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EFFICIENT ENERGY USE, LOW CO_2 EMISSIONS FOR TROPICAL ISLAND REGIONS

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SUMMARY OF DOCTORAL THESIS

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LIST OF PUBLISHED WORKS

1.Hoang-Phuong Nguyen, Viet-Cuong Vo, Vinh-Nghi Le, Thi-Thanh-Binh Phan, Thanh-Phong Tran, "Feasibility for solid waste power generation at Phu Quoc Island, Vietnam," *2018 4th International Conference on Green Technology and Sustainable Development (GTSD),* DOI: 10.1109/GTSD.2018.8595552, pp. 175-180, 2018.

2. Hoang-Phuong Nguyen, Viet-Cuong Vo, Van-Quan Vo, Thi-Thanh-Binh Phan, Thanh-Phong Tran, "A feasible proposal for small capacity solar power generation at Phu Quoc, Viet Nam," *2019 Innovations in Power and Advanced Computing Technologies*, DOI: 10.1109/i-PACT44901.2019.8960125, pp. 1-6, 2019.

3. Hoang-Phuong Nguyen, Viet-Cuong Vo, Tan-Dong Le, Thi-Thanh-Binh Phan, Thanh-Phong Tran, Le-Duy-Luan Nguyen, "CO2 reduction potential by putting electric vehicles into operation in Phu Quoc island, Viet Nam," *2019 International Conference on System Science and Engineering (ICSSE)*, DOI: 10.1109/ICSSE.2019.8823377, pp. 229-234, 2019.

4. Nguyễn Hoàng Phương, Nguyễn Phước Tín, Võ Viết Cường, Trần Thanh Phong, Võ Văn Quân, "Economic efficiency of rooftop solar power systems," *Proceedings of the 2019 National Conference on Natural Resources and Environment in the New Situation, Climate Change*, Science and Technology Publishing House, ISBN 978-604-67-1585-6, pp. 80-93, 2020.

5. Nguyễn Hoàng Phương, Võ Viết Cường, Nguyễn Ngọc Âu, Trần Thái An, "A new proposed operating mode of diesel - wind power generation system for Phu Quy island," *Journal of Science and Technology - University of Danang*, vol. 19, no. 5.1, pp. 29-34, 2021.

6. Nguyen H. Phuong, Luan D. L. Nguyen, Vu H. M. Nguyen, Vo. V. Cuong, Tran M. Tuan, Pham A. Tuan, "A new approach in daylighting design for buildings," *Engineering, Technology & Applied Science Research*, https://doi.org/10.48084/etasr.5798, vol. 13, no. 4, pp. 11344-11354, 2023. (Scopus Q2).

7. Nguyen Hoang Phuong, Vo Viet Cuong, Truong Phuc Khanh Nguyen, Tran Quoc Cuong, "Energy and energy models for tropical islands in Vietnam," *TNU Journal of Science and Technology*, DOI: https://doi.org/10.34238/tnu-jst.9833, vol. 229, no. 06, pp. 149-159, 2024.

8. Hoang Phuong Nguyen, Le Duy Luan Nguyen, Hoang Minh Vu Nguyen, Truong Phuc Khanh Nguyen, Viet Cuong Vo, Thi Thanh Binh Phan, "Green Power Generation for Phu Quy Island to 2040," *GMSARN International Journal*, vol. 19, pp. 540-552, 2025. (Scopus Q4).

CHAPTER 1. INTRODUCTION

1.1. Reason for choosing the topic

The islands in this dissertation include small islands that are part of mainland countries and small territorial islands located in tropical regions. These islands are spread across marine areas from the Pacific Ocean, Indian Ocean, Atlantic Ocean, and the Caribbean. Tropical islands around the world are considered key subjects in the development of coastal tourism economies, as well as having significant value in determining maritime and territorial sovereignty for countries [1].

Vietnam, with over 3,200 km of coastline, possesses more than 3,000 large and small islands [2]; this group of islands has great potential for the development of coastal tourism economies, but it has only been explored in the last decade. Islands such as Phú Quốc have been supplied with electricity from the national grid since 2014, with a substation capacity of 2x40 MVA. Diesel power is only used for peak load and backup capacity. The average forecasted electricity demand for 2030 in Phú Quốc is over 4,200 kWh per capita per year. Côn Đảo is currently primarily powered by 9 diesel generators with a total capacity of 11,820 kW, along with a 136 kWp solar power system. The electricity demand in Côn Đảo increases at an average rate of 23.4% annually. At Phú Quý, the diesel power supply has a total capacity of 9.7 MW, with a wind power system of 6 MW and solar power of 0.732 MW. Lý Sơn has been connected to the national grid through an underwater cable since 2014 with a capacity of 16.5 MVA.

This shows that Vietnam's islands depend on diesel-generated electricity, which results in significant CO_2 emissions, or in some cases, are supplied with electricity from the mainland. In the event of an underwater cable failure, these islands may face prolonged power outages. Meanwhile, these islands have favorable natural conditions for exploiting renewable energy sources such as solar, wind, and biomass. However, the application of energy efficiency solutions has not been implemented systematically. If given proper attention, this could be considered a strategic solution that creates conditions for the sustainable development of island economies without adding pressure on energy supply [45-46].

After surveying the current energy use situation of tropical islands around the world and studying energy models like the Gran Canaria model [6], and the "Kommod" model in Phuket, Thailand, which stands out for its ability to identify optimal electricity generation structures and energy management for tourism-potential islands [32], the dissertation proposes the topic “Energy Efficiency and Low CO_2 Emissions for Tropical Islands.” This dissertation not only proposes solutions for energy efficiency using energy models for Vietnamese islands but also considers their application to other tropical islands around the world.

1.2. Research subject

- Approaches and exploitation of local renewable energy potential for tropical islands. Solutions to improve energy efficiency in island power systems.

- Solutions to reduce electricity demand from the existing power system and optimize energy supply. Approaches to reduce fossil fuel use and increase renewable energy adoption.

- Solutions to promote the development and penetration of renewable energy into tropical island power systems.

1.3. Research scope

Research on effective and feasible energy solutions for tropical islands globally and in Vietnam. Specific application of energy solutions and models to Vietnamese tropical islands, aiming to optimize the use and development of renewable energy.

1.4. Research objectives

The objective of this dissertation is to propose and demonstrate the feasibility of energy efficiency solutions, while determining the optimal cost-effective electricity generation structure, applying primary energy sources for tropical islands, particularly in Vietnam.

1.5. Research tasks

Investigate the approach and potential for maximizing local renewable energy exploitation for tropical islands. Analyze and propose solutions to improve energy efficiency in island power systems.

Provide solutions to reduce electricity demand from the current electricity system and optimize energy supply. Research and propose approaches to reduce fossil fuel usage while enhancing renewable energy adoption.

Identify solutions to improve energy efficiency and encourage the development and penetration of renewable energy into power systems. Propose and demonstrate the feasibility of energy efficiency solutions for tropical islands in general and for Vietnam in particular.

1.6. Research methods

The dissertation employs flexible methods, including: literature review, field data collection, simulation and optimization methods, cost analysis, forecasting, and scenario building.

1.7. Practical value of the dissertation

The dissertation proposes and demonstrates the feasibility of energy efficiency solutions, determining the optimal electricity generation structure, selecting primary energy sources, and optimizing electricity generation costs, specifically for tropical islands in general and Vietnam in particular:

- Sustainable Development for Islands: The dissertation provides solutions towards the effective use of energy, reducing CO_2 emissions, protecting the environment, mitigating the negative impacts of climate change, and ensuring the sustainable development of tropical islands. The CO_2 emission reduction factor is formed by proposing green power generation scenarios (GREEN) and greener scenarios (HIGHER GREEN), involving varying levels of renewable energy participation.

- Optimizing Local Energy Resources and Reducing Energy Costs: The dissertation proposes and demonstrates the feasibility of energy efficiency solutions with five proposals and calculations. This will help islands become energy self-sufficient, reducing dependence on external energy sources. Effective energy use and reduced emissions not only save operational costs for energy systems but also support economic development:

(1) Electricity Generation from Solid Waste in Phú Quốc (2020-2030): Based on the socio-economic development plan for the island, the population is expected to increase from 360,000 to 532,888 during this period. Consequently, municipal waste will increase from 283 tons/year to 419 tons/year, with the power plant capacity increasing from 4.7 MW to 7.0 MW. Financial indicators include a net present value

(NPV) of 5.1 million USD with a discount rate of 7%, an internal rate of return (IRR) of 10.5%, and a payback period of 13.01 years. The total CO_2 reduction ranges from 23,118 to 34,220 tons/year. With a project lifespan of 25 years, the project meets economic criteria for investment.

(2) Feasibility of Rooftop Solar Power System in Phú Quốc (2020-2030): The solar power system capacity is evaluated through three scenarios, with installation capacities increasing from 805 MWp, 1,219 MWp to 1,931 MWp. Financial indicators for the rooftop solar systems are IRR at 10.5%, 11.88%, and 15.41%, with payback periods of 8, 7.5, and 6 years, respectively. CO_2 reduction totals are 193,844, 293,287, and 464,473 tons/year. With a project lifespan of 20-25 years, these projects meet the economic criteria for investment.

(3) CO_2 Emission Reduction by Electric Vehicles in Phú Quốc: A feasibility study for replacing internal combustion engine vehicles with electric vehicles is conducted under three scenarios with increasing substitution rates of 5%, 10%, and 15%. These scenarios are feasible, particularly in Vietnam, where the electric vehicle market is rapidly expanding. The CO_2 reduction rates by 2030 are approximately 17%, 18%, and 21% for the three scenarios.

(4) Optimization of Diesel-Wind Power System Operation in Phú Quý: The proposed operating method for the existing diesel-wind power system on Phú Quý yields significant results: wind power generation increases by 81.69%, and diesel consumption decreases by 31.23%. Even with 70% effectiveness, the diesel cost savings would amount to 12.5 billion VND in electricity generation, along with corresponding CO_2 reductions.

(5) Natural Lighting Design for a Multi-Function Building: A building with dimensions of 80m x 32m x 14m (one floor) is designed to optimize natural light. The building includes office spaces, a small mechanical workshop, and a commercial service area. The results show a 34% reduction in energy consumption, saving approximately 1.56 tons of CO_2/m^2/year, with a payback period of just over 9 months.

1.8. Thesis structure

Chapter 1. Introduction.

Chapter 2. Overview and Energy Models for Tropical Islands.

Chapter 3. Energy Efficiency Solutions and Optimal Power Generation Structure.

Chapter 4. Feasibility of Energy Efficiency Solutions and Optimal Power Generation Structure for Phú Quốc and Phú Quý Islands in Vietnam.

Chapter 5. Conclusion and Future Development Directions.

CHAPTER 2. OVERVIEW AND ENERGY MODELS FOR TROPICAL ISLANDS

Energy Transition on Tropical Islands Worldwide: Challenges and Opportunities

The energy systems of Mediterranean islands are struggling to meet economic development demands without a strong transition. Despite abundant renewable resources, these islands have yet to effectively harness them to build a sustainable power system. Expanding rooftop solar on households and hotels, developing large-scale solar farms, and integrating both onshore and offshore wind power are key solutions. Additionally, utilizing biomass and biogas from agricultural waste contributes to diversifying clean energy sources.

Beyond power generation, storage systems such as pumped hydro storage and battery energy storage systems (BESS) play a crucial role in balancing supply and demand. Interconnections with regional grids, such as the EuroAsia Interconnector project, enhance sustainability and reduce energy security risks. Furthermore, improving energy efficiency in the tourism and service sectors, as well as promoting clean transportation like electric vehicles powered by renewable energy, are essential measures.

The greatest challenge for European islands is reducing dependence on fossil fuels amid increasing electricity demand, especially during peak tourism seasons. The power system in Crete, for instance, faces significant pressure due to suboptimal operational efficiency. While public support for clean energy transition is growing, islands still require more synchronized strategies for developing solar, wind, and advanced storage systems to achieve sustainability goals.

International Experiences and Lessons for Vietnam

Mauritius, Maldives, and Reunion have made significant progress in renewable energy adoption but still face challenges in building autonomous and sustainable energy systems. In Reunion, CO2 emissions from the energy sector account for nearly 95% of total greenhouse gas emissions, with electricity production contributing over 49%. To achieve 100% renewable energy by 2025, the island government has implemented tax exemptions, subsidies, and incentives for importing clean energy equipment.

In Southeast Asia, countries like Thailand have developed optimized energy models for islands, such as the "Kommod" project in Phuket, which efficiently manages power generation and storage. This model can be adapted to suit tropical islands in Vietnam, where solar, wind, and biomass energy potentials remain underutilized.

Vietnam faces the risk of electricity shortages on its islands as demand surges. Although Phu Quoc is connected to the national grid, it is projected to be overloaded by 2030. Con Dao still relies mainly on diesel generators, while Ly Son is vulnerable to prolonged power outages in case of system failures. Clearly, diesel is not a sustainable solution.

Proposing energy models for sustainable island development—focusing on energy efficiency, optimal utilization of local resources, integration of storage, and consumption optimization—is the key to ensuring energy security and reducing CO2 emissions for islands worldwide and in tropical Vietnam. This is an urgent task. The dissertation on "Efficient Energy Utilization and Low-Carbon Emission for Tropical Islands" will contribute to finding optimal solutions, aiming for a green, autonomous, and sustainable energy system for islands in the future.

CHAPTER 3.
SOLUTIONS FOR EFFICIENT ENERGY USE AND OPTIMAL POWER GENERATION STRUCTURE

3.1. Proposed energy model for tropical islands

The model aims to maximize the potential of local renewable energy sources and promote sustainable development, as shown in Figure 3.1.

3.1.1. Policies: Policies are a decisive factor in the success of a low-carbon emission scenario. These policy packages include two main groups: the group of policies that create barriers or difficulties, and the group of policies that facilitate or provide support.

3.1.2. Solution groups

- **Feasibility calculation of rooftop solar power system**

To calculate the feasibility of a rooftop solar power system, ensuring technical feasibility and economic efficiency, the dissertation proposes a flowchart for researching solar power potential as shown in Figure 3.3.

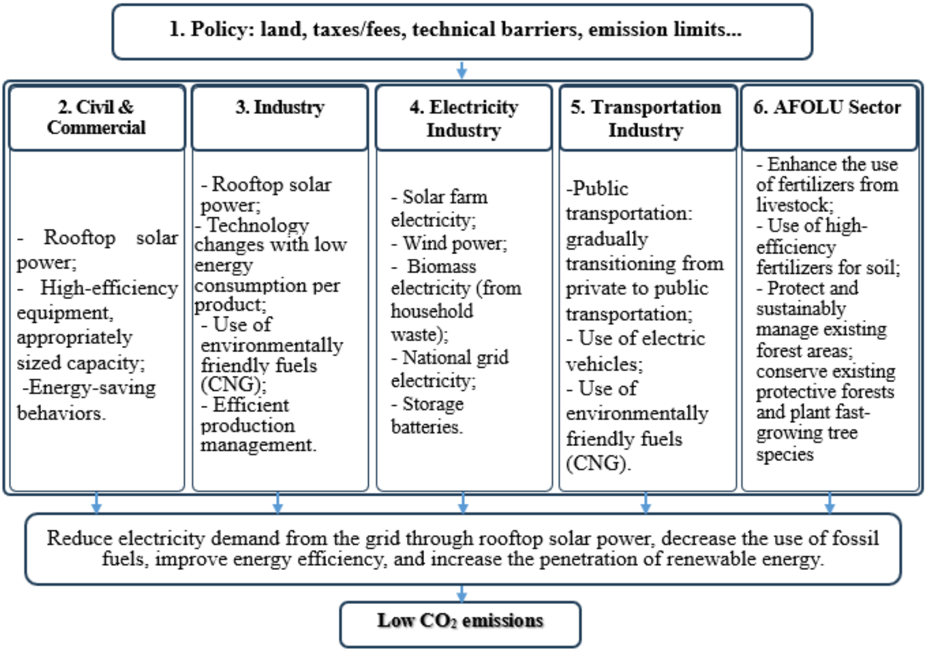


Figure 3.1. Energy Efficiency and Low CO_2 Emission Model for Tropical Islands in Vietnam

The economic potential of solar energy $EG_{Economic}$ t in the surveyed area each year is determined using Equation (3.3). The payback period for the solar energy system is calculated using the following formula (3.6):

$$EG_{Economic} = P_{PV} \times T_{year} \times \eta_{sys} \quad (3.3)$$

$$P_t = T - 1 + \frac{|CNCF_{T-1}|}{NCF_T} \quad (3.6)$$

Với P_t: Payback period, the time required to recover the total initial investment. T: The year when the transition occurs from a negative cumulative net cash flow to a positive CNCF. $CNCF_{T-1}$:

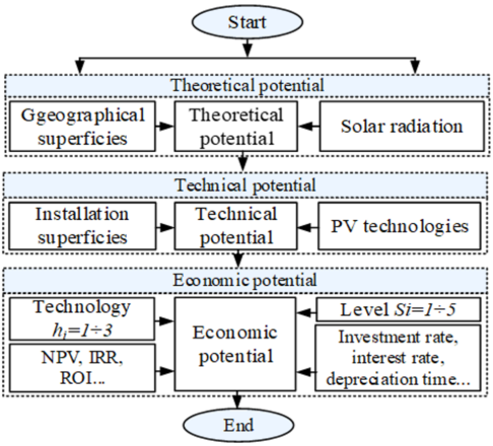


Figure 3.3. Feasibility flowchart dedicated to calculating PV potential

The cumulative net cash flow in the year $T-1$, $CNCF_{T-1}$ determined by equation (3.7) [56]:

$$CNCF_{T-1} = \sum_{t=1}^{T-1} NCF_t \tag{3.7}$$

The net present value (NPV) is calculated using equation (3.8) [56]:

$$NPV = \sum_{t=0}^{N} (CI_t - CO_t) \times (1+i)^{-t} \tag{3.8}$$

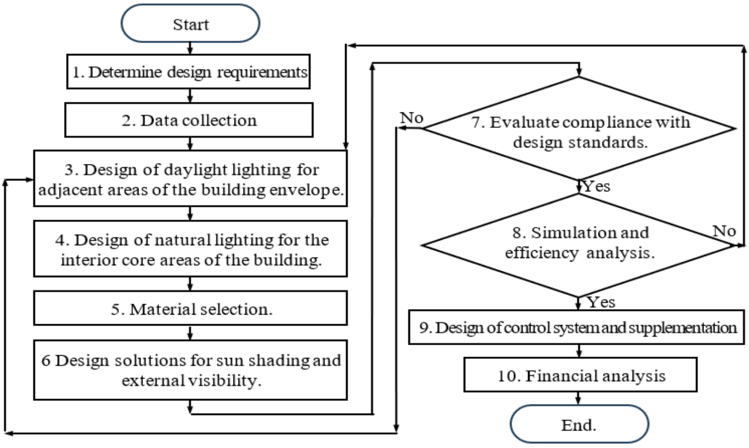
The internal rate of return (IRR) is determined using equation (3.9) [56]:

$$IRR = i_2 + (i_3 - i_2) \times \frac{NPV_2}{NPV_2 + |NPV_3|_2} \tag{3.9}$$

- **Energy - Saving solutions for architectural lighting**

Energy-saving solutions for architectural lighting focus on enhancing natural daylight and optimizing daylighting design. The design process utilizes simulation software such as Dialux and Relux to minimize artificial lighting while ensuring energy efficiency and spatial quality. Elements such as Low-E glass, sun-shading systems, sloped ceilings, and horizontal windows are employed to optimize natural light utilization, enhance reflectance through light-colored surfaces, and reduce glare through domed roofs.

The calculation of the Daylight Factor (DF) and the Window-to-Wall Ratio (WWR) helps determine the adequacy of natural lighting. Financial evaluation based on metrics such as Net Present Value (NPV) and Internal Rate of Return (IRR) ensures the feasibility of energy-saving projects. The daylighting design flowchart is illustrated in Figure 3.4.



Hình 3.4. Lưu đồ thiết kế chiếu sáng ban ngày

- **Solution for modifying the operation of existing diesel - wind power systems on islands**

Although islands possess significant wind power potential, the current utilization efficiency remains low. To optimize operations, the thesis introduces an operational algorithm based on the segmentation of electrical loads and wind speeds. Load segmentation is performed using the K_{max}-K_{min} algorithm combined with an expert system. If load segmentation is successful, wind speed segmentation follows to meet demand. The calculation process identifies the optimal operational strategy with the lowest diesel cost, including load data simulation and determining the capacity of wind turbines and diesel generators. Load segmentation plays a critical role in the planning and operation of power systems. The algorithm flowchart is illustrated in Figure 3.8.

The objective function for operating the diesel-wind generation system is to optimize the total generation cost over the years, as described in Equation (3.14) [65]

$$O_{D,W} = \sum_{g_{D,W},q,t,y} W_y \times CE_{g_{D,W},y} \times X_{g_{D,W},q,t,y} \rightarrow \min \quad (3.14)$$

Với $g_{D,W}$: là loại hình phát điện gió hoặc diesel. q: tháng trong năm. t: là thời gian (giờ). y: là năm thực hiện nghiên cứu. $CE_{g_{D,W},y}$: là chi phí phát điện của nhà máy điện $g_{D,W}$. $X_{g_{D,W},q,t,y}$: là công suất phát tối ưu về chi phí của nhà máy sử dụng nguồn phát $g_{D,W}$ (MWh). W_y là hệ số quy đổi thời giá.

The constraints associated with the objective function include: constraints on the power capacity and output of generation sources, power balance, reserve capacity, power factor, the range of power generation variation between consecutive hours, the maximum hourly power generation of solar energy, and the limits on the discharge and charge capacities of the energy storage system.

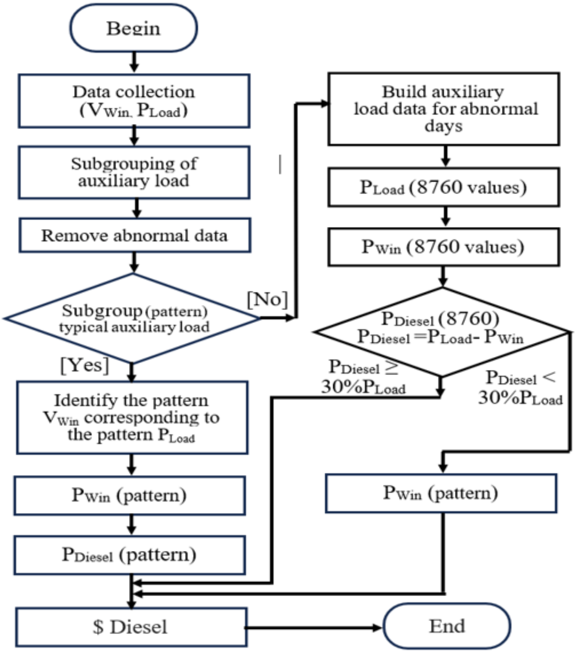


Figure 3.8. Algorithm flowchart for diesel-wind power system operation

- **Biomass power generation solution from household waste (MSW)**

The thesis proposes using inorganic MSW as a biomass fuel for power generation, reducing waste accumulation, and optimizing recycling. The block diagram illustrating the feasibility of power generation from household waste is shown in Figure 3.12.

The daily volume of municipal solid waste generated is determined by [70]:

$$M_T = \frac{P_y \times wc_y}{365} \quad (3.25)$$

M_T: The mass of municipal solid waste generated per day (tons/day), wc_y: The per capita municipal solid waste index in year y (kg/person/day). P_y: The urban population in year y (people).

For tourists visiting islands in Vietnam that are just beginning to develop as tourist destinations (e.g., Phú Quý), the average stay per visitor is 4 days. When determining the waste generated with the participation of tourists P_y is replaced by $P_{y\Sigma}$, where $P_{y\Sigma} = P_y + P_{T,y}$.

With $P_{y\Sigma}$: representing the urban population in year y, adjusted for the tourist population, and $P_{T,y}$: representing the estimated number of tourists in year y.

The useful heat required to rotate the steam turbine is calculated by the formula (3.31):

$$Q_{inc} = b \times HHV \times \frac{(100-e)}{100} \quad (3.31)$$

With e: Total heat loss percentage (%), b: Dry mass of the input material (lb/h), HHV: High heating value (Btu/lb).

The annual potential electricity production is determined as follows [70], [98]:

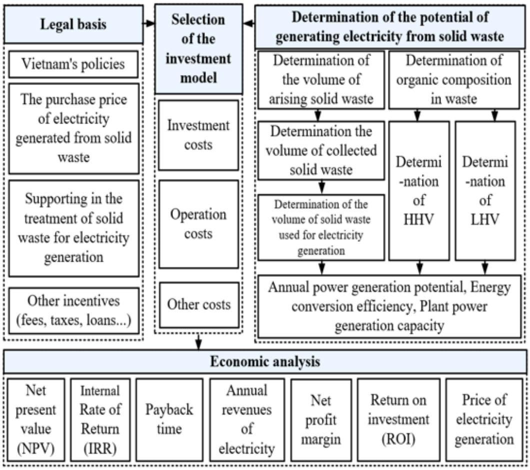


Figure 3.12 Block diagram for the feasibility study of electricity generation from municipal waste.

$$E_{P(INC)} = \frac{Q_{inc} \times \eta \times 8760}{3412{,}14} \quad (3.40)$$

With i $E_{P(INC)}$: Annual potential electricity output (kWh/năm), Q_{inc}: Annual input useful heat (Btu/giờ).

The power output of the plant is determined by (3.41):

$$G_{P(INC)} = \frac{E_{P(INC)}}{8760 \times CF} \quad (3.41)$$

With $G_{P(INC)}$: Nominal power output of the plant (MW), $E_{P(INC)}$: Actual annual electricity output (MWh).CF: Capacity factor [98].

The investment cost of the plant is determined by (3.42) [100]:

$$C_{inv} = 4900 \times (M_F)^{0,8} \times Q \times R \times S \quad (3.42)$$

With Q, R, S: Cost adjustment factors.

The operating cost is determined by (3.43) [100]:

$$C_{O\&M} = 700 \times (M_F)^{-0,29} \times Q \times R \times S \quad (3.43)$$

The annual revenue from electricity sales and waste processing subsidies is (3.44):

$$Rev = E_P \times F_d \quad (3.44)$$

With Rev: Annual revenue (USD), E_P: Electricity output (kWh/năm). F_d: Electricity price (USD/kWh).

The Levelized Cost of Electricity (LCOE) is calculated by (3.46) [70]:

$$LCOE = \frac{LCC \times CRF}{E_P} \quad (3.46)$$

With LCC: Life cycle cost of the project (USD), CRF: Capital recovery factor,, E_P: Total electricity produced over the project's lifetime (kWh).

The payback period, net present value (NPV), and internal rate of return (IRR) are determined in the same way as for the rooftop solar power system when analyzing the economic and technical efficiency.

- **Solution to reduce CO_2 emissions by gradually replacing fossil fuel vehicles with electric vehicles**

The thesis calculates the potential reduction in CO_2 emissions by replacing fossil fuel vehicles with electric vehicles, based on population data, GDP, and the number of motor vehicles. The block diagram illustrating the potential CO_2 reduction when applying electric vehicles is shown in Figure 3.13.

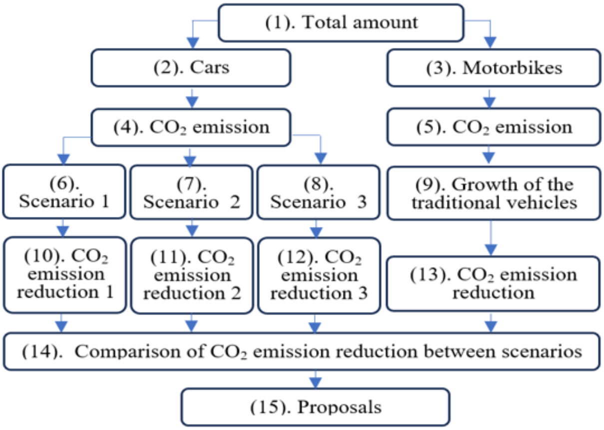


Figure 3.13. Block diagram illustrating the CO_2 reduction potential by introducing electric vehicles.

The study proposes three scenarios for the development of electric vehicles:

- Low-level Scenario (Scenario 1): The market share of electric vehicles, taxis, and buses reaches 5%, with a total market penetration of 7% due to operating costs and subsidy policies.

- High-level Scenario (Scenario 2): The market share of electric vehicles, taxis, and buses reaches 10%, with market penetration of 12%.

- Super High-level Scenario (Scenario 3): The market share of electric vehicles, taxis, and buses reaches 15%, with market penetration of 20%.

Forecast growth for electric motorcycles, according to the Asian Development Bank's research, shows that in the reference scenario, electric motorcycles will capture 40% of the market by 2050, while in the low-emission scenario, electric motorcycles will account for 90% of the market by 2050.

The thesis uses the Bass model to model the technology diffusion as shown in Equation (3.22):

$$\frac{dF(t)}{dt} = [p + qF(t)] \times [1 - F(t)] \quad (3.22)$$

With $F(t)$: the cumulative proportion of customers who have adopted the product at time t. The solution to equation (3.22) is as follows. Assuming no customers have adopted the product at time $t = 0$, $F(0) = 0$, the equation is restated as equation (3.23) (Bass 1969):

$$F(t) = \frac{1-exp(-(p+q)t)}{1+\frac{q}{p}exp(-(p+q)t)} \quad (3.23)$$

The CO_2 emissions from traditional vehicles are calculated using equation (3.24) [82]:

$$CE = L \times FC \times CE_{fuel} \quad (3.24)$$

With CE: CO_2 emissions from traditional vehicles (kCO_2). L: Distance traveled by the vehicle (km). FC: Fuel consumption of the vehicle (l/km). CE_{fuel}: CO_2 emissions of the fuel (kCO_2/l).

The CO_2 emissions of the fue CE_{fuel} are determined by equatio (3.25):

$$CE_{fuel} = D \times E \times CF \times 10^{-3} \quad (3.25)$$

With D: Fuel density (kg/l). E: Net calorific value (GJ/t). CF: Default CO_2 emission factor (tCO_2/TJ).

Although electric vehicles do not emit CO_2 directly during operation, there are still indirect emissions from the electricity generation and supply system. These CO_2 emissions are calculated by equation (3.26) [83]:

$$EF = L \times EG \times FE_{Grid} \tag{3.26}$$

With EF: CO_2 emissions from the electric vehicle (kCO_2). EG: Electricity consumption of the vehicle per km, depending on the vehicle type (kWh/km). FE_{Grid}: CO_2 emission factor of the power grid (kCO_2/kWh).

The CO_2 reduction ΔE when transitioning from a traditional vehicle to an electric vehicle is determined by equation (3.27):

$$\Delta E = CE - EF \tag{3.27}$$

With CE: CO_2 emissions from the traditional vehicle (kCO_2). EF: CO_2 emissions from the electric vehicle (kCO_2).

3.2. Optimal power generation structure for islands using the energy model

The thesis proposes a block diagram to determine the optimal power generation structure for applying the Energy Model to islands, as presented in detail in Figure 3.14.

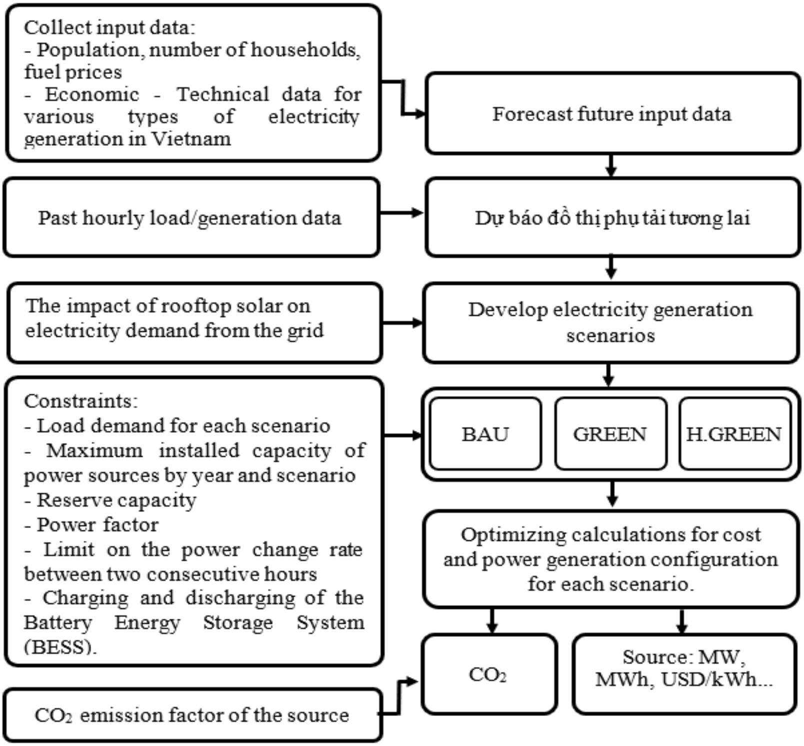


Figure 3.14. Block Diagram for Researching the Optimal Power Generation Structure for Islands

3.2.1. Development of power generation scenarios for islands

The thesis proposes three power generation scenarios for the island:

- BAU Scenario (Business As Usual): The p ower system continues to maintain the growth of renewable energy sources such as wind and solar power. An energy storage system (BESS) will be integrated from 2030 to meet the demand load.

- GREEN Scenario: By 2025, the current power plants will still be dominant. From 2030, renewable energy sources (RE) will gradually replace diesel, while rooftop solar energy from households will help relieve the grid load.

- HIGHER GREEN Scenario: Starting from 2030, diesel will be completely phased out and replaced by renewable energy sources (RE) and BESS. There will be significant growth in rooftop solar power.

3.2.2. Forecasting social indicators

Population and household estimations: In the thesis, the population and number of households on the island are estimated based on recent local statistical data, using a growth trend curve to forecast future population and household numbers. Forecast of diesel prices: Diesel prices in the study are adjusted according to the island's purchasing power and forecasts from the EIA for the 2025-2040 period.

Table 3.6. Forecast of Oil Prices for 2025-2040 and Purchasing Power Parity Conversion

Year	2025	2030	2035	2040
Forecast oil price (USD/b)	67	74	79	84
Oil price equivalent to purchasing power (USD/b)	71.08	91.01	112.64	138.84

According to the Vietnam Power Master Plan VIII, diesel will no longer be part of the national power system. However, due to the continuous 24/7 load demand on islands, diesel power generation may still be utilized. In future scenarios, the thesis leaves the possibility of diesel growth open, with the growth rate determined through optimization calculations to meet load requirements.

3.2.3. Economic and technical data for power plants

Diesel power plant: Parameters such as installed capacity, lifetime, investment costs, operational, and maintenance costs need to be collected from manufacturer reports, energy consultancy organizations, national energy agencies, and the "Vietnam Technology Handbook 2021." This data supports cost optimization, operational efficiency, and sustainability evaluation based on real-world data and energy scenarios.

Wind power plant: Technical and economic parameters affecting optimal costs and development potential. Investment costs for wind power have decreased thanks to improved technology, although interest rates, materials, and construction costs have risen. The study uses an investment rate of $1,875 USD/MW before 2020, with a 5% annual increase, based on local data, energy scenarios, and the "Vietnam Technology Handbook 2021."

Solar power: There are two main development directions: rooftop systems and solar power plants. The investment cost for solar power has decreased from 1,200 USD/kW (2018) to below 900 USD/kW (2025), but other cost factors tend to increase. The economic-technical data is based on local real-world data and the "Vietnam Technology Handbook 2021."

Biomass power plant: Socio-economic development has led to increased pressure on solid waste management (SWM), negatively impacting the environment and public health. Biomass power plants reuse SWM, helping address pollution issues and promoting sustainable development. Necessary technical parameters include population size, the potential increase in waste, and real-world local data. The study is based on the "Vietnam Technology Handbook 2021," ensuring detailed and reliable information.

Battery energy storage system (BESS): Local authorities and the Vietnam Electricity Group (EVN) have implemented policies to enhance the use of renewable energy and reduce fossil energy consumption. The goal is to store surplus energy from renewable sources in BESS and supply electricity when needed, helping stabilize the system.

The C-rate in BESS is the charging or discharging speed of the battery relative to its nominal capacity. A high C-rate is suitable for applications that require a quick response, such as grid stabilization, while a low C-rate is used for long-term applications like peak load shaving. The Depth of Discharge (DOD) indicates the portion of energy used compared to the battery's capacity, with a high DOD providing more energy but reducing the battery's lifespan. To maintain battery life, the DOD should be kept between 60% - 80%.

Zihang Qiu's research shows that the relationship between C-rate and the number of cycles consumed affects performance and energy loss. A low C-rate helps reduce cycle loss but is not suitable for fast operation requirements. A C-rate of 0.5 C is chosen as the binding level in the thesis. The economic-technical data is determined based on the "Vietnam Technology Handbook 2021."

3.2.4. Load demand forecast

The forecast of electricity demand for islands is based on historical consumption data, population growth, economic development, consumption structure, power generation policies, and renewable energy targets. The study utilizes the average power generation over the past five years, the average demand growth rate, and local characteristics to forecast load demand for 2025, 2030, 2035, and 2040.

3.2.5. Impact of rooftop solar power on grid electricity demand

In the future, the increase in electricity prices, combined with policies encouraging the development of rooftop solar power, will strongly promote renewable energy, especially at the household level. This not only helps reduce grid electricity consumption but also limits the need to expand the island's power system capacity. However, forecasting rooftop solar power growth faces challenges due to a lack of detailed data on roof area.

To address this, the study makes the following assumptions: (1) Each household on the island has the potential to install up to 3 kWp of rooftop solar power. (2) The maximum penetration rate of rooftop solar power in the BAU scenario is 0%. (3) In the GREEN scenario, this rate reaches 5%, 7%, and 10% in 2030, 2035, and 2040, respectively. (4) In the HIGHER GREEN scenario, the penetration rate increases to 10%, 15%, and 20% for the same timeframes.

To calculate the output capacity of the rooftop solar power system for future years, the following formula is applied (3.58):

$$P_{PV} = Y_{PV} \times f_{PV} \times \left(\frac{G_T}{G_{T,STC}}\right) \quad (3.58)$$

P_{PV}: Output capacity of the rooftop solar power system (kWp). Y_{PV}: Designed capacity (kW). f_{PV}: Degradation factor of the photovoltaic panel (%). G_T: Solar radiation incident on the photovoltaic panel (kW/m^2). $G_{T,STC}$: Solar radiation under standard test conditions (1 kW/m^2).

The development of rooftop solar power modifies the load curve, reducing daytime electricity demand (06:00 - 18:00) unevenly across hours. Hourly load demand is calculated using the following formula (3.59):

$$D'_{i,y} = D_{i,y} - Psr_{i,y} \quad (3.59)$$

Với $D'_{i,y}$: The reduced load demand (kWh). $D_{i,y}$: The future load demand (kWh). $Psr_{i,y}$: The output capacity of rooftop solar power.

Figure 3.20 provides an illustrative example of the new load curve created by the combination of the load curve and the penetration level of rooftop solar power.

Figure 3.20. Load demand and PV rooftop generation production

3.2.6. Objective function

The objective function for optimizing the power generation structure is to minimize the total generation cost over the years 2025, 2030, 2035, and 2040, represented by equation (3.60) [65]:

$$\sum costs = \sum_{\text{g,q,t,y}} W_y \times CE_{g,y} \times X_{g,q,t,y} \rightarrow \min \quad (3.60)$$

Với W_y: Discount factor. $CE_{g,y}$: Generation cost of power plant g in year y (USD/MWh). $X_{g,q,t,y}$: Optimized power output from source g for load type q at time t in year y (MWh). g: Type of power generation. q: Month of the year (1 to 12). t: Hour of the day (1:00 - 24:00). y: Year of calculation (2025, 2030, 2035, and 2040).

3.2.7. Constraints of the objective function

The constraints of the objective function are a combination of the constraints in the optimization problem, including: (1) constraints on the capacity and output of generation sources; (2) operational constraints such as power balance, reserve power, power factor, the range of power output variation between two consecutive hours, maximum hourly solar power generation, and charge/discharge capacity limits of the storage system:

The power balance equation is expressed as (3.63) [65]:

$$\sum_g X_{g,q,t,y} = P_{q,t,y} \quad (3.63)$$

Với $X_{g,q,t,y}$: Power output of plant g at time t in year y (MW). $P_{q,t,y}$: Power load demand for load type q at time t in year y.

Maximum installed capacity constraint (3.64) [65]:

$$C_{g,y} \leq C_{max,g,y} \quad (3.64)$$

Với $C_{g,y}$: Installed capacity of generation type g in year y (MW). $C_{max,g,y}$: Maximum installed capacity of generation type g in year y (MW). g: Generation type. y: Year under consideration.

Reserve power constraint (3.65) [65]:

$$\sum C_{g,y} \geq (1 + \propto_y) \times P_{max,y} \quad (3.65)$$

Với $\sum C_{g,y}$: Total installed capacity of the entire power generation system in year y (MW). $P_{max,y}$: Maximum load demand in year y (MW). $\propto_y$: Reserve power coefficient for year y.

Power Factor Constraint (3.66) [65]:

$$\sum_t X_{g,q,t,y} \leq 24 \times L_{g,q} \times C_{g,y} \quad (3.66)$$

Với $\sum_t X_{g,q,t,y}$: Total daily actual power output of plant g (MWh). $C_{g,y}$: Installed capacity of plant g in year y (MW). $L_{g,q}$: Load factor of power plant g according to load type q, ($L_{g,q} = 0 \div 1$).

Power output variation limit between two consecutive hours (3.67) [65]:

$$\left(1-\rho_g\right) \times X_{g,q,t,y} \leq X_{g,q,t,y} \leq \left(1+\rho_g\right) \times X_{g,q,t-1,y} \quad (3.67)$$

Với ρ_g: Permissible power output variation limit between two consecutive hours for power plant g. $X_{g,q,t,y}$: Actual power output of plant g for load type q at time t in year y (kWh). $X_{g,q,t-1,y}$: Actual power output at time $t-1$ for the same load type q in year y (kWh).

For wind and solar power plants, the specific power generation per hour and per month has already been calculated; therefore, the hourly variation limit can be omitted. For diesel and biomass plants, the permissible power output variation is set at 20% per hour.

Maximum hourly wind power output constraint (3.68):

$$C_{wind,t} \leq k \times C_{\max wind,t} \quad (3.68)$$

Với $C_{wind,t}$: Actual wind power output at time t (MW). $C_{\max wind,t}$: Maximum installed capacity of wind turbines at time t (MW). k: Hourly wind power coefficient, $k \leq 1$.

Maximum hourly solar power output constraint (3.70):

$$C_{solar,t} \leq m \times C_{max\ solar,t} \quad (3.70)$$

Với m: Solar power availability factor, $m \leq 1$. $C_{solar,t}$: Actual solar power output at time t (MW). $C_{max\ solar,t}$: Maximum installed capacity of the solar system at time t (MW).

Battery energy storage system (BESS) constraints:

$$C_{bess\ discharge,t} \leq \mu \times C_{bess\ max} \quad (3.71)$$

$$C_{bess\ charge,t} \leq \mu \times C_{bess\ max} \quad (3.72)$$

Với $C_{bess\ discharge,t}$: BESS discharge capacity at time t (MWh). $C_{bess\ charge,t}$: BESS charge capacity at time t (MWh). $C_{bess\ max}$: Maximum capacity of the BESS (MWh). μ: Maximum hourly charge/discharge coefficient.

Mutual exclusivity.

$$C_{bess\ discharge,t} > 0\ ;\ C_{bess\ charge,t} = 0 \quad (3.73)$$

$$C_{bess\ charge,t} > 0\ ;\ C_{bess\ discharge,t} = 0 \quad (3.74)$$

Total discharge capacity:

$$\sum C_{bess\ discharge,t} \leq \gamma \times C_{bess\ max} \quad (3.75)$$

Where γ: Adjustment coefficient for maximum BESS discharge.

Total charge capacity (3.76):

$$\sum C_{bess\ charge,t} \leq C_{bess\ max} \quad (3.76)$$

3.2.8. Installed capacity limits of generation sources

- Wind power: Dependent on wind speed, exploitation potential, technical infrastructure, and energy policy. No feasible projects are expected by 2025, with future capacity dependent on location, technical, environmental, and land planning analysis.

- Solar power: Similar to wind power, no new solar projects are expected by 2025. Post-2025 growth will depend on land availability, with up to 1% of island land area utilized by 2040.

- System reserve power: Required for emergencies or renewable power shortfalls, with reserve capacity assumed as follows: Bau scenario: 10%; GREEN scenario: 15%; HIGHER GREEN scenario: 20%

3.2.9. Optimization tool

The study proposes using the LINDO software for cost optimization of power generation structures. Developed by LINDO Systems, Inc. since 1981, this tool efficiently solves linear and nonlinear problems in various sectors, including energy. The study employs the Branch and Bound algorithm to minimize total costs.

3.2.10. CO_2 emissions

To calculate CO_2 emissions based on the generation mix, emission factors are used as shown in Table 3.7**.**

Table 3.7. CO_2 emission factors for power generation types in Vietnam.

Generation Type	Diesel	Biomass	Wind	Solar
CO_2 Emission (g-CO_2/kWh)	763.6	20	11.7	40

Total CO_2 emissions are calculated as

$$CE_{gy} = \sum_g \sum_t X_{g,y} \times EG_{gCO_2} \qquad (3.77)$$

CE_{gy}: CO_2 emissions of the system (g-CO_2). $\sum_t X_{g,y}$: Actual power output based on the optimal generation structure (kWh). EG_{gCO_2} : CO_2 emission factor of generation type g (g-CO_2/kWh).

CHAPTER 4
FEASIBILITY OF ENERGY-EFFICIENT SOLUTIONS AND OPTIMAL POWER GENERATION STRUCTURES FOR PHÚ QUỐC AND PHÚ QUÝ ISLANDS, VIETNAM

4.1. Energy - efficient solutions for islands

4.1.1. Feasibility study on electricity generation from solid waste on Phú Quốc island (2020 - 2030)

The dissertation examines the potential for electricity generation from solid waste on Phú Quốc Island, a solution that helps reduce pollution while supplying electricity to the island's grid. Calculations reveal that Phú Quốc could generate electricity from solid waste with a capacity ranging from 4.7 MW to 7.0 MW during the 2020–2030 period, with electricity production costs estimated between 6.4 and 5.3 cents/kWh.

The project requires an estimated investment of 34.1 million USD, with a construction duration of 2 years and an operational lifespan of 23 years. Financial indicators, such as a return on investment (ROI) of 18.9% and 14.9%, demonstrate the economic feasibility of the project.

The project is expected to benefit from substantial incentives during its development and operational phases. The results indicate that the net present value (NPV) of the project reaches 5.1 million USD at a discount rate of 7%, with an internal rate of return (IRR) of 10.5% and a payback period of 13.01 years.

4.1.2. Feasibility study of rooftop solar power systems on Phú Quốc island by 2030

The dissertation examines the potential of solar power on Phú Quốc Island, based on its geographical location, solar radiation levels, land area, and infrastructure planning, using a top-down approach aimed at the year 2030. The installation area for photovoltaic (PV) systems was determined based on land-use planning, construction density, and suitable rooftop areas.

The study compares three popular solar panel technologies in Vietnam, evaluating the economic and technical performance of PV systems ranging from 3 kWp to 300 kWp using metrics such as investment cost, payback period, internal rate of return (IRR), and net present value (NPV).

Three scenarios for rooftop solar development by 2030 were analyzed. Scenario 1 achieves a capacity of 805 MWp, generating 304,499 MWh/year and reducing 193,844 tons of CO_2 annually. Scenario 2 expands to 1,219 MWp, a 51.4% increase, producing 460,709 MWh/year (51.2% increase) and reducing 293,287 tons of CO_2/year (51.2% reduction). Scenario 3 maximizes capacity at 1,930 MWp, a 139.5% increase, generating 729,615 MWh/year (139.8% increase) and reducing 464,473 tons of CO_2/year (139.2% reduction).

Scenario 3 is the most optimal in terms of economic and environmental effectiveness but requires substantial investment. Scenario 2 offers a balanced approach, suitable for the current conditions of Phú Quốc. Scenario 1 is easier to implement but provides lower economic and environmental benefits. The choice of scenario depends on the availability of funding and supportive renewable energy policies.

4.1.3. CO_2 emission reduction calculation from the introduction of electric vehicles in Phú Quốc

The thesis examines the deployment of electric vehicles in Phú Quốc to reduce CO_2 emissions, improve air quality, and build a green tourism image. With the development of renewable energy infrastructure, Phú Quốc aims to become a smart city, integrating electric vehicles into its transportation system.

The study assumes the growth rate of transportation vehicles and estimates the CO_2 emissions of traditional vehicles. Vehicles such as motorcycles, buses, and 4-seat and 7-seat cars have significant CO_2 emissions, with motorcycles emitting 0.0505 kg/km and 4-seat cars emitting 0.1838 kg/km. Compared to traditional vehicles, electric vehicles, with their lower electricity consumption, have the potential to significantly reduce CO_2 emissions.

Three scenarios for the development of electric vehicles in Phú Quốc by 2030 were studied, considering the growth of different types of electric vehicles such as buses, 4-seat cars, 7-seat cars, and taxis. The forecast results indicate that the deployment of electric vehicles could reduce CO_2 emissions by approximately 17-21% compared to traditional vehicles.

Additionally, the study proposes a policy framework to support electric vehicles, including exemptions from import taxes, special consumption taxes, and incentives for both customers and electric vehicle manufacturers, aiming to facilitate the development of electric vehicles, similar to advanced countries.

4.1.4. New operating method for the existing diesel-wind power system in Phú Quý

Improving the operation method of the diesel-wind power system on Phú Quý Island is essential to reduce fuel costs, decrease CO_2 emissions, protect the environment, enhance energy security, and optimize the use of renewable resources. Phú Quý Island has significant wind energy potential, with an average wind speed exceeding 9 m/s, while the existing diesel power system has a capacity of 4.5 MW, and the wind power capacity is 6 MW. The island's electricity demand is increasing, but the wind power generation is not proportional to the wind speed, indicating the system's inefficiency.

The research aims to propose a new operating method focused on reducing diesel costs by maximizing wind power capacity and ensuring system stability. The study employs the Kmax - Kmin algorithm combined with an expert system to classify loads and wind speeds, then determine the optimal operating strategy.

The results show that the new method increases wind power generation by 81.69%, reduces diesel power consumption by 31.23%, saves nearly 1.07 million liters of fuel, reduces CO_2 emissions by 3,376 tons, and saves 17.79 billion VND. If 70% of the effectiveness is achieved, it could save 12.5 billion VND annually.

4.1.5. Design for utilizing natural lighting in a building

The design focuses on utilizing natural light for a building with dimensions of 80m x 32m x 14m, consisting of one floor. The building is multifunctional, incorporating office spaces, a small mechanical workshop, and commercial service areas.

The project collects data related to both natural and artificial lighting design for the building, including factors such as orientation, coordinates, light-transmitting materials, and electrical equipment specifications. The building's façade faces north, with the highest solar radiation intensity in the morning on the east and southeast sides, gradually decreasing towards the evening. Architectural drawings and visual renderings of the structure were simulated in DIALux Evo software to calculate both natural and artificial lighting. The building uses double-glazed Low-E glass for windows and doors to optimize natural light. Optical and motion sensors are installed to adjust lighting levels. Daylight lighting designs for office and production areas are integrated with artificial lighting systems, adjusted according to natural light intensity. Energy-saving sensors are in place to reduce power consumption when areas are unoccupied.

Lighting simulations show that the building receives good natural light in the morning, with illuminance levels ranging from 300 lux to 1000 lux. Financial analysis indicates that the investment cost for the natural lighting system and related equipment increases by approximately 7%, but it significantly reduces electricity consumption and saves costs.

Key results are as follows: a 34% reduction in energy consumption; savings of approximately 1.56 tons of CO_2/m^2/year; and a payback period of just over 9 months.

4.2. Optimal power generation structure for Phú Quý island, Vietnam

4.2.1. Development of three power generation scenarios for Phú Quý island

- BAU scenario: The Phú Quý power system maintains diesel and wind power as the primary sources. The increase in renewable energy sources (RES) such as wind and solar power depends on land availability and power density. Battery Energy Storage Systems (BESS) will be integrated starting in 2030 to meet load demand.
- GREEN scenario: Growth in renewable energy sources replaces diesel power plants reaching their end-of-life. Rooftop solar power from households and biomass energy, starting from 2030, will support the reduction of load demand.
- HIGHER GREEN scenario: This scenario aims to minimize reliance on and completely replace diesel with wind, solar, BESS, and biomass energy by 2030, along with an increase in rooftop solar installations to further reduce load demand.

4.2.2. Forecasting Phú Quý's social indicators

The population of Phú Quý grew nearly linearly from 2015 to 2021. Forecasting the number of households encounters difficulties due to inconsistent and conflicting data sources. This study assumes the historical population data and a constant household size of 4.18 persons per household for future projections. Based on the theoretical foundation of linear regression in statistical data analysis and using the "Add Trendline" tool in Excel, the mathematical representation of the population growth trend line on Phú Quý Island is expressed as follows:

$$P_y = 131{,}07x + 26302 \tag{4.1}$$

Where P_y: is the population in the forecast year (persons), and xxx: is the order of the forecast year.

Based on Equation (4.1), the future population and the number of households on Phú Quý Island are calculated and projected. The results are presented in Table 4.29.

Fuel prices for the proposed power generation scenarios in Phú Quý mainly depend on diesel prices, as wind power, solar power, and energy generated from waste incur no fuel costs. Forecasts for diesel prices from 2025 to 2040, adjusted for purchasing power parity, are presented in Chapter 3.

Table 4.29. Population and Household Forecast for Phú Quý Island

Year	2025	2030	2035	2040
Population (persons)	27,744	28,399	29,054	29,710
Households (units)	6,631	6,788	6,944	7,101

4.2.3. Economic indicators of power plants in Phú Quý

Due to the unique characteristics of Phú Quý Island, diesel power generation is maintained to ensure a continuous 24/7 electricity supply. The existing diesel power plant has an installed capacity of 9.7 MW, and its economic and technical parameters, based on the BAU, GREEN, and HIGHER GREEN scenarios, are gathered from the "Vietnam Technology Handbook 2021" [90] and presented in Table 4.30.

Table 4.30. Economic and technical indicators of the diesel power plant.

Description	Current	2030	2035	2040
Existing installed capacity (MW)	9.7	≤ 9.7	≤ 7.0	≤ 7.0
Future installed capacity limit (MW) (*)		≥ 0	≥ 0	≥ 0
Technical lifespan (years)	25			
Financial data				
Nominal investment (million USD/MW)	0.60			
Fixed O&M costs (USD/MW/year)	19,000	20,500	22,000	23,500
Variable O&M costs (USD/MWh)	500			

(*) This parameter indicates diesel plants to be installed in the future to serve as reserve capacity in cases where all power generation sources are dispatched but remain insufficient to meet demand.

- **Wind Power Plant**

Based on the existing 6 MW wind power system and the BAU, GREEN, and HIGHER GREEN scenarios, along with the "Vietnam Technology Handbook 2021" [90], the economic and technical indicators of the Phú Quý wind power plant are presented in Table 4.31.

Table 4.31. Economic and technical indicators of the Phú Quý wind power plant

Description	Current	2030	2035	2040
Existing installed capacity (MW)	6.0	6.0	6.0	6.0
Technical lifespan (years)	35			
Financial data				
Nominal investment (million USD/MW)	1,875	3,054	3,897	4,975
Fixed O&M costs (USD/MW/year)	42,000			
Variable O&M costs (USD/MWh)	3.5			

- **Solar Power**

Table 4.32. Economic indicators of the Phú Quý solar power plant.

Description	Hiện tại	2030	2035	2040
Installed capacity (MW)	0.732	0.732	0.732	0.732
Technical lifetime (years)	30			
Financial Data				
Nominal investment (million USD/MW)	976.5	1,590	2,030	2,591
Fixed O&M costs (USD/MW/year)	13.85			

Phú Quý island possesses significant solar energy potential due to its high sunshine hours and radiation levels; however, only about 732 kWp has been utilized as of 2024. In this study, the economic and technical parameters of the solar power plant on Phú Quý Island were collected from the existing plant and analyzed based on the BAU, GREEN, and HIGHER GREEN scenarios, as well as data from the "Vietnam Technology Handbook 2021" [90]. The economic indicators of the Phú Quý solar power plant are detailed in Table 4.32.

- **Biomass Power Plant**

Phú Quý Island exhibits a high rate of solid waste generation, with an estimated waste generation of 2 kg per person per day by 2030, increasing by 0.2 kg every 5 years, reaching 2.4 kg per day by 2040. Additionally, tourists contribute to the waste volume, with an average stay of 4 days. This study analyzes the potential of utilizing solid waste as a feedstock for power generation. The economic and technical indicators of a waste-fueled power plant, collected from real-world data and the "Vietnam Technology Handbook 2021" [90], are presented in Table 4.33.

Table 4.33. Economic and Technical Indicators of the Solid Waste-Fueled Power Plant.

Data	Unit	2030	2035	2040
Population	People	28,399	29,054	29,710
Tourist volume	Visits	74,000	121,692	200,119
Daily solid waste volume	Tons	58	66	75
Solid waste processed for power	Tons/year	16,240	16,787	19,245
Energy conversion efficiency (*)	kWh/ton		341	
Installed capacity	kW	791	900	1.023
Annual electricity generation potential	MWh	5,537	6,296	7,159
Investment cost (*)	USD/kW		1,000	
Operation & maintenance cost (*)	USD/kW/year		29	
Technical lifetime	Years		23	

(*) Data from the "Vietnam Technology Handbook 2021" [90].

- **Energy Storage System (BESS)**

Table 4.34. Economic and Technical Indicators of the BESS System [130].

Description	2030	2035	2040
Technical lifespan (years)		8	
Financial Data			
Nominal investment (million USD/MW)	140	120	100
Fixed O&M costs (USD/MW/year)		0.311	

The integration of a Battery Energy Storage System (BESS) is crucial for balancing the intermittent nature of renewable energy sources such as solar and wind. The economic and technical indicators of the BESS system, based on scenarios and the "Vietnam Technology Handbook 2021" [90], are summarized in Table 4.34.

4.2.4. Electricity demand forecast for Phú Quý island

Phú Quý Island primarily relies on small-scale fisheries and tourism, with accommodations including mini-hotels and homestays. Despite the modest scale of its economy, electricity demand is projected to grow at a stable rate of 9% annually due to increasing tourism and local development. The forecasted electricity demand is shown in Table 4.36.

Table 4.36. Electricity Demand Forecast for Phú Quý Island.

Year	2025	2030	2035	2040
Electricity Demand (MWh/year)	33,596	51,704	79,540	122,372
Peak Load (P_{max}, MW)	6.843	10.531	16.201	24.925

4.2.5. Impact of rooftop solar power on grid demand

When electricity prices increase and policies promoting the development of rooftop solar power are strongly implemented, the installation of such systems becomes attractive to households, enabling them to meet self-consumption needs. This will drive the growth of rooftop solar power, reduce dependence on the main grid, and avoid increasing the power capacity of the Phú Quý Island system. The forecasted rooftop solar penetration rates are shown in Table 4.37, assuming that each household can install up to 3 kWp..

Table 4.37. Rooftop solar penetration rates by scenario.

Year	2030	2035	2040
BAU Scenario	0%	0%	0%
GREEN Scenario	5%	7%	10%
HIGHER GREEN Scenario	10%	15%	20%

Table 4.38. Forecasted rooftop solar installed capacity for Phú Quý.

Year	Number of households	Maximum installed rooftop solar capacity (kWp)	Installed rooftop solar capacity by scenario (kWp)	
			GREEN	HIGHER GREEN
2025	6,631	19,893	398	796
2030	6,788	20,364	1,018	2,036
2035	6,944	20,832	1,458	3,125
2040	7,101	21,303	2,130	4,261

After calculating the electricity demand and hourly rooftop solar generation capacity for the years 2025, 2030, 2035, and 2040, the scenarios are applied using Equation (3.58). Figure 4.40 shows the load demand graph for November and December 2025 under the HIGHER GREEN scenario, highlighting a significant reduction in load demand from 06:00 to 18:00 due to the penetration of rooftop solar power.

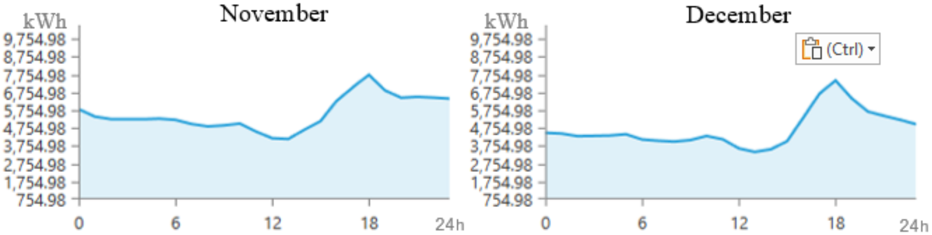


Figure 4.46. Load demand graph for the HIGHER GREEN scenario in november and december 2030.

4.2.6. Installation capacity limits of power generation sources

- **Wind power installation capacity limits**

Currently, Phú Quý does not have any feasible wind power projects, and the wind power capacity will not grow by 2025 due to the long construction period. The installation of turbines depends on location, technical factors, environmental conditions, and land planning. Data from the National Hydro-Meteorological Center indicates that the northern part of the island has the highest wind potential, with three potential zoning areas (Zone 1, Zone 2, Zone 3). Turbines with capacities ranging from 1 to 10 MW, particularly large ones, are suitable for the limited space available on the island.

Figure 4.53. Wind Power Planning Map for Phú Quý by 2030.

The study selects the Enercon E-101 E2 turbine, with a height of 78m and a capacity of 3.5 MW, suitable for the wind conditions and the requirement not to exceed a height of 80m in order to ensure the visibility of the 126m lighthouse. Wind power capacity is calculated based on a power density of 10.5 MW/km², meeting the area and safety distance requirements. The maximum power capacity reaches 9.5 MW in Zone 1, 7 MW in Zone 2, and 10.5 MW in Zone 3. The locations for wind turbine planning and installation are shown in Figure 4.53.

- **Solar power installation capacity limits**

By 2025, Phú Quý will not have any new solar power plants, and the capacity will remain at the current level. Solar power capacity growth after 2025 depends on the available land area. The study assumes that by 2040, 1% of the island's land area will be used for solar power development, as presented in Table 4.42.

Table 4.42. Assumed Solar Power Installation Capacity for Different Scenarios.

Assumptions	2025	2030	2035	2040
Solar power penetration (%)	0%	50%	65%	100%
Installed solar power capacity (MWp)	0,0	14,0	18,0	28,5

- **Battery energy storage system (BESS)**

The BESS capacity at Phú Quý in 2025, 2035, and 2040 will be determined based on the growth of solar and wind power. BESS will store energy when renewable power generation exceeds demand and provide energy when renewable sources are insufficient. The optimization solution for BESS capacity is based on load demand, renewable integration rate, and investment and operational costs. The proposed starting BESS capacity for Phú Quý is ≥ 0 MW, with a maximum capacity not exceeding the Pmax/DOD of the system. The specific capacity will be calculated through an optimization model to ensure economic efficiency and system stability.

4.2.7. Objective function and constraints

The objective function and constraints, as presented in Chapter 3, include the following constraints: the power generation capacity and output limits of each power source, power balance, reserve power, power factor, the variation of power generation between two consecutive hours, the maximum hourly solar power generation, and the charge/discharge limits of the energy storage system. All of these factors must be ensured according to the content outlined in Chapter 3.

Table 4.43. Summary of installation values for LINDO software.

Indicators	Plant	DIESEL				WIND				SOLAR				BIOMASS				BESS			
	Year	2025	2030	2035	2040	2025	2030	2035	2040	2025	2030	2035	2040	2025	2030	2035	2040	2025	2030	2035	2040
Existing installed capacity Scenarios: BAU & GREEN (MW)		≤9,7	≤9,7	≤7,0	≤7,0	6,0	6,0	6,0	6,0	0,73	0,73	0,73	0,73	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Existing installed capacity Scenarios HIGHER GREEN (MW)		≤9,7	0,0	0,0	0,0	6,0	6,0	6,0	6,0	0,73	0,73	0,73	0,73	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Maximum Capacity of Power Sources (MW)	BAU	≥ 0	≥ 0	≥ 0	≥ 0	No	No	7,0	14,0	No	≤14,0	≤18,0	≤28,5	0,0	0,0	0,0	0,0	No	≤21,06	≤32,4	≤49,86
	GREEN	≥ 0	≥ 0	≥ 0	≥ 0	No	3,5	10,5	17,5	No	≤14,0	≤18,0	≤28,5	0,0	1,0	1,0	1,0	No	≤21,06	≤32,4	≤49,86
	HIGHER GREEN	≥ 0	≥ 0	≥ 0	≥ 0	No	7,0	14,0	21,0	No	≤14,0	≤18,0	≤28,5	0,0	1,0	1,0	1,0	No	≤21,06	≤32,4	≤49,86
Fuel Cost (USD/MWh)		285	352	420	488	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	No	0,0	0,0	0,0	No	0,0	0,0	0,0
Variable O&M Cost (USD/MWh)		500	500	500	500	3,3	2,8	2,7	2,6	0,0	0,0	0,0	0,0	No	24,3*	24,3*	24,3*	No	2,1*	2,1*	2,1*
Depreciation cost of existing machines (thousand USD/year/MW)		33,6	33,6	0	0	107	107	0,0	0,0	65	65	65	0,0	No	No	No	No	No	No	No	No
Depreciation cost of new machines (thousand USD/year/MW)		48	48	48	48	137	175	223	284	No	106	135	173	No	67	67	67	No	35	30	25
Fixed O&M cost (thousand USD/year/MW)		19,0	20,5	22,0	23,5	42	42,0	42,0	42,0	No	13,9	13,9	13,9	No	234	226	217	No	0,3	0,3	0,3

Note: No: Not in use. * Data provided by Homer software.

4.2.8. Solving the optimization problem

To determine the optimal power generation structure, the study uses the LINDO software to solve the optimization problem based on the objective function and constraints. The input data, after being collected, forecasted, calculated, and processed, will be entered into the software. Specific values are detailed in Table 4.43.

4.2.9. Results

1. Installed capacity

Table 4.44. Results of power capacity calculations for the mobilized power sources to meet load demand under different scenarios over the years (MW).

Year	Scenario	DIESEL	WIND	SOLAR	BIOMASS	BESS	P_{max} Capacity
2025	BAU	3.68	6.00	0.73	0.00	0.00	6.84
2030	BAU	2.51	6.00	14.73	0.00	20.92	10.53
	GREEN	0.50	9.50	13.38	1.00	21.00	10.53
	H. GREEN	0.00	13.00	9.64	1.00	20.14	10.53
2035	BAU	3.30	13.00	18.73	0.00	29.67	16.20
	GREEN	1.45	16.50	15.73	1.00	28.89	16.20
	H. GREEN	0.00	20.00	14.98	1.00	31.34	16.20
2040	BAU	4.75	20.00	29.23	0.00	46.36	24.93
	GREEN	3.05	23.50	28.04	1.00	46.32	24.93
	H. GREEN	0.00	27.00	29.16	1.00	49.80	24.93

In 2025, the BAU scenario shows a significant dependency on diesel, with a high proportion in the energy mix, while wind and solar energy account for only a small share, reflecting limited renewable energy (RE) utilization. This dependency leads to high CO_2 emissions and is unsustainable. To move towards sustainable development, the share of RE in the energy mix needs to be increased.

By 2030, in the BAU scenario, solar energy operates at full capacity (100%), and diesel decreases to 25.77%, with the installed capacity to peak load ratio (Pmax) reaching 288%. However, RE has not yet fully replaced diesel. In the GREEN scenario, wind energy operates at full capacity (100%), solar energy at 90%, with the addition of biomass, significantly reducing diesel use. This reflects efforts in energy transition. In the HIGHER GREEN scenario, diesel is completely eliminated, with wind and biomass fully utilized, aiming for sustainable development and CO_2 emission reductions.

Table 4.45. Reserve capacity ratio by scenario over the years.

Year	Scenario	Peak Load (MW)	Unused Diesel Capacity (MW)	Reserve Capacity Ratio (%)
2025	BAU	6.84	6.02	88.01
2030	BAU	10.53	7.19	68.28
	GREEN	10.53	9.20	87.37
	H. GREEN	10.53	9.70	92.12
2035	BAU	16.20	3.70	22.84
	GREEN	16.20	5.55	34.26
	H. GREEN	16.20	7.00	43.21
2040	BAU	24.93	2.25	9.03
	GREEN	24.93	3.95	15.84
	H. GREEN	24.93	7.00	28.08

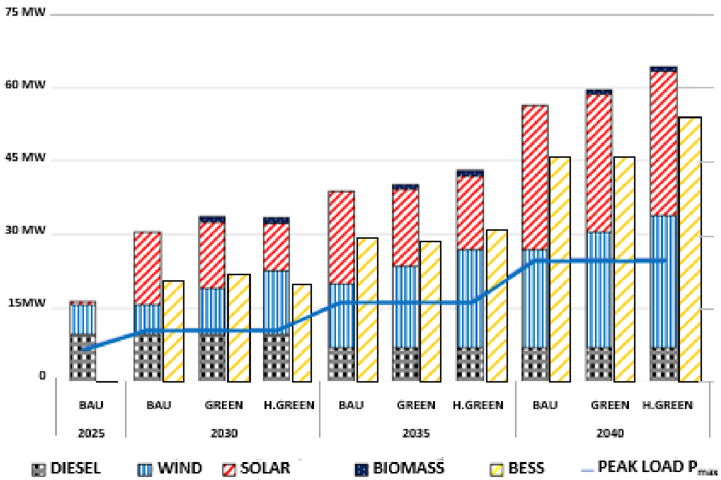


Figure 4.58. Installed Capacity of Power Sources and BESS Capacity by Scenario.

By 2035, in the BAU scenario, wind and solar energy make up the majority share, with diesel capacity reduced to 3.3 MW, reflecting a gradual decrease in fossil fuel dependency. In the GREEN scenario, wind power operates at 100%, solar at 83.98%, biomass begins to contribute with a small share, while diesel still accounts for 21.4%, due to the depreciation of existing plants, showing a strong transition to renewable energy. The HIGHER GREEN scenario eliminates diesel entirely, maximizing the use of renewable energy with wind and solar as the main sources, supplemented by biomass, aiming for sustainable development.

By 2040, in the BAU scenario, renewable energy, primarily wind (100%) and solar (95.6%), will account for a large share, while diesel reduces to 4.7 MW, continuing to meet peak load but gradually decreasing. In the GREEN scenario, wind and solar will reach full installed capacity, with biomass contributing in small amounts, but diesel remains essential, reflecting the gradual transition to renewable energy. The HIGHER GREEN scenario shows the electricity system completely transitioning to renewable energy, with wind (100%) and solar (99%) as the dominant sources, and no diesel usage, demonstrating comprehensive sustainable development.

- **Evaluation of installed capacity exceeding maximum load capacity:**

In **2025**, the installed capacity is determined based on actual needs. In the following years, capacity will be adjusted based on the maximum output of each power source, multiplied by the corresponding capacity factor:

- Impact of Rooftop Solar Power: The penetration of rooftop solar power will reduce grid electricity consumption from 6 AM to 6 PM. The system's peak load will shift to the 6 PM to 11 PM timeframe, when sources like diesel, wind, BESS, and electricity from solid waste will work together to meet demand.

- Characteristics of Wind Power: Wind power has the highest output in January and December, and the lowest in April and May. During peak months, wind power will be maximized, reducing reliance on other sources. However, in April and May, when wind power output decreases, diesel and BESS will have to increase their operations.

- Optimal Operation Management: Although the system's peak capacity is large, the capacity factor of the power sources is low and inconsistent. Therefore, optimal operation requires flexible coordination of the power sources over time to ensure efficiency and meet load demands.

- Reserve Capacity: The unused diesel capacity is considered reserve power, and the reserve ratio changes according to each scenario. Detailed reserve ratios are provided in Table 4.45, and the installed capacity configurations of the scenarios over the years are illustrated in Figure 4.58.

2. Electricity generation output

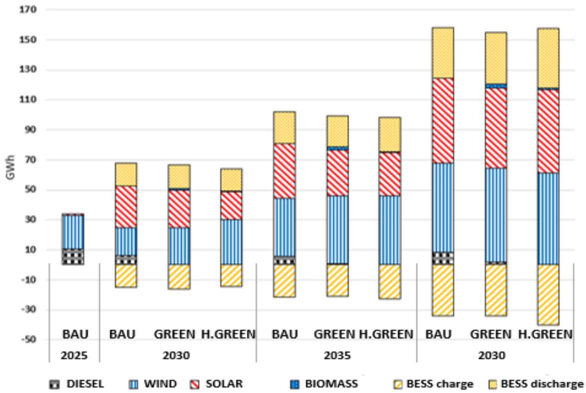


Figure 4.59. Electricity generation output by scenario.

2025: In the BAU scenario, electricity generation reaches 34,088 GWh, with wind power (64.6%), diesel (31.1%), and solar (4.3%) as the main sources. Biomass does not participate.

2030: In the BAU scenario, generation increases to 52,461 GWh, with wind power decreasing to 35.3% and solar rising to 52.5%. In the GREEN scenario, 50,825 GWh is produced, with 97.4% from renewable energy (wind and solar), and 0.5% from diesel. The HIGHER GREEN scenario generates 49,189 GWh, with no diesel used, and wind (61.2%) and solar (38%) are the main sources.

2035: The BAU scenario produces 80,505 GWh, with wind (47.9%) and solar (44.9%) almost balanced, while diesel decreases to 7.2%. In the GREEN scenario, 78,362 GWh is generated, with wind (57.2%), solar (39.2%), and biomass (2.4%) contributing. The HIGHER GREEN scenario generates 75,493 GWh, with wind (61%), solar (38.5%), and biomass (0.6%), and no diesel.

2040: In the BAU scenario, generation reaches 124,025 GWh, with wind (47.8%) and solar (45.5%), and diesel at 6.7%. The GREEN scenario generates 120,686 GWh, with wind (51.7%), solar (44.5%), and biomass (2.2%), while diesel decreases to 1.6%. In the HIGHER GREEN scenario, 117,525 GWh is produced, with wind (52.3%), solar (47.1%), biomass (0.7%), and no diesel.

Evaluation: Renewable energy (wind and solar) accounts for a significant and increasing share over the years, especially in the GREEN and HIGHER GREEN scenarios, with a near 100% share by 2040. Diesel use gradually decreases, particularly in the GREEN and HIGHER GREEN scenarios. The BESS (Battery Energy Storage Systems) plays a crucial role in stabilizing the supply of renewable energy.

3. Electricity generation cost

2025: In the BAU scenario, the cost is 22 UScent/kWh. At this point, green solutions haven't had a strong impact, and energy demand follows a natural growth trend.

2030: The BAU cost is expected to decrease to 15 UScent/kWh due to reduced dependence on diesel. The GREEN scenario has a generation cost of just 8 UScent/kWh, 46.7% lower than BAU, thanks to the strong development of renewable energy and BESS systems. The HIGHER GREEN scenario costs 9 UScent/kWh, 40% lower than BAU, but higher than GREEN due to investments in renewable energy and BESS.

2035: In the BAU scenario, the cost drops to 13.2 UScent/kWh, but remains high due to diesel dependency. The GREEN scenario achieves 9.8 UScent/kWh, 25.8% lower than BAU, due to the robust development of renewable energy. The HIGHER GREEN scenario costs 10 UScent/kWh, 24.2% lower than BAU but still higher than GREEN.

2040: The BAU cost is projected to rise to 15.5 UScent/kWh, 13% higher than in 2035, due to increased dependence on diesel as renewable energy reaches its limits. The GREEN scenario maintains the cost at 9.9 UScent/kWh, increasing by just 1% from 2035 and remaining 36% lower than BAU, thanks to the use of a small amount of diesel to compensate for energy shortages**.**

Overall Evaluation: The generation cost in GREEN and HIGHER GREEN scenarios is significantly lower than in BAU, due to the strong growth of renewable energy. Though the HIGHER GREEN scenario has a higher cost than GREEN, it still effectively reduces CO_2 emissions and optimizes renewable energy penetration.

4. CO_2 emissions

Forecasts of total CO_2 emissions for the different scenarios over the years are shown in Figure 4.61.

2025: All three scenarios (BAU, GREEN, and HIGHER GREEN) still rely heavily on diesel for electricity generation, resulting in high CO_2 emissions. However, the increased use of renewable energy in GREEN and HIGHER GREEN helps reduce emissions, though not significantly since diesel still plays a major role.

2030: In the BAU scenario, CO_2 emissions remain high (6.2 $ktCO_2$) due to diesel reliance. However, GREEN and HIGHER GREEN significantly reduce emissions due to the increased share of renewable energy, particularly solar and wind power.

The HIGHER GREEN scenario eliminates diesel completely, reducing emissions to just 1.11 ktCO_2, achieving the long-term emission reduction goal.

2035: The BAU scenario continues to see high CO_2 emissions (6.34 ktCO_2) due to diesel use. Meanwhile, GREEN and HIGHER GREEN continue to reduce emissions thanks to the increased share of renewable energy, especially rooftop solar, biomass, and the BESS system. The HIGHER GREEN scenario maintains lower emissions than the GREEN scenario (1.71 ktCO_2 versus 2.5 ktCO_2) due to the complete elimination of diesel.

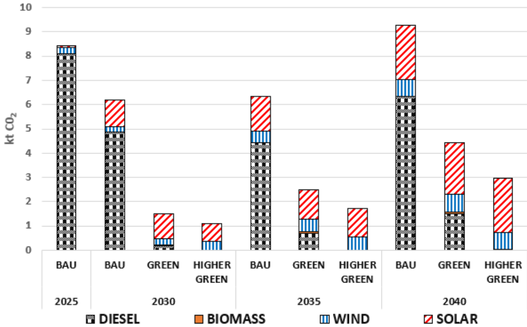


Figure 4.61. CO_2 Emissions of the Scenarios.

2040: The BAU scenario sees an increase in CO_2 emissions to 9.28 ktCO_2, as diesel still represents the dominant share in the power generation system. The GREEN and HIGHER GREEN scenarios continue to reduce emissions due to the increased use of renewable energy, particularly rooftop solar and biomass energy. The HIGHER GREEN scenario maintains the lowest emissions level (2.95 ktCO_2) and eliminates diesel entirely from 2030.

Overall Evaluation: The HIGHER GREEN scenario is the optimal solution both technically and economically, with the goal of reducing CO_2 emissions and promoting sustainable growth for the electricity system on Phú Quý Island. The increase in renewable energy, particularly rooftop solar, helps reduce dependence on CO_2 diesel and achieves the lowest emissions over the years. Compared to the BAU scenario, where CO_2 emissions remain high, the HIGHER GREEN scenario not only achieves long-term and sustainable emissions reduction goals but also proves the feasibility of applying this model to other tropical islands. Along with the GREEN scenario, HIGHER GREEN is an effective and feasible approach to reduce CO_2 emissions and promote sustainable development for islands**.**

CHAPTER 5
CONCLUSIONS AND DEVELOPMENT DIRECTIONS

5.1 Conclusion

The objective of this dissertation is to propose and demonstrate the feasibility of solution groups for efficient energy utilization, while also determining the optimal power generation system structure—identifying the primary energy forms that minimize generation costs—applicable to tropical islands in general and Vietnam in particular.

The proposed solution groups are evaluated based on the feasibility criterion of achieving competitive energy costs when implementing the recommendations. The power generation structure is formulated with the objective function of minimizing electricity generation costs while incorporating renewable energy sources and energy efficiency measures. CO2 emission reduction is addressed through the introduction of green (GREEN) and greener (HIGHER GREEN) power generation scenarios, which involve varying levels of renewable energy integration.

The main results of the dissertation are as follows:

• Energy model:

After surveying the current energy usage of tropical islands globally, Phuket Island in Thailand stands out for applying the "Kommod" model, which helps find the optimal power generation structure, indicating a new approach for energy management and exploitation in islands with tourism potential. The energy efficiency and low CO_2 emission model for tropical islands is presented in Figure 3.1, which outlines solutions for six work groups and economic sectors, specifically:

(1) policy systems to support/subsidize technology changes or increase the penetration rate of renewable energy; this solution group covers and supports the other five sectors: (2) commerce & services, (3) industry, (4) power sector, (5) transportation, and (6) AFOLU (Agriculture, Forestry, and Other Land Use).

• Energy efficiency solution groups:

Based on the model presented in Figure 3.1, the dissertation selects and presents five proposals and calculations, including:

(1) Electricity generation from solid waste: For Phú Quốc Island during the 2020-2030 period, based on socio-economic development planning, the population is expected to increase from 360,000 to 532,888. Consequently, household waste will rise from 283 tons/year to 419 tons/year, leading to a power plant capacity increase from 4.7 MW to 7.0 MW. Financial indicators show a net present value (NPV) of USD 5.1 million with a 7% discount rate, an internal rate of return (IRR) of 10.5%, and a payback period of 13.01 years. CO_2 reduction ranges from 23,118 to 34,220 tons CO_2/year. With a project lifetime of approximately 25 years, the project meets the economic criteria for investment.

(2) Solar rooftop system development on Phú Quốc Island by 2030: Evaluated across three scenarios based on the floor area defined by Phú Quốc's 2020-2030 planning. The total installed capacity increases progressively to 805 MWp, 1,219 MWp, and 1,931 MWp. Financial indicators for rooftop solar systems are as follows: IRR of 10.5%, 11.88%, and 15.41%; payback period of 8, 7.5, and 6 years, respectively. CO_2 reduction ranges from 193,844 to 464,473 tons CO_2/year. With a project lifetime of 20 to 25 years, the project meets the economic criteria for investment.

(3) Feasibility calculation for reducing CO_2 emissions through electric vehicles on Phú Quốc Island: This is evaluated in three scenarios of replacing internal combustion engine vehicles with electric vehicles at gradually increasing rates of 5%, 10%, and 15%. These scenarios are entirely feasible, especially for Vietnam, as the electric vehicle market is growing rapidly. The results show a CO_2 reduction of approximately 17%, 18%, and 21% by 2030, respectively, for the three scenarios.

(4) New operating method for the diesel-wind power generation system on Phú Quý Island: Significant results include an 81.69% increase in wind energy generation

compared to the current method, a 31.23% reduction in diesel consumption, and a savings of 12.5 billion VND in diesel costs if 70% of the proposed method's efficiency is achieved. The corresponding CO_2 emission reduction follows.

(5) Natural lighting design for a building: The building measures 80m x 32m x 14m and includes one floor. It is a multifunctional building with offices, a small mechanical workshop, and commercial service areas. The main results are a 34% reduction in energy consumption, saving approximately 1.56 tons CO_2/m^2/year, with a payback period of just over 9 months.

• Optimal Power Generation Structure for Phú Quý Island:

The next part of the dissertation involves finding the optimal power generation structure with the lowest cost. Constraints in the objective function include a combination of planning problem constraints, such as maximum and minimum power capacities, and operational constraints, such as power balance, reserve capacity, power factor, variations in hourly power output, solar power generation limits, and storage system charge/discharge limits.

The application for Phú Quý Island produced the following results:

- Three green power generation scenarios were proposed: BAU (Business As Usual), which represents no changes, and two CO_2 emission reduction scenarios-GREEN and HIGHER GREEN-based on assumptions that solar rooftop energy will reduce the system's electricity demand, and renewable energy capacity will increase.

- The generation cost in the HIGHER GREEN scenario is lower than in BAU by 3 to 6 US cents/kWh. The HIGHER GREEN scenario achieves the greatest CO_2 reduction, which is 5.2, 9.8, and 16.2 ktCO_2 lower than BAU in 2030, 2035, and 2040, respectively.

- Although diesel power generation is still utilized, its share decreases, leading to lower electricity generation costs and CO_2 emissions.

The results of optimizing the power generation structure for Phú Quý Island confirm its economic feasibility, with significantly reduced and competitive power generation costs, along with substantial CO_2 reductions.

5.2 Development Directions

The dissertation makes several significant contributions but also has some limitations: (1) It has not surveyed all six sectors of the model (Figure 3.1), particularly energy in agriculture due to a lack of data. (2) It has not applied the optimal power generation structure to Phú Quốc Island, but only to the smaller Phú Quý Island, which reduces its broader applicability. (3) There are limitations in data: a lack of continuity, granularity, and reliability. Future research should focus on improving data collection to enhance accuracy and efficiency.