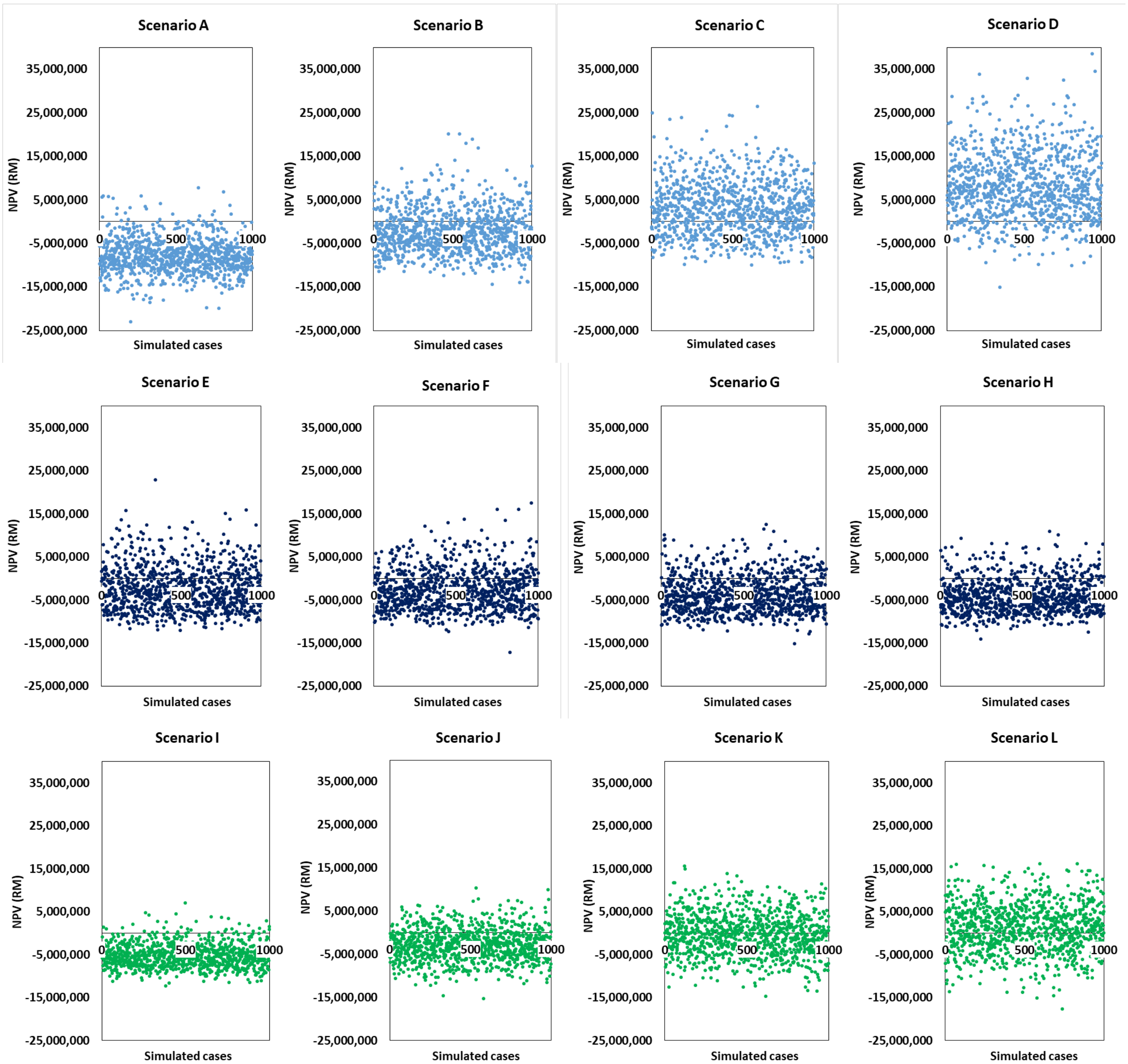

Fig. 2. Predicted NPV profit per simulated cases for all scenarios

The range from Scenario A to Scenario D, as shown in Figure 2, investigates the impact of Test Number on NPV following the expiration of the PPA term. The observed NPV distribution varies significantly as the Test Number range expands. When the Test Number falls between 0 and 1 annually per power plant, the majority of the NPV distribution falls below zero, indicating significant losses. However, as the Test Number range is expanded, as shown in Scenarios B to D, the NPV distribution begins to ascend. Notably, Scenario D depicts a broad NPV distribution above zero, indicating a favourable outcome in terms of NPV. Scenarios A through D represent the most realistic scenarios in terms of PPA Reduction because they were set between 0 and 1, which is an ideal PPA reduction year for power plants to recover capital costs and earn a return on equity [27].

Scenario E to Scenario H represent the impact of PPA Reduction variation towards the NPV. As compared to Scenario A to Scenario E, the NPV distribution is less widespread. Scenario H, which presents the highest PPA Reduction, shows the majority of the NPV falls below zero. The higher the PPA Reduction, the lower the duration of the SFTF to be operational due to a lesser amount of SFTF Test. Scenarios E to H represent the most realistic scenarios in terms of Test Number, as they were established between 1 and 2. This range corresponds to previous pre-qualification assessments conducted by TNB Research and TNB Fuel, which indicate an average annual testing of 1 to 2 solid fuels.

Scenarios A through H stand out as the most realistic scenarios in this analysis because they effectively account for the variability of the Test Cost. The lower and upper limits of the Test Cost range were set at RM 80,000 and RM 220,000, respectively. The SFTF system's distinct work packages are responsible for the Test Cost's fluctuations. Coal-fired thermal power plants face a variety of operational challenges, the most serious of which are boiler tube failures (BTF) [31]. These problems can be attributed to three major operational factors: operation and maintenance (O&M), boiler design, and coal quality [32-33]. Among these factors, coal quality stands out as a particularly significant contributor to BTF issues. To understand the "boiler appetite" and cater to a diverse set of needs, extensive solid fuel testing is required. Different boilers exhibit distinct problems that necessitate specific solid fuel tests to identify the problem. As a result, the SFTF system includes a wide range of tests capable of determining intricate fuel quality details. This complex testing spectrum underpins the variations in Test Cost.

Taking this into account, the impact of Test Cost was investigated further within Scenarios I through L, which encompassed the various work packages provided by the SFTF system. As expected, the Test Cost ranging from RM 200,000 to RM 220,000 primarily yields NPV values greater than zero.

5.2 Probability NPV Profit and Sensitivity Analyses

Figure 3 depicts the probabilities of achieving a positive Net Present Value (NPV) across all scenarios. Notably, Scenario D has the highest probability of achieving a positive NPV, at 86%. In Scenario D, the Test Number ranges from 3 to 4 per power plant per year. Scenario A makes an intriguing observation: it has the lowest probability of achieving positive NPV of all scenarios, at only 3%. Scenario A maintains the lowest Test Number, which ranges from 0 to 1. Surprisingly, the difference in NPV Profit Probability between Scenarios A and D exceeds that of all other scenario ranges (E to F and I to L) by an astounding 83%. This demonstrates the Test Number parameter's unrivalled sensitivity to NPV valuation.

As a result, the Test Number is crucial in ensuring the economic feasibility of the SFTF system. The Test Number has a direct correlation with the coal demand from Peninsular Malaysia's power sector. As coal demand grows, so does the influx of coal, necessitating the incorporation of a broader range of new coal brands into power plant operations. According to the International Energy Agency (IEA), Malaysian coal demand is expected to remain stable in 2022 at around 33 million tonnes. However, it is expected to rise to around 35 million tonnes by 2025 [2]. This expansion is primarily due to rising electricity consumption and increased load factors [2]. As a result, the possibility of an increased Test Number for the SFTF system exists until the end of the PPA tenure.

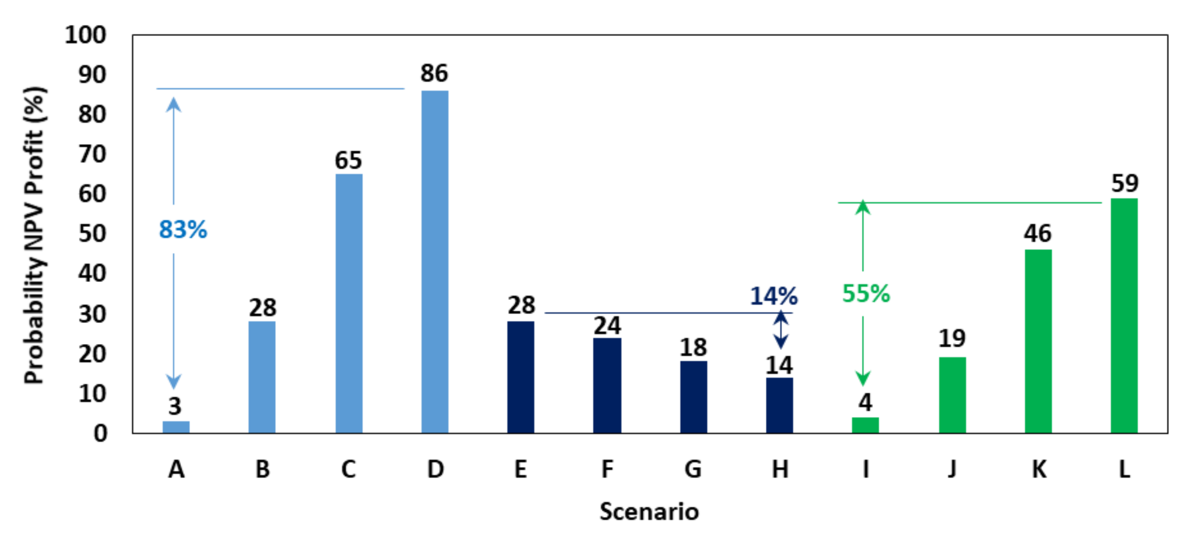

Fig. 3. Probability of positive NPV profit for all scenarios

Scenarios E through H, which depict variations in PPA Reduction, are the least susceptible to NPV sensitivity when compared to other scenario ranges. The difference in NPV Profit Probability between Scenarios E and H is only 14%. Notably, Scenario E has the highest NPV, reaching 28%, corresponding to the lowest PPA Reduction range (0 to 1). This finding indicates that the PPA Reduction has the lowest inherent risk in relation to NPV, among all parameters under consideration. This result has promising implications for major utility players such as TNB, especially when considering the reduction of PPA tenure. The proposed SFTF system has a minimal economic impact on the proposed PPA tenure reduction. This suggests that the SFTF system can withstand policy changes related to PPA tenure reduction, albeit within a range of 3 to 4 years of reduction.

Nonetheless, the maximum Probability NPV Profit within Scenarios E to H is 28%, which is significantly lower when compared to Scenario A's figure of 86%. This disparity arises from the use of a lower Test Number in Scenarios E to H, which corresponds to historical pre-qualification evaluations conducted by TNB Research and TNB Fuel. These assessments revealed an average annual testing of 1 to 2 solid fuels.

Scenarios I through L, which cover the entire range of Test Cost variations, have a higher NPV sensitivity than Scenarios E through H. However, when compared to Scenarios A through D, this sensitivity is noticeably lower. The difference in NPV Profit Probability between Scenarios I and L is 55%, with Scenario L having the highest NPV within this range, approaching 59%. Scenario L, in particular, corresponds to the upper band of the Test Cost, which ranges from RM 200,000 to RM 220,000.

6. Conclusions

The study developed a Monte Carlo-based model to investigate the intricate economic factors that influence the profit of the proposed SFTF system as a pre-qualification assessment tool for solid fuels intended for adoption into the Peninsular Malaysian power sector. The main goal of this analysis is to determine the likelihood of achieving a positive NPV profit under various scenarios. Within this context, three key factors have been identified as contributing to the SFTF system's economic viability uncertainty: the Test Number, PPA Reduction, and Test Cost.

When compared to the other parameters under consideration, the Test Number has the highest sensitivity in terms of NPV valuation. Given its direct relationship to coal demand in Peninsular

Malaysia's power sector, the anticipated increase in coal demand necessitates the incorporation of a broader range of new coal brands into power plant operations. As a result, the possibility of an expanded Test Number for the SFTF system exists until the end of the PPA tenure. Hence, the potential for a favourable NPV remains high throughout the PPA's term.

When compared to the other parameters under consideration, the PPA Reduction exhibits the least susceptibility to NPV sensitivity. This result has positive implications for major utility players like TNB, particularly when considering PPA tenure reduction. This suggests that the SFTF system can effectively navigate policy shifts related to PPA tenure reduction, albeit within a range of 3 to 4 years of reduction. It is suggested that a broader range of parameters be considered in order to gain a more comprehensive understanding of the economic viability of the proposed SFTF system.

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