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Research Article

Hybrid renewable energy system design for a green port using HOMER Pro: A techno-economic assessment

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Abstract. Maritime plays an important role in the national economy since a large number of goods in the world are transported by sea, although maritime transport is found to generate the largest greenhouse gas emission among transportation means. For maritime activities, the port is considered the key chain in logistics, thus, the transformation of ports into sustainable energy centres has emerged as a major need in the worldwide initiative to decarbonize marine activities. This research provides a comprehensive techno-economic evaluation of a Hybrid Renewable Energy System (HRES) for Thi Nai Port, Vietnam, utilizing HOMER Pro software. The suggested system seeks to eradicate dependence on fossil fuels by including solar photovoltaics, wind turbines, a biogas generator, and sophisticated battery storage, therefore providing operational robustness. Simulation outcomes demonstrate that an ideal configuration, consisting of a 6,175-kW photovoltaic array, a 500-kW biogas generator, and a 2,357-kW converter, results in a net present cost of 44.6 million USD and a levelized cost of energy of 0.394 USD/kWh. Renewable sources constitute 100% of the installed and operational capacity, with yearly carbon dioxide emissions diminished to a modest 1,286 kg. The research verifies that hybrid renewable solutions may provide competitive economic returns, with a payback period of eight to ten years, while delivering substantial environmental advantages. The study portrays Thi Nai Port as a scalable paradigm for green port transformation, offering a repeatable framework for other mid-sized ports in Southeast Asia pursuing sustainable energy solutions.

Keywords: Green Port; Sustainability; Homer Pro; Techno-economic assessment; Renewable energy; Optimization

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1. Introduction

Climate change and energy depletion represent an urgent global challenge, necessitating a broad-scale transition towards sustainable and renewable energy systems (Swardika *et al.* 2020; Hoang *et al.* 2021). The Paris Agreement exemplifies the unified resolve of nations to curb greenhouse gas emissions and stabilize the average global temperature rise, striving to maintain it significantly under 2°C, with an aspirational target of limiting it to 1.5 °C above pre-industrial benchmarks (UNITED NATIONS 2019; Jacoby 2025). Achieving this objective requires extensive efforts in carbon mitigation, particularly in emissions-intensive sectors like steel, cement, petroleum refining, and chemical production (Moumin *et al.* 2020; Yong and Chun 2023; Kaci *et al.* 2023). These industries depend heavily on fossil energy sources such as coal, crude oil, and natural gas, which are predominantly used in power generation, manufacturing operations, and refining activities, thereby contributing markedly to global carbon emissions. The International Energy Agency (IEA) reported that in 2022 alone, combustion and industrial operations were responsible for approximately 36.8 Gt of CO_2 emissions. Among these, the iron and steel industry accounts for about 2.6 Gt CO_2 annually, constituting nearly 7% of the global carbon output (International Energy Agency 2022). According to the IEA's decarbonization strategy for this sector, coal currently supplies roughly 75% of its energy requirements, underscoring the industry's dependence on carbon-intensive fuels and its status as the largest energy consumer in the manufacturing domain (International Energy Agency 2021).

Shipping generally exhibits relatively lower greenhouse gas (GHG) emissions per ton of freight compared to other transport modes, but it remains a prominent contributor to global emissions (Aminzadegan *et al.* 2022; Hoang *et al.* 2023). In 2023 alone, maritime operations were responsible for approximately 3% of total worldwide CO_2 emissions, thus, projections suggest a substantial rise in emissions without decisive mitigation strategies (Pham *et al.* 2023; Ha *et al.* 2023; Vu *et al.* 2024). The International Maritime Organization (IMO) anticipates that, in the absence of additional control measures, carbon emissions from shipping could grow by 0% to 50% by 2050 relative to 2018 levels, possibly reaching 90% to 130% of the emissions reported in 2008 (IMO 2021; Nguyen *et al.* 2025b). The accelerating increase in GHG emissions is intensifying the global threat of

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climate instability, thereby compelling the maritime sector to reevaluate its environmental responsibilities. As a cornerstone of international commerce, maritime transport facilitates the movement of over 80% of global goods through an extensive network of ships and port infrastructure (UNCTAD 2023).

The transition toward sustainable energy systems is becoming increasingly critical in the global maritime industry, including shipping, port and logistics, and shipbuilding activities (Hoang *et al.* 2022; Vakili *et al.* 2022; Le *et al.* 2023). Ports are being advised to follow sustainable energy policies as environmental damage, climate change, and energy insecurity take the front stage in worldwide policy debates (Garg *et al.* 2023; Zhang *et al.* 2024). Port operations and logistics historically have mostly depended on fossil fuels, especially diesel fuel, which greatly increases environmental pollution and GHG emissions (M. D. Nguyen *et al.*, 2023; V. N. Nguyen *et al.*, 2023; Sathish *et al.*, 2023). Along with raising running expenses, these conventional energy sources endanger the health and ecology of the nearby coastal towns (Sharif *et al.* 2023; Nguyen *et al.* 2023a). For countries all around, including Vietnam, the drive for decarbonization and renewable energy integration has therefore become a strategic need (Le *et al.* 2014)(Nguyen *et al.* 2025). Vietnam is a fast-growing nation with a 3,000-kilometer coast. The geographic advantage of the nation has helped it to become a major actor in regional marine trade and logistics. But this growth has also resulted in higher energy demand, especially in port operations, where round-the-clock functioning depends on constant electrical use. Though they are vital for domestic logistics, fisheries, and regional trade, small and medium-scale ports sometimes get less attention and funding among the several types of ports running in the nation (Roh *et al.* 2016; Kuo *et al.* 2020). Thi Nai Port is one such small port in Quy Nhon City in Binh Dinh Province. Though little in scale, Thi Nai Port is essential for the local economy as it facilitates the transportation of industrial items, seafood, and agricultural products throughout the area. The port is projected to consume a huge amount of electric power for container handling equipment, refrigerated storage, high towers, and area lighting. Also, the administrative buildings, security and surveillance systems, fuelling stations, and seasonal HVAC needs are among the several operational components where this energy is utilized throughout. Among them, container cranes and high mast lights are among the biggest energy users; each makes around 12 % of the whole demand. Especially active during the hot dry months from April to August, HVAC systems can greatly add to the energy consumption. The port's energy requirement is not steady all year round. Consumption varies seasonally; heavier port traffic and more cooling loads cause the summer months to peak. Seasonal unpredictability calls for a flexible and strong energy system able to manage changing demands while preserving the economy of cost.

The geography and climate of Vietnam make it rather fit for the growth of renewable energy sources. Quy Nhon averages 4.8 to 5.2 kWh per square meter per day from strong sun exposure. This degree of solar resource is adequate to build a sizable solar photovoltaic array capable of meeting the daytime energy needs of the port in great part. The coastal site also gains from strong and constant wind patterns, particularly during the northeast monsoon season, when wind speeds can approach 5.5 m/s. This makes it possible to augment solar energy generation with small to medium-scale wind turbines. Especially for nighttime energy use and as a backup power supply, including biogas in the port's energy system, offers further benefits (MOIT and DEA 2017; Do *et al.* 2021). From food markets to agriculture to seafood processing, Binh Dinh's environment generates significant organic waste. Anaerobic digestion allows one to transform this biomass into sustainable biomethane (Hoang *et al.*, 2022). By processing trash like food scraps, waste tea leaves, and chicken manure, a specialized biogas plant next to the port may generate a local supply of ongoing energy. This helps local environmental management and trash reduction as well (Silva *et al.* 2016; Nguyen Thuy Lan *et al.* 2023). The transition toward low-carbon maritime operations has become a global imperative, especially as ports evolve into critical nodes within sustainable logistics networks. Ports not only support economic development but also serve as major energy users with large environmental impacts. In this regard, the conversion of traditional ports into centers of green energy is not only relevant but also required. The present work investigates the techno-economic feasibility of a hybrid renewable energy system (HRES) specifically designed for Thi Nai Port in Vietnam, a mid-sized facility confronting issues typical of many regional ports: reliance on fossil-based grid electricity, high operational costs, and vulnerability to power disruptions. Though it has great potential, Thi Nai Port has not yet made notable progress in including renewable energy in its operational ecology.

The novelty of this research lies in its integrative approach to optimizing a multi-source hybrid energy system (HRES) that leverages the port's local solar irradiance, wind resources, and biomass potential. Unlike studies concentrated on single renewable sources or generic modeling, this work models a highly specific and replicable HRES architecture for port environments in Southeast Asia, combining solar photovoltaic (PV) panels, wind turbines, a methane-fueled biogas generator, and advanced battery storage. Using HOMER Pro, a widely known instrument for HRES analysis, the aim is to build and simulate an ideal renewable-based system, thereby enabling a real-world transformation route for Thi Nai Port into a model green port. Thi Nai is an important port handling a significant volume of bulk cargo in Central Vietnam. With break bulk ports, energy efficiency management is more complex due to the specific nature of this type of transportation. According to Dinh (Dinh *et al.*, 2025), when compared to the container and dry bulk shipping industries, the transshipment of general cargo typically occurs at a slower pace with more unpredictable loads, requiring careful adherence to safety precautions. This adds to the challenges of optimizing energy efficiency and reducing emissions. Dinh and colleagues' research applied the Analytic Network Process (ANP) model to analyze key factors affecting break bulk port efficiency, emphasizing the importance of port infrastructure, labor proficiency, and technological integration in maintaining operational effectiveness. These findings provide valuable reference points when considering sustainable energy solutions for Vietnamese ports. This study employs comprehensive simulations of multiple system configurations to evaluate technical performance and economic feasibility under realistic operational conditions. HOMER Pro modeling takes into account things like capital investment, running and maintenance expenses, fuel pricing, equipment lifetime, and emissions. Important performance measures include net present cost (NPC), levelized cost of energy (LCOE), proportion of renewable energy, and decrease in carbon emissions. Beyond environmental benefits, the system offers substantial economic resilience by reducing fuel expenditures and exposure to fluctuating electricity tariffs (Giao *et al.* 2024; Nguyen *et al.* 2025a). Moreover, the incorporation of distributed renewables improves energy security by reducing reliance on outside supply sources and strengthening operations against grid outages, an increasingly vital element in guaranteeing port dependability (Khalil *et al.* 2021; Rahmat *et al.* 2022). The study positions Thi Nai Port as a scalable pilot for sustainable port electrification. Its location, energy load profile, and accessible

Fig. 1 Geographical location of Thi Nai port

renewable resources make it a perfect choice for modeling green port transition plans suitable for ports throughout Vietnam and Southeast Asia. The outcomes underline the feasibility of tailored hybrid energy planning at small- to medium-sized ports, where technical and economic limitations sometimes prevent the acceptance of clean energy (Huong *et al.* 2021; Nguyen *et al.* 2022). This study contributes to the evolving body of research on sustainable maritime infrastructure by providing a robust, scenario-based analysis that bridges environmental stewardship with economic pragmatism. Ports like Thi Nai may not only decarbonize their operations but also improve operational efficiency and long-term cost-effectiveness by including renewable energy sources in port infrastructure. Policymakers, port authorities, and energy planners can use the suggested hybrid system as a strategic framework, either adopted or adapted, to propel the following generation of green ports in the area.

2. Methods

2.1 Location of port and traffic

Thi Nai Port is located in Hai Cang Ward at the eastern edge of Quy Nhon City in Binh Dinh Province, along Vietnam's south-central coastline. The location is depicted in Figure 1. Its

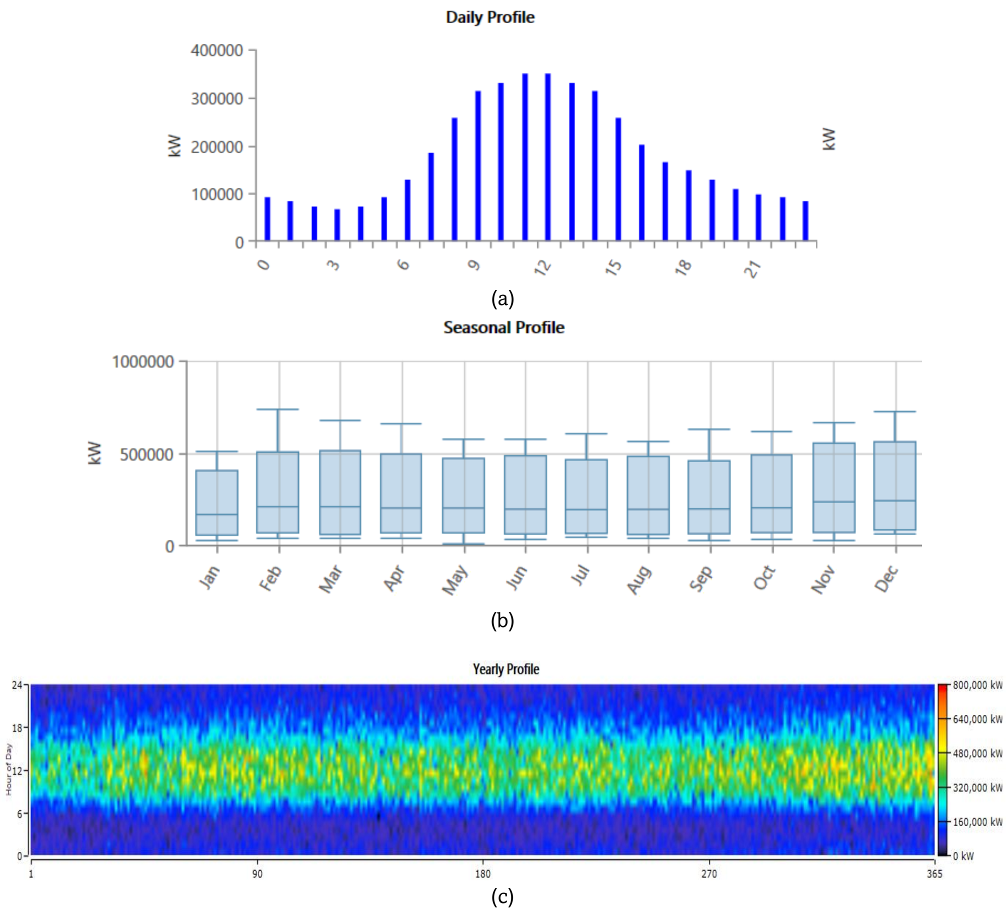


Fig. 2 Electric load profile (a) daily, (b) seasonal, (c) yearly

Table 1
Month-wise variability in the electric load taken for modeling

Month	Energy (kWh)	
January	218000	High operational activity post-holiday
February	180000	Slight dip due to Tết (Vietnamese New Year)
March	218000	Dry season, normal port operations
April	215000	Stable conditions
May	210000	Start of the rainy season
June	210000	Heavy rain impacts solar yield
July	205000	Monsoon peak, moderate load
August	205000	Same as July
September	200000	Slightly reduced activity
October	197600	Rain tapers off
November	215000	Dry season begins
December	244400	Peak cargo handling (year-end shipments)

Table 2
Item-wise distribution of electric load assumed for modeling

System / Equipment	Load (kW)	Hours/day	kWh/day	Annual (kWh)
High-Mast & Area Lighting	80	12	960	350400
Container Cranes & Forklifts	100	8	800	292000
Refrigerated Cargo	30	24	720	262800
Office Buildings & Admin	20	24	480	175200
IT & Security Systems	10	24	240	87600
HVAC & Cooling (Dry Season)	40	8	320	116800
Fueling Stations & Compressors	20	10	200	73000
Misc. (Pumps, Tools, etc.)	20	12	240	87600

strategic position near Thi Nai Lagoon offers easy access to both domestic and international maritime routes, making it an important hub for regional trade. The port's proximity to important transportation hubs like National Route 1A and the North-South railway helps to ensure seamless freight flow to and from the Central Highlands and other inland provinces. Covering 31 hectares overall, the port infrastructure consists of 200,000 square meters of open storage yards and 28,000 square meters of warehouses. Designed in a "T" form, the jetty runs eastward and has a total dock length of 320 meters, supporting up to four berths. Though regarded as a little port, Thi Nai is quite important for the surrounding economy, especially in industrial sectors, fisheries, and agriculture (Vietnam Seaport Association; The Museum of Underwater Archaeology 2012).

The monthly energy consumption pattern at Thi Nai Port has been modeled to reflect realistic variations in port activity and seasonal conditions. In January, energy demand peaks at 218,000 kWh due to heightened post-holiday operations. As port operations stall during the Tet holiday, a major cultural celebration in Vietnam, February sees a fall to 180,000 kWh. Demand rebounding in March to 218,000 kWh will match the dry season and resume regular port operations. With May starting the wet season, April and May saw modest declines to 215,000 and 210,000, respectively. Energy consumption stays constant at 210,000 kWh in June; frequent rain affects the availability of solar resources. Peak monsoon conditions in July and August cause a slight decline to 205,000 kWh. As port traffic declines, September shows a further drop to 200,000 kWh. Demand barely drops to 197,600 kWh by October as rainfall starts to decline. Starting the dry season, November indicates a comeback to 215,000 kWh. Driven by more cargo handling and logistic operations connected with year-end exports, December finally records the highest yearly consumption at 244,400 kWh. Optimized hybrid system design in HOMER Pro depends on this monthly profile. The daily, seasonal, and yearly profile of load is depicted in Figure 2a, Figure 2b, and Figure 2c, respectively. The electric load data showing monthly and item-wise variability taken for modeling are listed in Tables 1 and 2, respectively.

2.2 Solar data

The dataset representing the monthly variation in the clearness index and daily solar radiation (in kWh/m²/day) for Thi Nai port is plotted in Figure 3 for solar energy assessment. The data was downloaded from the National Renewable Energy Laboratory database. As a measure of sky clarity, the clarity index shows the proportion of solar energy reaching the Earth's surface relative to what would be received free from air interference. Usually, values go from 0 (very cloudy) to 1(clear sky). The clearness index of this dataset swings from 0.414 to 0.527, implying a somewhat sunny temperature with seasonal fluctuations. April (0.527) has the best clearness index, which corresponds to the daily radiation peak of 5.563 kWh/m²/day, thereby suggesting perfect circumstances for solar photovoltaic performance during this month. With radiation levels exceeding 5 kWh/m²/day, February and March also indicate rather strong solar resource availability. On the other hand, November (0.414)

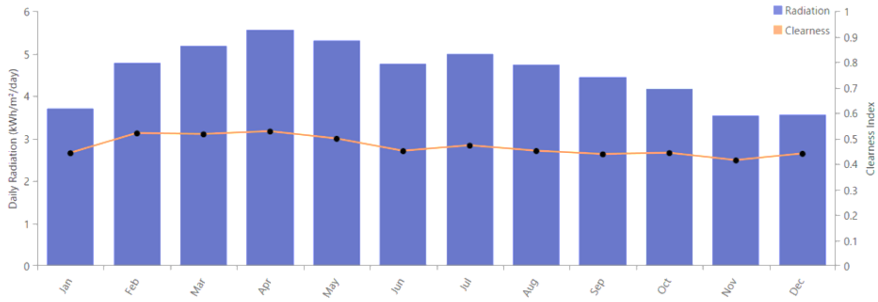


Fig. 3 Solar radiation and clearness data

has the lowest clearness index, which corresponds to the minimal radiation value of 3.53 kWh/m²/day, therefore indicating cloudier and less productive solar circumstances (Gueymard and Wilcox 2011; Dierauf *et al.* 2013). The results show that while November through January suffers decreased sun availability, overall, the data show that from February to May, solar energy generating potential is strongest. Especially for solar-based components in energy planning, this temporal profile is crucial for maximizing the design and scheduling of hybrid renewable energy systems.

2.3 Biomass availability

The biomass availability data across twelve months, as depicted in Figure 4, indicates a dynamic yet generally stable supply pattern influenced by agricultural cycles, seasonal climate variations, and socio-economic activities. In January, post-harvest periods provide a substantial amount of rice husk, yielding approximately 420 tons. Post-harvest times in January bring a significant supply of rice husks, about 420 tons. Due mostly to Tet holidays in Vietnam, which reduce municipal rubbish collecting activities, this availability somewhat decreases to 350 tons in February. March is the dry season; good circumstances cause biomass collecting to revive, reaching 420 tons, especially from green trash. Supported by moderate agricultural activity, the supply is somewhat constant in April at 400 tons. As the pre-monsoon season starts, May shows a little drop to 390 tons, during which food waste somewhat rises. Arriving in June, the monsoon presents difficulties for biomass collecting, particularly in rural regions, therefore limiting the available biomass to 380 tons. The monsoon peaks in July, when access problems further limit supplies and cause a slight decline to 375 tons. Still, in August things start to get better; thanks to more organic waste output, biomass availability rises to 385 tons. With 390 tons, September follows this tendency and gains from the regular post-monsoon availability of agricultural trash. October is yet another important season, aligned with the harvest season, which causes an increase of 400 tons as agricultural wastes abound. The start of the dry season and great agricultural output in November improved the availability to 410 tons. Driven by year-end events and more trash from both municipal and agricultural sources, December finally shows the highest biomass availability at 440 tons. The statistics show that biomass resources vary very seasonally, with clear maxima in the dry and post-harvest seasons. With careful planning needed during monsoon months to minimize the transitory declines, this pattern offers a somewhat consistent feedstock supply for continuous biogas generation (Duc 2024).

Fig. 4 Variation of biomass supply data

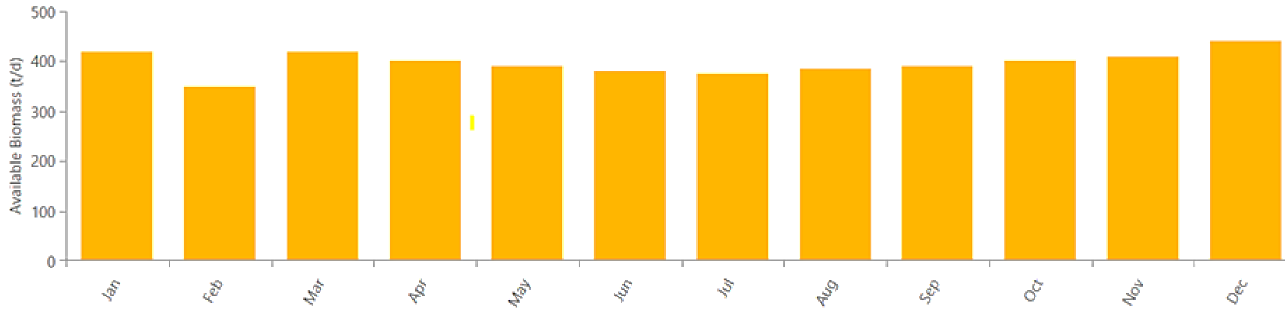


Fig. 5 Monthly average wind speed

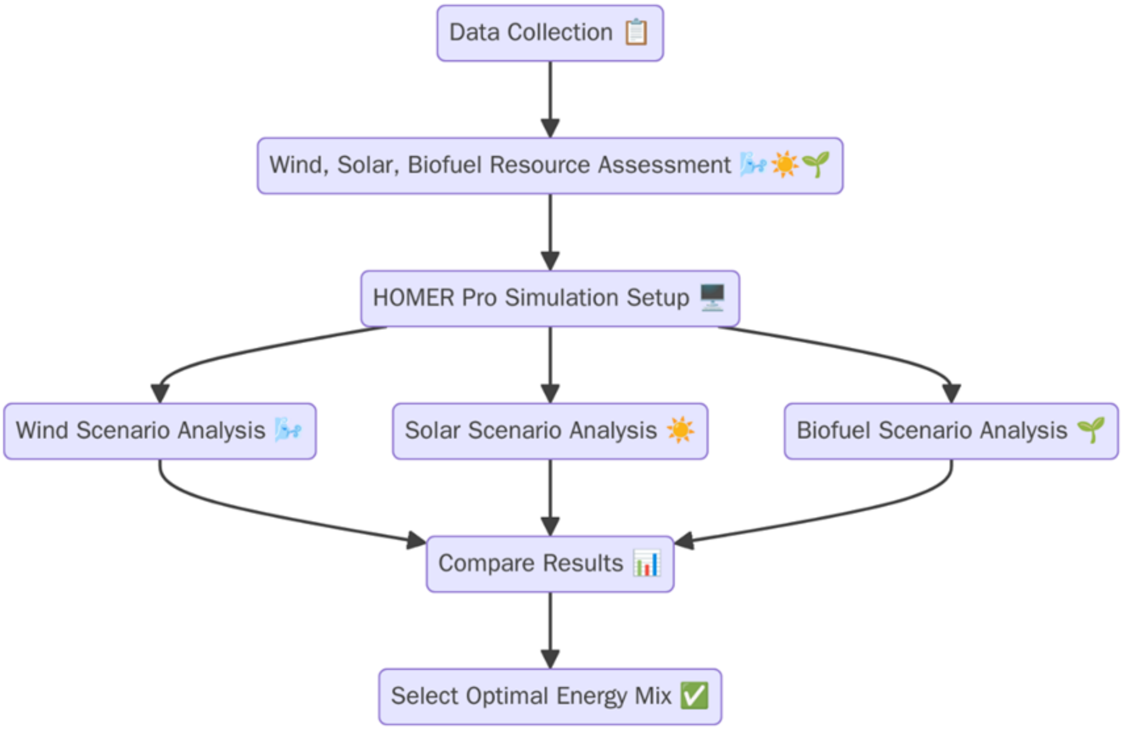


Fig. 6 Flow chart of the study

2.4 Wind resource availability for wind energy

At Thi Nai Port, the wind regime exhibits clear seasonal dynamics, marked by lower values during summer and greater wind speeds in the winter as shown in Figure 5. December has the highest average wind speed of 8.02 m/s, followed by November (7.53 m/s) and January (6.91 m/s), therefore reflecting the predominance of strong northern monsoon flows. From February to April, wind speeds ranging from 5.84 m/s to 4.73 m/s show a steady declining trend. With an average wind speed of 4.19 m/s, the summer months, especially September, register the lowest effect of the Southwest monsoon. Between June and August, there is a small rebound in which wind speeds level about 4.93–4.98 m/s. October brings rising wind intensities, achieving 5.82 m/s. These trends show Thi Nai Port's potential for seasonal wind energy collection, particularly from October to February, and imply the requirement for adaptable solutions during the weaker wind seasons spanning late spring to early fall.

2.5 Homer Pro-based simulation

The flowchart in Figure 6 outlines the methodology used for conducting a techno-economic analysis of a hybrid renewable energy system incorporating wind energy, biofuel-based generation, and solar photovoltaics to power Thi Nai Port through the application of HOMER Pro simulation software. The month-wise variability in the electric load taken and item-wise distribution of electric load assumed for modeling are provided in Table 1 and Table 2, respectively. Starting with the formulation of the research objective—which centers on the assessment of the viability, economy, and environmental advantages of converting Thi Nai Port into a green energy port, the procedure proceeds Data collecting follows the aim setting and covers thorough information on port energy consumption, local solar radiation (DNI), wind speed data, biomass resource availability, fuel pricing, and component costs and specifications (Antonio Barrozo Budes *et al.* 2020; Khalil *et al.* 2021; Basheer *et al.* 2022). After that, the system architecture is built by choosing appropriate technologies: converters, solar panels, battery storage, wind turbines, and a biogas-powered generator. Every element is designed in line with operational traits and site-specific statistics. All pertinent parameters are loaded into HOMER Pro once the configuration is finished to run simulations under several combinations and operating conditions. While economic indicators such as the net present cost (NPC), levelized cost of energy (COE), initial capital investment, operating costs, and payback period are concurrently assessed, HOMER Pro computes technical outputs including energy production, load balance, battery performance, and the contribution of each energy source during the simulation phase (Singh *et al.* 2015; Babu and Ray 2023). The best system architecture that reduces cost and increases renewable energy penetration and emission lowering is then found by means of the analysis of the outcomes. At last, based on techno-economic results, conclusions are made that offer practical advice and suggestions for expanding comparable green energy projects in minor and medium-sized ports throughout Vietnam and Southeast Asia.

3. Results and discussion

3.1 Hybrid renewable energy system configuration

The schematic outlines the structural arrangement and operational flow of a hybrid renewable energy system developed for Thi Nai Port using HOMER Pro. Three separate energy sources flow into a core load inside an AC bus architecture that underpins the system. The main producing components are a photovoltaic (PV) solar panel system, a wind turbine (G3), and a biofuel generator (Bio). Collectively aimed at

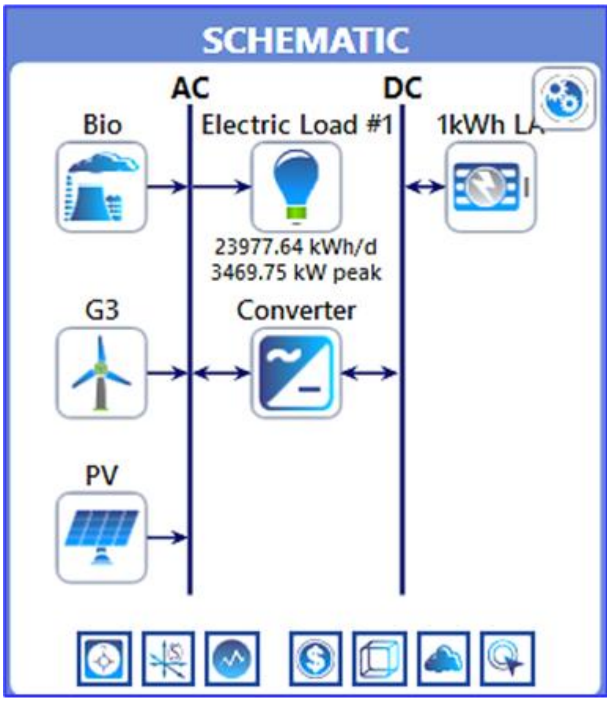


Fig. **7** Schematic of hybrid renewable energy installation

meeting the energy requirement of the port, each of these sources generates electricity in alternating current (AC) form. Figure 7 shows that with a peak load of 3469.75 kW and a daily demand designated as "Electric Load #1," the electric load requires 23,977.64 kWh. Combining the energy inputs from solar systems, wind, and biofuel supports this significant AC load. Additionally included in the schematic is a converter, which is essential in turning AC power to DC and vice versa. This offers operational flexibility through integration between DC loads or energy storage systems without endangering system stability. On the DC side, there is a little load tagged "1kWh LA". This probably shows little DC loads or a sign of battery charging or discharge activity controlled via the converter. The configuration guarantees that the same energy management system addresses even low-voltage or direct current requirements. The converter controls the flow of power between the AC and DC buses, while renewable generating units provide AC electricity to satisfy the primary power load methodically. Dynamic interactions among all elements satisfy real-time energy needs depending on resource availability and load circumstances. Emphasizing the design to optimize self-sufficiency by locally generated renewable energy sources, no external grid connection or diesel backup is specified.

3.2 Net Present Cost (NPC) in best-case scenario

The simulation outcomes derived from HOMER Pro demonstrate a comprehensive techno-economic analysis of various hybrid renewable energy system configurations aimed at powering a coastal port with a high daily energy demand of approximately 24,000 kWh and a peak load of 3,470 kW. Under cycle charging schemes, the findings show many designs, including photovoltaic (PV), biogas generators, diesel backup (G3), battery storage (1kWh LA), and converters, all dispatched. Finding the most reasonably priced, renewable-intensive, technically sound system arrangement was the main goal. Based on net present cost (NPC), the first configuration—which included a 6,175 kW PV array, 500 kW biogas generator, and 2,357 kW converter—emerged as the most affordable. Having an NPC of over 44.6 million USD, it presented a yearly running cost of 1.08 million USD and an initial capital cost of 30.6 million USD. Keeping the biogas system at 500 kW, the second scenario raised PV penetration to 14,108 kW. This configuration increased the NPC to 64.5 million USD through a bigger battery bank of 31,799 kWh and a 2,641-kW converter. While removing the biogas component, the third design kept a high PV input of 15,446 kW and included 489 kW of diesel generating capacity. Although technically strong with a completely renewable portion, this design displayed an NPC of 79.5 million USD. By pushing PV installation beyond 22,500 kW, the fourth option eliminates both biogas and diesel generators. This ultra-renewable system attained full energy autonomy but at a significant NPC of 109 million USD. The fifth arrangement consisted of just diesel and biogas systems without PV. This system obtained an NPC of 128 million USD. In the last scenario, no contribution from PV or biogas; the diesel-only architecture contained a 5,009-kW generator and 189,053 kWh of storage. The least economically and ecologically friendly choice this arrangement produced was a 243 million USD NPC.

3.3 Cost of energy in best-case scenario

The simulation results obtained using HOMER Pro provide a thorough techno-economic analysis of several hybrid renewable energy system designs designed to provide a coastal port with a substantial daily energy need of around 24,000 kWh and a peak load of 3,470 kW. The results reveal several configurations, including PV, biogas generators, diesel backup (G3), battery storage (1kWh), and converters, all dispatched under cycle charging schemes. The major objective was to find the most competitively priced, renewable-intensive, technically sound system configuration. The most reasonably priced arrangement, based on cost of energy (COE), came out to be one including a 6,175 kW PV array, a 500 kW biogas generator, and a 2,357 kW converter. Its COE of 0.394 USD/kWh indicated an initial capital cost of 30.6 million USD and an annual running cost of 1.08 million USD. In keeping the biogas system at 500 kW, the second scenario produced a PV penetration of 14,108 kW. By way of a larger battery bank of 31,799 kWh and a 2,641 kW converter, this arrangement raised the COE to 0.57 USD/kWh. The third version preserved a high PV input of 15,446 kW and incorporated 489 kW of diesel-producing capacity while deleting the biogas component. Although this design showed a COE of 0.70 USD/kWh, technically robust with the entire renewable component. The fourth alternative completely removes biogas and diesel generators by pushing PV installation over 22,500 kW. Although at a COE of 0.96USD/kWh, this ultra-renewable system achieved full energy autonomy. The fifth configuration comprised solely diesel and biogas systems devoid of PV. This system came up with a COE of 1.13 USD/kWh. In the last scenario, PV or biogas was not used; the diesel-only architecture had a 5,009-kW generator and 189,053 kWh of storage. With a COE of 2.14 USD/kWh, this combination yielded the least environmentally and economically beneficial option.

To power Thi Nai Port, the first hybrid design combining solar PV and biogas turns out to be the most balanced one. With the lowest COE and NPC, it offers complete energy autonomy; also, it guarantees steady year-round operation using biomass generation and effective battery backup. Such a system preserves grid independence, uses nearby renewable resources, and advances long-term sustainability. Other setups are less practical even if they provide little increases in capacity or

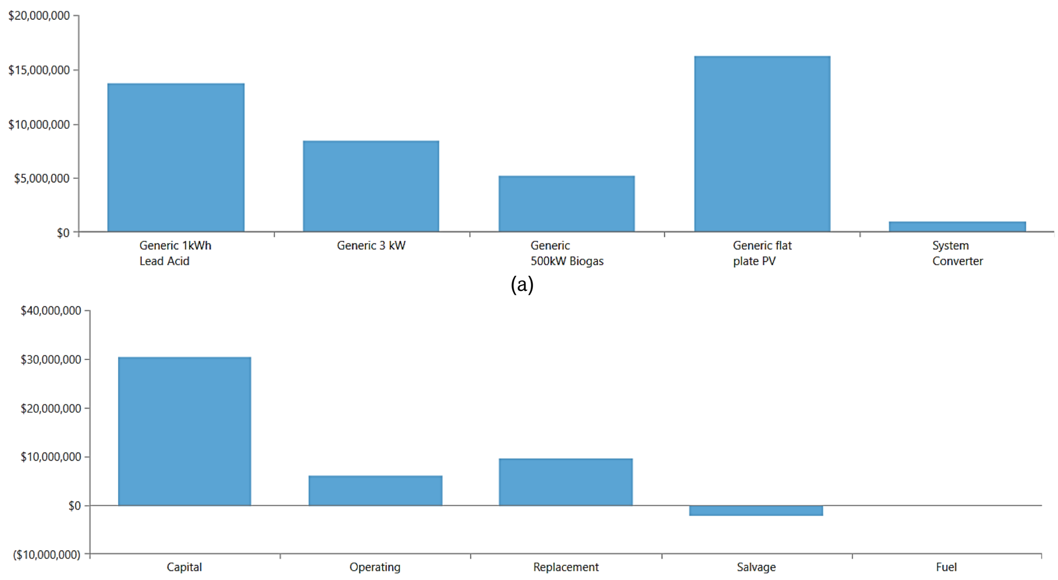


Fig. 8 Net present cost summary on the basis of (a) component (b) cost type

autonomy, as they suffer disproportionate cost penalties. From a techno-economic and environmental perspective, then, the solar-biogas-storage system makes a strong case for use in small - to medium-sized coastal infrastructure projects in Southeast Asia.

3.4 Cost summary

The study based on HOMER Pro provides a comprehensive evaluation of the techno-economic performance of a hybrid renewable energy system configuration intended to supply power to a coastal port. The assessed system incorporates photovoltaic (PV) panels, biogas producers, lead-acid battery storage, and a system converter. The capital investment necessary for the system is roughly 30.57 million USD. The predominant portion is ascribed to the flat plate photovoltaic installation, amounting to around 15.44 million USD, illustrating the substantial initial expenditure commonly linked to solar energy infrastructure. Utilizing standard 1 kWh lead-acid battery storage necessitates a significant capital investment of 6.25 million USD, underscoring the essential function of storage in maintaining energy dependability. The general 3 kW component and the 500-kW biogas generator set represent investments of 6.68 million USD and 1.5 million USD, respectively, underscoring a substantial yet balanced commitment to auxiliary and renewable power technologies as depicted in Figure 8a and Figure 8b.

The replacement expenditures, primarily attributed to batteries and the biogas generator, are around 9.79 million USD. Batteries account for roughly 5.5 million USD in replacement costs due to their limited lifespan compared to other components. The operation and maintenance (O&M) costs amount to 6.34 million USD, with biogas generators bearing the most O&M responsibility, signifying a requirement for consistent service and operational supervision. The system's renewable architecture, particularly utilizing solar and biogas inputs, incurs no fossil fuel expenses, significantly improving long-term economic viability. Salvage values, denoting the remaining value of components after the project's conclusion, reduce the total costs by about 2.09 million USD, mostly due to batteries and inverters. The entire system cost is around 44.61 million USD. This indicates a well-structured investment prioritizing substantial renewable integration, significant operational independence, and reduced fuel use, rendering the hybrid design financially and ecologically resilient for sustained port operations.

3.5 Cash flow analysis

The results present a detailed cost breakdown for four energy system components over a 25-year lifespan: a 1kWh Lead Acid battery system, a 3kW generic system, a 500kW biogas genset, and a generic flat plate PV system. The starting capital outlay for the 1kWh Lead Acid battery comes out to be $6,245,101. Except in years 10 and 20, where notable replacement expenditures of $6,245,101 are shown, annual running expenses are stable at $208,170 from year 1 through year 25 (Figure 9a). At the end of the 25 years, one finds a final salvage value of $3,122,550. After its service life, the system produces a positive balance of $2,914,380 despite the regular running expenses and replacements. Comparably, the 3kW system begins with a $6,678,000 capital cost. The running cost is constant at $66,780 a year. Up until year 20, when an extra replacement cost of $6,678,000 is spent, no intermediate replacement costs are noted. With $5,008,500 recovered at the end, the system gives more salvage value than the battery system. After 25 years, the net financial result is $4,941,720, which shows rather greater economic sustainability than the Lead Acid battery design.

With a $1,500,000 starting capital cost, the 500kW biogas generator has a rather lower value. Operating expenses come to $153,720 annually; replacement costs of $625,000 show up every four years starting with year 4. At the conclusion of the term, one finds a salvage value of $371,875. The last net result indicates a positive balance of $218,155 even with regular replacement costs. Although biogas genset technology requires modest initial inputs, the recurrent replacement costs suggest that maintenance and renewal are very essential to running operations. At $15,439,917 the flat plate PV system boasts the lowest capital cost, as shown in Figure 9b. At $61,760 annual running expenses, the dataset given does not include any

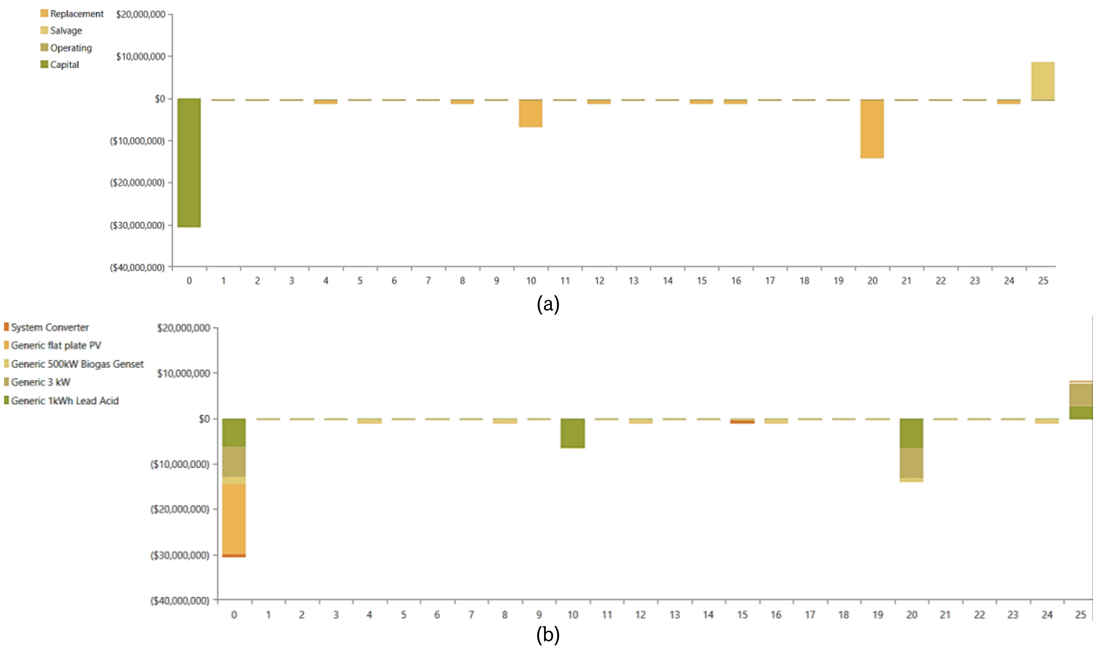


Fig. 9 Cash flow on the basis of (a) cost type, (b) component

replacement or salvage value. This implies that even if PV systems need large upfront costs, over the years their running expenses are quite modest. Still, the lack of system replacement planning or salvage value might influence long-term financial forecasts.

Though with regular replacement requirements, the biogas genset shows the optimum balance between investment and running expenditures at the end. Because of better salvage value, the 3 kW system also demonstrates good long-term financial returns. Although practical, the Lead Acid battery is costly considering replacements. Although PV systems have significant starting costs, their operational expenditure profile is appealing, their lack of salvage consideration demands rigorous economic study. These results highlight the need to balance capital, running, replacement, and salvage expenses in the design of sustainable energy plants.

3.6 Photovoltaic power output

The results presented in Table 3 offer a comprehensive analysis of the photovoltaic system performance based on the simulation study. The system has a rated capacity of 6,176 kW, indicating the greatest potential production under optimal conditions. The measured mean production is 951 kW, much lower than the rated value due to natural fluctuations in solar irradiation, system losses, and ambient factors. This output reflects a daily average energy generation of 22,817 kWh/d, signifying a substantial contribution to meeting energy demand. The capacity factor is determined to be 15.4%, representing the ratio of actual energy output to theoretical maximum output for a designated timeframe. A capacity factor of this value indicates modest solar resource availability at the location and corresponds with standard photovoltaic system performance under comparable climatic circumstances. The system's total yearly production is projected to be 8,328,242 kWh/year, indicating a robust and reliable renewable energy output sufficient to meet significant electricity demands.

Table 3
PV power output

Qty	Value	Units
Rated Capacity	6,176	kW
Mean Output	951	kW
Mean Output	22,817	kWh/d
Capacity Factor	15.4	%
Total Production	83,28,242	kWh/yr
Minimum Output	0	kW
Maximum Output	5,946	kW
PV Penetration	95.2	%
Hours of Operation	4,367	hrs/yr
Levelized Cost	0.151	$/kWh

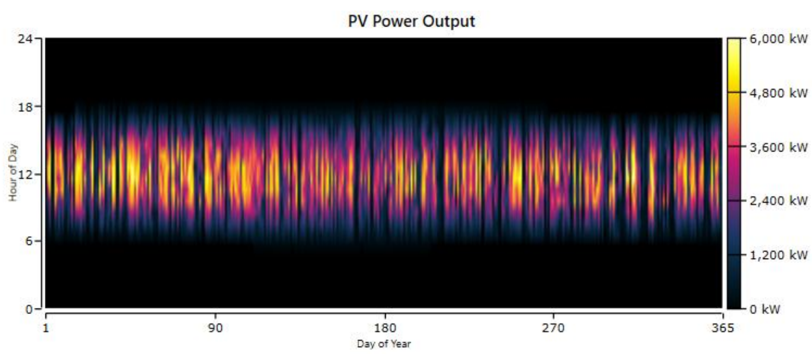


Fig. 10 PV power output variation

The lowest documented output is 0 kW, signifying intervals devoid of solar energy production, such as during nighttime or adverse weather conditions. The highest output attained is 5,946 kW, somewhat below the specified capacity, which is justifiable owing to unavoidable issues like temperature derating, inverter losses, and partial shade. PV penetration is at an amazing 95.2%, indicating that during peak generation periods, the solar system can practically fulfil the total energy demand. The elevated penetration rate illustrates the system's capacity to diminish reliance on auxiliary power sources and improve overall energy self-sufficiency. Moreover, the system functions for around 4,367 hours annually as depicted in Figure 10, indicating that it generates electricity for a substantial part of the year, which is essential for dependable renewable energy integration. The levelized cost of electricity is established at $0.151 per kilowatt-hour. This value encompasses the complete lifespan costs, including installation, maintenance, and operational charges, allocated across the total power generated.

A levelized cost of $0.151/kWh indicates a competitive and economically feasible alternative to traditional fossil fuel-based power generation, especially when accounting for environmental advantages and any regulatory incentives. These computational results affirm that the photovoltaic system is both technically feasible and economically advantageous under the examined conditions.

3.7 Monthly electricity production

The electricity production and consumption analysis highlight a highly renewable-dominated energy system with a total annual production of 12,817,590 kWh/yr, as depicted in Figure 11 and Table 4. The basic flat plate photovoltaic system produces 8,328,242 kWh annually, accounting for 65% of the whole output. The standard 500 kW biogas generator produces 2,370,591 kWh annually, representing 18.5%, whilst the standard 3 kW system generates 2,118,758 kWh per year, constituting 16.5%. The overall consumption of 8,749,251 kWh/year is entirely attributed to the AC primary load, representing 100% of the demand, with no load recorded under the DC primary or deferrable categories. The energy balance indicates a significant surplus in electricity generation of 3,873,634 kWh per year, or 30.2% of total production, implying huge opportunities for energy storage integration or grid export to mitigate waste and enhance system economics. The system indicates an unmet electric load of 2,588 kWh/year, equating to a minimal 0.0296%, with a capacity deficit of 8,528 kWh/year, about 0.0974%, highlighting the exceptional dependability and stability of the energy supply during the operating year. The renewable portion is unequivocally 100%, confirming that all electrical requirements are met only by renewable energy sources, devoid of any dependence on fossil fuels or external energy systems. Moreover, the system attains a maximum renewable penetration of 964%, indicating that at specific peak hours, renewable generation surpasses the load by over tenfold, illustrating the resilience and substantial output capability of the installed renewable infrastructure. These performance indicators demonstrate a meticulously crafted, efficient, and sustainable energy system characterized by high operational resilience, minimal losses, and substantial prospects for future expansion via energy storage systems or smart grid interactions, particularly in areas with considerable renewable energy potential.

3.8 Biofuel consumption for electricity generation

The biofuel consumption analysis depicted in Figure 12, for the HRES, reveals a total feedstock utilization of 7,139 tons per year. This consumption amounts to an average feedstock need of about 19.6 tons daily and almost 0.815 tons per hour. With greater densities clustering around the 1,000 kg/hr mark, the monthly box plot in the upper left shows that the feedstock consumption essentially varies between 200 kg/hr and 1,200 kg/hr throughout all months. Especially, the range is very constant from January to December, therefore verifying steady operating demand free from major seasonal fluctuations. Labeled "Fuel Consumption," the heat map on the upper right provides a thorough picture spanning 24 hours for every day of the year. The hues run from blue (0 kg/hr) to dark red (1,200

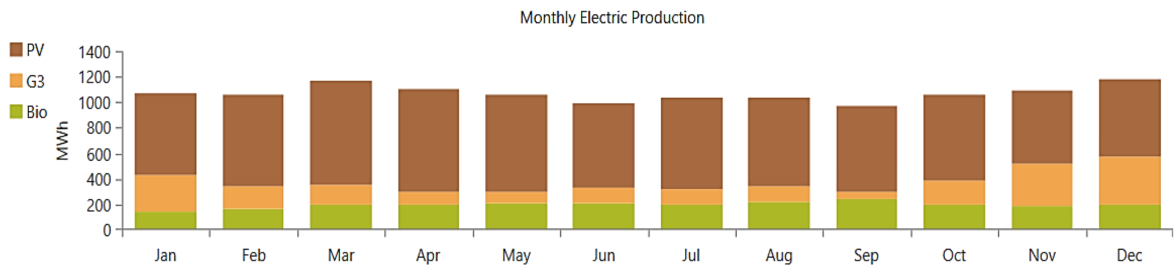


Fig.11 Monthly electricity production from all three renewable sources

Table 4
Details of electricity production

Production			Consumption			Balance		
Production	kWh/Yr	%	Consumption	kWh/Yr	%	Qty	kWh/Yr	%
Generic flat plate PV	83,28,242	65	AC Primary Load	87,49,251	100	Excess Electricity	38,73,634	30.2
Generic 500kW Biogas Genset	23,70,591	19	DC Primary Load	0	0	Unmet Electric Load	2,588	0.03
Generic 3 kW	21,18,758	17	Deferrable Load	0	0	Capacity Shortage	8,528	0.097
Total	1,28,17,590	100	Total	87,49,251	100			

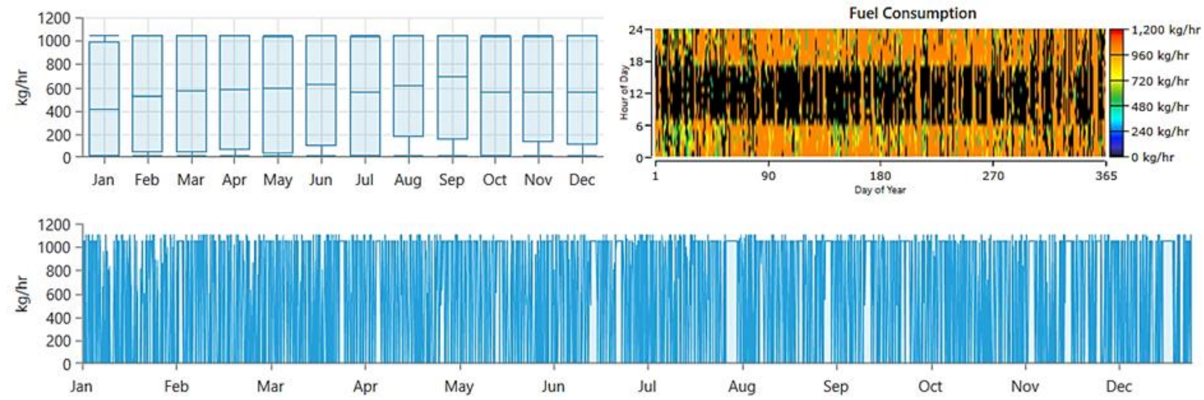


Fig. 12 Biofuel consumption for electricity generation

kg/hr). Orange and red tones indicate higher consumption hours, which mostly fall between 6:00 and 20:00 hours, implying that the biofuel system is significantly loaded during daytime and early evening hours. Hourly feedstock usage across the year is shown on the lower plot. Reflecting the great operational continuity of the system, it exposes dense and regular spikes typically between 600–1,000 kg/hr. This constant fuel demand emphasizes how dependable the bioenergy system is in maintaining power output throughout several seasons and daily load variations.

3.9 Renewable energy penetration

The capacity-based metrics show a strong dominance of renewable sources in the system, where the nominal renewable capacity accounts for 100% of the total nominal capacity, and similarly, the usable renewable capacity also stands at 100% of the total usable capacity. The results are depicted in Figure 13. This means that the system depends only on renewable energy technology and has no non-renewable backup. The examination of peak value emphasizes even more the dependability of the renewable energy source. Based on the usual meter, the renewable output divided by the load comes out to be a robust 964%, implying that during peak conditions, the renewable output may over ten-fold surpass the immediate demand needs. One less non-renewable output divided by total load likewise reflects 100%; this confirms that all generated energy during peak hours originates from renewable sources without any non-renewable input. The renewable output divided by total generation similarly obtains a value of 100%. In terms of energy-based measures, the total renewable output split by load yields 146%, meaning that 46% more energy is produced by renewable sources than the annual total load requirement. Furthermore, the whole renewable output split by generation comes out to be 100%, thereby confirming that the portfolio of generation is entirely renewable. One less the total non-renewable output divided by load produces 72.9%, indicating that a significant portion of the energy demand is satisfied sustainably, with the least reliance on non-renewable sources during the operational duration.

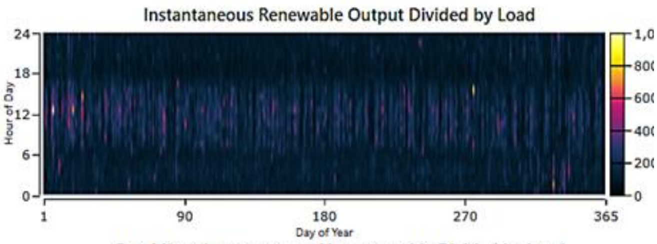
3.10 Emission analysis

In continuation of the capacity, peak, and energy-based metrics, the emission analysis further demonstrates the environmentally sustainable nature of the energy system. When compared to traditional fossil-fuel-based systems, where emissions often exceed several hundred tons per year, the reported carbon dioxide emissions of 1,286 kg/yr are rather modest. Once more suggesting limited incomplete combustion in the system, the carbon monoxide emissions stood at 14.3 kg/yr, as given in Table 5. Significantly, there are zero emissions of sulfur dioxide, particulate matter, and unburned hydrocarbons - usually important contaminants linked with environmental damage and health risks. Their whole absence demonstrates the cleanliness of the feedstock utilized and the great quality of combustion. Maintaining a low level of 8.92 kg/yr, nitrogen oxides, which contribute to smog and acid rain, further underline the effectiveness of the process control and

Capacity-based metrics	Value	Units
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%

Peak values	Value	Units
Renewable output divided by load (HOMER standard)	964	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

Energy-based metrics	Value	Units
Total renewable production divided by load	146	%
Total renewable production divided by generation	100	%
One minus total nonrenewable production divided by load	72.9	%



Instantaneous Renewable Output Divided by Generation

One Minus Instantaneous Nonrenewable Divided by Load

Fig. 13 Renewable energy penetration

Table 5
Emission data

Quantity	Value	Units
Carbon Dioxide	1,286	kg/yr
Carbon Monoxide	14.3	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	0	kg/yr
Nitrogen Oxides	8.92	kg/yr

combustion technologies used. These emission data, together with the previously mentioned renewable dominance measurements, confirm that the system not only reaches energy self-sufficiency but also has almost zero environmental impact. All things considered, the proposed energy system runs with exceptional sustainability, preserves high rates of renewable penetration and peak performance, and guarantees rather low emissions over all important pollutants.

4. Conclusion

The thorough techno-economic study performed with HOMER Pro conclusively demonstrates the feasibility of converting Thi Nai Port into a green energy port with a hybrid renewable energy system. The most economical solution, comprising a 6,175-kW solar PV array, a 500-kW biogas generator, and a 2,357-kW converter, yielded a net present cost (NPC) of 44.6 million USD and an annual running cost of 1.08 million USD. This system provides a total renewable energy supply at a levelized cost of energy (COE) of 0.394 USD/kWh, reaching 100% nominal and usable renewable capacity. The yearly energy production exceeded the port's daily load of 24,000 kWh, with renewable output achieving 146% of the overall load needed. Carbon dioxide emissions were significantly decreased to 1,286 kg/year, while sulfur dioxide, particulate matter, and unburned hydrocarbons were entirely eradicated. The negligible emissions of carbon monoxide (14.3 kg/year) and nitrogen oxides (8.92 kg/year) further demonstrate the system's environmental integrity. The research validates that strategic hybridization—utilizing local solar, wind, and biomass resources—can concurrently provide substantial operational savings, enhance energy security, and provide environmental advantages. The anticipated payback period varies from 8 to 10 years, depending upon legislative support and financial incentives. In contrast to traditional diesel-based systems, which have a net present cost of 243 million USD and a cost of energy of 2.14 USD/kWh, the hybrid system provides significant economic and environmental benefits. As a future scope of the study, explainable machine learning may be used for model prediction and feature analysis.

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