TECHNO-ECONOMIC ANALYSIS AND OPTIMAL DESIGN OF GRID-CONNECTED HYBRID RENEWABLE ENERGY SYSTEMS FOR A UNIVERSITY IN MALAYSIA

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I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged

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ABSTRAK

Peningkatan permintaan tenaga di institusi pendidikan, ditambah dengan kenaikan kos operasi, kebergantungan yang semakin tinggi terhadap bahan bakar fosil, serta peningkatan pelepasan gas rumah hijau (GRH), menimbulkan cabaran kelestarian yang kritikal di peringkat global. Peralihan kepada tenaga boleh diperbaharui adalah amat penting bagi mengurangkan pelepasan karbon dan memastikan bekalan elektrik yang andal. Walaupun kecenderungan penyelidikan terhadap pengintegrasian tenaga boleh baharu semakin berkembang, jurang yang ketara masih wujud dalam penilaian tekno-ekonomi-alam sekitar yang komprehensif serta reka bentuk optimum sistem tenaga boleh baharu hibrid (STBH) yang bersambung ke grid, khususnya yang disesuaikan untuk kampus institusi di ekonomi membangun, terutamanya di iklim tropika. Tesis ini menangani cabaran-cabaran tersebut dengan mengkaji sama ada STBH yang bersambung dengan grid dapat menggabungkan tenaga suria fotovoltaik, turbin angin, penyimpanan tenaga, dan teknologi berasaskan hidrogen yang mampu menawarkan alternatif dari segi teknikal, berdaya maju dari segi ekonomi, dan lebih berkesan dari segi alam sekitar berbanding dengan bekalan tenaga konvensional yang bergantung sepenuhnya kepada grid, di sebuah kampus universiti di Malaysia. Matlamat utama penyelidikan ini adalah untuk menentukan saiz optimum, mereka bentuk, dan menilai STBH bersambung grid yang diintegrasikan dengan sumber tenaga boleh diperbaharui, serta menilai prestasi tekno-ekonomi dan potensi pengurangan GRH dalam konteks institusi di Malaysia. Metodologi pengiraan dua peringkat telah digunakan: analisis kebolehlaksanaan tekno-ekonomi menggunakan platform simulasi HOMER GRID dan HOMER PRO, diikuti oleh reka bentuk dan penentuan saiz sistem yang optimum, yang disahkan menggunakan perisian PVsyst. Dua konfigurasi utama telah dikaji secara sistematik: sistem suria PV bersambung grid dengan dan tanpa penyimpanan tenaga, serta sistem hibrid lanjutan PV/angin/elektrolizer/penyimpanan hidrogen/sel fuel. Konfigurasi pertama telah mengenal pasti sistem suria PV bersambung grid berdaya 295 kWp sebagai penyelesaian paling kos efektif, dengan mencapai kos tenaga yang dinormalisasi (LCOE) sebanyak 0.296 MYR/kWh, kos kini bersih (NPC) sebanyak RM 3.56 juta, tempoh bayar balik selama 8.2 tahun, dan pengurangan pelepasan CO_2 tahunan sebanyak kira-kira 48% berbanding dengan grid konvensional. Penggabungan sistem penyimpanan tenaga bateri pada 303 kWp seterusnya meningkatkan kebolehpercayaan sistem, dengan pengesahan reka bentuk PVsyst menghasilkan nisbah prestasi masing-masing sebanyak 86% dan 85.3%. Konfigurasi kedua, yang terdiri daripada tatasusunan PV berdaya 600 kWp, turbin angin 6 kWp, elektrolizer 200 kWp, tangki hidrogen 50 kg, dan sel fuel 50 kWp, berjaya mencapai LCOE sebanyak $0.0673/kWh, NPC sebanyak $817 668, tempoh bayar balik selama 8.5 tahun, dan pengurangan pelepasan CO_2 yang luar biasa sebanyak ~74% berbanding senario bergantung sepenuhnya kepada grid, dengan PVsyst mengesahkan purata output tenaga sebanyak 4.21 kWh/kWp/hari dan nisbah prestasi sebanyak 86%. Penyelidikan ini menyumbang kepada pembangunan reka bentuk tekno-ekonomi bersepadu bagi sistem tenaga boleh diperbaharui hibrid bersambung grid yang menggabungkan penyimpanan tenaga hidrogen untuk aplikasi institusi. Dapatan kajian ini menyediakan para penggubal dasar, pentadbir universiti, dan perancang tenaga dengan maklumat berharga bagi menyokong peralihan tenaga kampus yang lestari, serta bagi merumuskan strategi pengintegrasian tenaga boleh diiperbaharui yang menyediakan kos efektif, selaras dengan matlamat tenaga rendah karbon dan polisi Malaysia.

ABSTRACT

The escalating energy demand in educational institutions, coupled with rising operational costs, increasing reliance on fossil fuels, and growing greenhouse gas (GHG) emissions, poses critical sustainability challenges globally. Transitioning to renewable energy is essential to reducing carbon emissions and ensuring a reliable electricity supply. Despite growing interest in integrating renewable energies, a significant gap persists in comprehensive techno-economic-environmental assessment and optimal design of grid-connected hybrid renewable energy systems (HRES) tailored to institutional campuses in developing economies, particularly in tropical climates. This thesis addresses these challenges by investigating whether grid-connected HRES incorporating solar photovoltaic, wind turbines, energy storage, and hydrogen-based technologies can offer a technically feasible, economically viable, and environmentally superior alternative to conventional grid-dependent energy supply at a Malaysian university campus. The primary aim of this research is to optimally size, design, and evaluate grid-connected HRES integrated with renewable energy sources, assessing their techno-economic performance and GHG-reduction potential in an institutional context in Malaysia. A two-stage computational methodology was employed: techno-economic feasibility analysis using the HOMER GRID and HOMER PRO simulation platforms, followed by optimal system design and sizing, validated using PVsyst software. Two principal configurations were systematically investigated: a grid-connected solar PV system with and without energy storage, and an advanced hybrid PV/wind/electrolyzer/hydrogen storage/fuel cell system. The first configuration identified a 295 kWp grid-connected solar PV system as the most cost-effective solution, achieving a levelized cost of energy (LCOE) of 0.296 MYR/kWh, a net present cost (NPC) of RM 3.56 million, an 8.2-year payback period, and approximately 48% annual CO_2 emission reduction relative to the conventional grid. Incorporating battery energy storage at 303 kWp further enhanced system reliability, with PVsyst design validation yielding performance ratios of 86% and 85.3%, respectively. The second configuration, comprising a 600 kWp PV array, 6 kWp wind turbine, 200 kWp electrolyzer, 50 kg hydrogen tank, and 50 kWp fuel cell achieved an LCOE of $0.0673/kWh, an NPC of $817 668, an 8.5-year payback period, and a remarkable ~74% reduction in CO_2 emissions compared to the grid-only baseline, with PVsyst confirming an average energy output of 4.21 kWh/kWp/day and a performance ratio of 86%. This research contributes to the development of an integrated techno-economic design framework for grid-connected hybrid renewable systems incorporating hydrogen energy storage for institutional applications. The findings provide policymakers, university administrators, and energy planners with valuable insights to support sustainable campus energy transitions and to formulate cost-effective renewable energy integration strategies aligned with Malaysia's low-carbon energy goals and policies.

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LIST OF SYMBOLS

%	Percentage
°	Degree
°C	Celcius
A	Ampere
Ah	Ampere hour
CO_2-eq/kWh	Carbon dioxide equivalent per kilowatt-hour
GWh	Gigawatt-hour
Hz	Hertz
Kg	Kilogram
kg/m^3	kilogram per meter per cubic
Ktoe	Kiloton oil equivalent
kW	Kilowatt
kWh	Kilowatt-hour
kWh/yr	kilowatt hour per year
kWp	Kilowatt-peak
m/s	meter per second
m^2	meter square
Mt	Megaton
MWh	Megawatt-hour
TWh	Terawatt-hour
V	Voltage
W/m^2	Watt per meter square

LIST OF ABBREVIATIONS

AC	Alternating Current
AI	Artificial Intelligence
BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
CF	Capacity Factor
CRF	Capital Recovery Factor
DC	Direct Current
DER	Distributed Energy Resource
DoD	Depth of Discharge
EMS	Energy Management System
ESS	Energy Storage System
EV	Electric Vehicle
FC	Fuel Cell
FiT	Feed-in Tariff
GCSPV	Grid Connected Solar Photovoltaic
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiance
HICoE	Higher Institution Centre of Excellence
HOMER	Hybrid Optimization Model for Electric Renewables
HRES	Hybrid Renewable Energy System
HVAC	Heating, Ventilation and Air Conditioning
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
MD	Maximum Demand
MENA	Middle East and North Africa
MYR	Malaysian Ringgit

NEM	Net Energy Metering
NPC	Net Present Cost
NPV	Net Present Value
O&M	Operation and Maintenance
OPEX	Operational Expenditure
PEM	Proton Exchange Membrane
POA	Plane of Array
PR	Performance Ratio
PV	Photovoltaic
PVsyst	Photovoltaic System Simulation Software
RE	Renewable Energy
RES	Renewable Energy Source
ROI	Return on Investment
SOC	State of Charge
STBH	Sistem Tenaga Boleh Baharu Hibrid
STC	Standard Test Conditions
TNB	Tenaga Nasional Berhad
TOU	Time-of-Use
UKM	Universiti Kebangsaan Malaysia
USD	United States Dollar
WT	Wind Turbine

LIST OF NOMENCLATURE

CO_2	Carbon Dioxide
H_2	Hydrogen

CHAPTER I

INTRODUCTION

1.1 RESEARCH BACKGROUND

Global energy demand has grown significantly over the previous two decades, rising from approximately 15 000 TWh to 28 000 TWh from 2000 to 2023. Meanwhile, an annual growth rate of 3.1% is projected from 21 400 TWh to 73 000 TWh between 2010 and 2050 ("World Energy Outlook 2024 – Analysis - IEA" n.d.). The global energy system is undergoing a profound transformation driven by increasing electricity demand, continued reliance on fossil fuels, and escalating environmental concerns. Rapid industrialization, population growth, urban expansion, and technological advancement have significantly increased global electricity consumption over the past few decades (Zahid et al. 2025). However, this growing demand has largely been met by fossil fuel-based generation, as shown in Figure 1.1, which continues to dominate the global energy mix despite its environmental and economic limitations. Coal, natural gas, and petroleum remain the primary sources of electricity worldwide, creating vulnerabilities related to resource depletion, fuel price volatility, and geopolitical instability stemming from their uneven geographical distribution. More critically, fossil fuel combustion is the largest contributor to anthropogenic greenhouse gas emissions, particularly carbon dioxide, which accelerates climate change and contributes to air pollution, ecosystem degradation, and public health risks (Ahmad & Chen 2020). The urgency of mitigating these impacts has intensified following international commitments such as the Paris Agreement, which seeks to limit global temperature rise to well below 2°C above pre-industrial levels. Achieving this objective requires a fundamental restructuring of energy systems, transitioning from carbon-intensive fuels to sustainable, low-carbon alternatives. Importantly, this transition is increasingly supported by declining costs and technological maturity of renewable energy technologies, which have enhanced their competitiveness and feasibility worldwide (“The Paris Agreement | UNFCCC” n.d.).

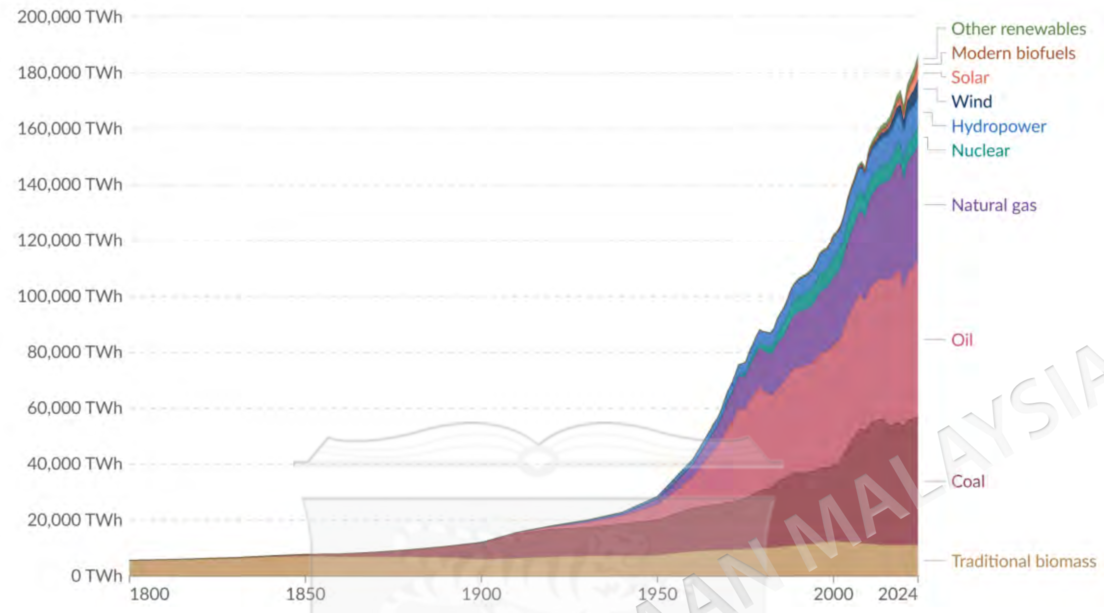

Figure 1.1 Global primary energy consumption by source

Source: Energy Production and Consumption - Our World in Data n.d.

Over the past decade, renewable energy deployment has expanded significantly, particularly in solar photovoltaic (PV) and wind energy technologies. While these technologies offer substantial environmental benefits, their intermittent and weather-dependent nature poses reliability challenges when deployed individually (Hassan et al. 2023). Solar generation fluctuates with irradiance and time of day, while wind output depends on variable wind speeds. To overcome these limitations, hybrid renewable energy systems (HRES) have emerged as an effective solution that integrates multiple renewable sources such as solar PV, wind turbines, and biomass generators often combined with battery energy storage and grid connectivity (Mahmood et al. 2024). By leveraging complementary resource availability patterns, HRES enhances reliability, improves renewable energy penetration, and optimizes overall system performance. The integration of energy storage further smooths power fluctuations, increases dispatchability, and reduces energy curtailment. From an economic perspective, optimized hybrid systems have demonstrated lower levelized cost of energy, lower net present cost, and attractive returns compared to standalone renewable or fossil-fuel-based systems (Mahmoud et al. 2026). The availability of advanced optimization tools, such as HOMER, enables comprehensive techno-economic modeling and sensitivity analysis to determine optimal system sizing and operational strategies. Additionally, hybrid systems significantly reduce greenhouse gas emissions and other pollutants, contributing to both climate mitigation and public health improvements (Mahmoud et al. 2026).

The techno-economic analysis of a hybrid renewable energy system evaluates the technical performance and economic feasibility of integrated energy resources using indicators such as reliability, efficiency, Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and environmental sustainability. In Malaysia, the energy landscape reflects both significant challenges and promising opportunities. The country remains heavily dependent on fossil fuels, with coal and natural gas accounting for more than 80% of electricity generation (Wang et al. 2024). This reliance contributes to substantial carbon emissions and exposes the nation to global fuel market volatility. Projections indicate that natural gas and oil reserves may deplete within several decades, reinforcing the need for energy diversification (Yahoo et al. 2024). Nevertheless, Malaysia possesses considerable renewable energy potential, particularly solar energy, due to its equatorial location and high year-round solar irradiance. The country also benefits from substantial biomass resources derived from the palm oil and agricultural sectors. Recognizing these opportunities, the Malaysian government has established ambitious renewable energy targets, aiming to achieve 31% renewable energy capacity by 2025 and 40% by 2035, alongside commitments to reduce greenhouse gas emission intensity by 45% by 2030 relative to 2005 levels (Wang et al. 2024). Policy mechanisms such as Feed-in Tariffs, Net Energy Metering (NEM), and competitive bidding for large-scale solar projects have been introduced to support the deployment of renewable energy. However, renewable penetration, excluding large hydropower, remains below expectations, hindered by challenges including grid integration, intermittency management, high upfront capital costs, financing constraints, regulatory complexity, and land availability constraints (Ariffin et al. 2022). While solar PV has become the dominant renewable technology in Malaysia, wind resources are limited, biomass remains underutilized, and hydropower expansion faces environmental and spatial restrictions. These factors highlight the potential advantages of hybrid renewable systems that integrate multiple resources to maximize reliability and performance (Woo et al. 2024).

Universities and educational institutions represent a strategically important sector for renewable energy deployment. University campuses typically exhibit substantial, relatively predictable electricity demand driven by academic buildings, laboratories, residential facilities, data centers, and extensive air conditioning, particularly in tropical climates such as Malaysia, as illustrated in Figure 1.2 (de Wilde & Coley 2024). As major energy consumers, universities face both financial and environmental pressures to improve energy efficiency and reduce carbon emissions. Beyond operational considerations, universities serve as centers of innovation and sustainability leadership, often committing to carbon neutrality and to adopting renewable energy. Campus renewable installations can function as living laboratories, providing educational and research opportunities while demonstrating practical sustainability solutions (Rus et al. 2025). In Malaysia, several universities have initiated feasibility studies into renewable energy. For example, Universiti Malaysia Pahang has proposed a large-scale floating solar installation, while Universiti Teknikal Malaysia Melaka and Universiti Utara Malaysia have evaluated grid-tied photovoltaic systems. However, most existing assessments focus primarily on standalone solar PV systems rather than on optimized hybrid configurations that incorporate storage and grid interaction. Considering the Malaysian government's requirement for public institutions to reduce utility expenditures annually, a comprehensive techno-economic evaluation of hybrid systems is necessary to guide practical implementation (Amirruddin et al. 2011; Islam et al. 2023).

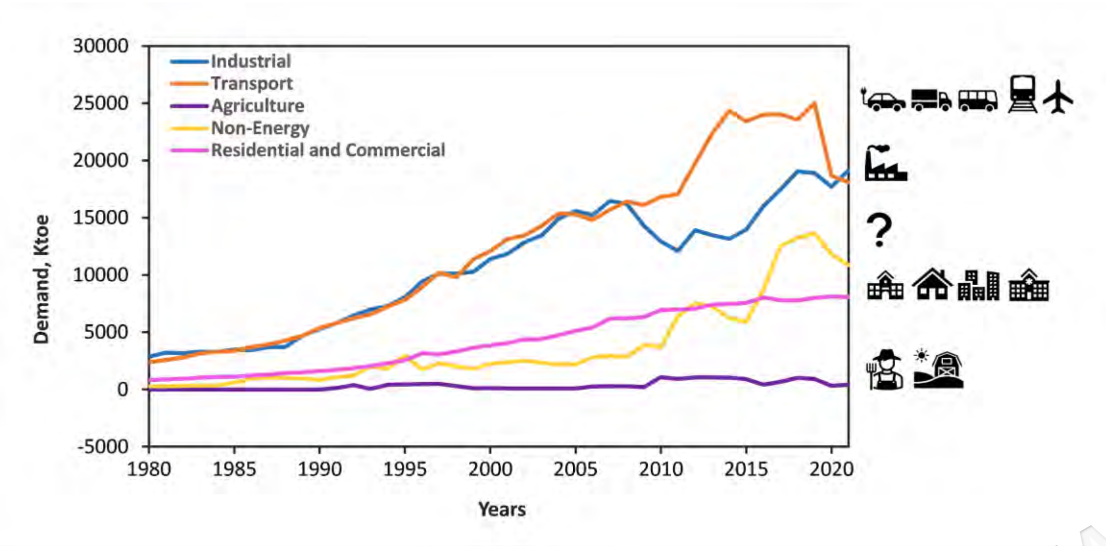

Figure 1.2 Energy consumption by Malaysian sectors measured in kilo ton oil equivalent (ktoe)

The deployment of grid-connected hybrid renewable energy systems requires rigorous techno-economic analysis to ensure both feasibility and long-term viability. Such analysis evaluates system performance across technical, economic, and environmental dimensions, including renewable fraction, reliability, net present cost, levelized cost of energy, and emission reductions (Kumar et al. 2024; Wong & Li 2023). Optimization is particularly important due to the complex trade-offs involved in system sizing, component selection, and dispatch strategies. Oversized systems increase capital expenditure, while undersized systems compromise reliability (Rozzi et al. 2025). Grid connectivity introduces additional considerations, such as energy export opportunities, tariff structures, interconnection regulations, and potential revenue under Net Energy Metering schemes. Accurate modeling of Malaysia's current policy framework is therefore essential for realistic economic evaluation. Moreover, feasibility extends beyond technical and economic metrics to include environmental benefits, institutional capacity, regulatory compliance, and spatial constraints specific to university campuses (Wang et al. 2024).

Despite growing interest in renewable energy systems, several research gaps remain within the Malaysian university context. Existing studies often focus on standalone solar installations rather than comprehensive grid-connected hybrid systems because they are proposing systems for rural areas with no grid electricity. Many lack systematic optimization and sensitivity analysis to evaluate robustness under varying economic and policy conditions. Furthermore, recent developments in Malaysia's renewable energy policy landscape, including updated NEM mechanisms, are not consistently incorporated into existing analyses (Som et al. 2025). Environmental assessments are frequently limited to emission quantification without linking results to institutional sustainability commitments or national decarbonization targets. Practical implementation challenges, including financing structures, infrastructure integration, and institutional readiness, are also underexplored (Munir & Pratama 2025).

These gaps underscore the necessity for a comprehensive, optimized techno-economic analysis of grid-connected hybrid renewable energy systems tailored specifically to Malaysian university campuses. Such research will provide evidence-based guidance for decision-makers, enabling universities to translate sustainability commitments into actionable renewable energy investments. Beyond individual institutions, the findings can support national renewable energy targets and contribute to broader climate mitigation efforts. By integrating technical, economic, environmental, and institutional considerations within a tropical developing-country context, this study advances scholarly understanding of hybrid renewable systems while offering practical insights for sustainable energy transition. Figure 1.3 depicts the research background of this thesis.

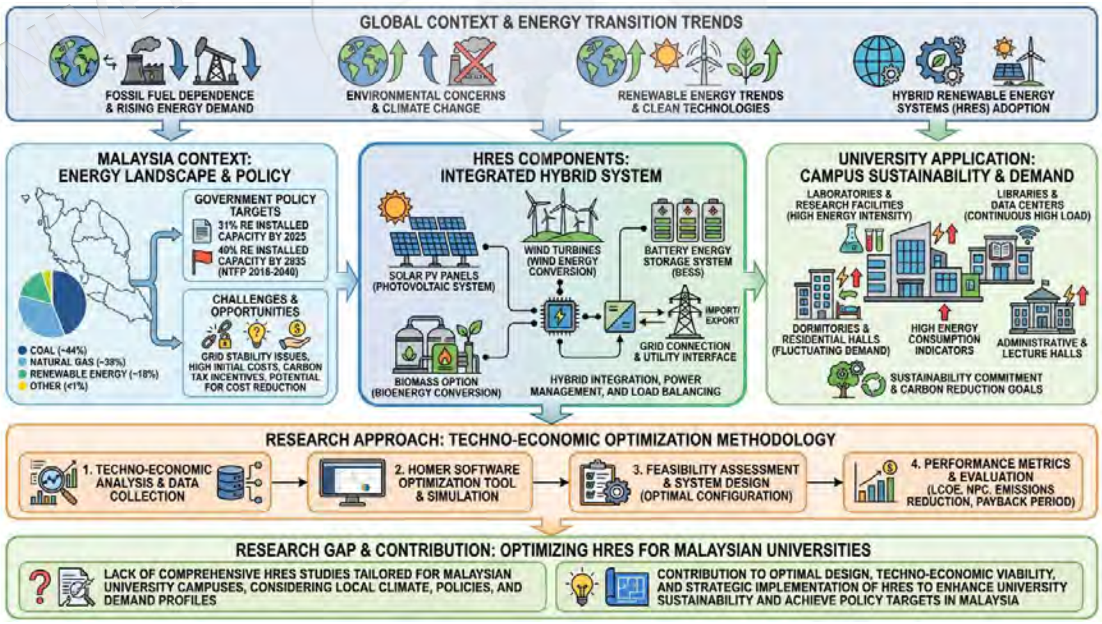

Figure 1.3 Graphical representation of the research background of this thesis

1.2 PROBLEM STATEMENT

The education sector (residential and commercial facilities) has experienced a sustained increase in energy consumption over the past decade, as illustrated in Figure 1.2. This upward trend is attributed to the rising number of educational institutions, increased educational infrastructure, enhanced academic research activities, heavy lab equipment and machinery, and extended operational hours, all of which have led to higher electricity demand (Laporte & Cansino 2024). In 2022, the education sector (residential and commercial facilities) was responsible for approximately 4.31 megatons (Mt) of CO_2 emissions ("Malaysia - Countries & Regions - IEA" n.d.). Notably, the sector remains largely reliant on conventional energy generation systems, which significantly contribute to GHG emissions ("Malaysia - Countries & Regions - IEA" n.d.).

Many countries continue to rely mainly on grid-based electricity, largely generated from fossil fuels, to meet the rising energy needs of their educational institutions("World - IEA" n.d.). However, the growing number of educational institutions, along with a significant increase in student enrollments, new educational buildings and infrastructure, electric vehicles, advanced academic research, and the use of heavy lab equipment, can lead to high electricity consumption and increased energy demand on the grid. Conventional energy systems face several challenges, particularly in educational institutions, where peak energy usage can be quite high during operating hours (Laporte & Cansino 2024). Another significant challenge is the high level of greenhouse gas (GHG) emissions, as nearly all power generation plants rely on conventional fossil fuels. This reliance is a major contributor to climate change and global warming. Additionally, infrastructural limitations and the limited integration of renewable energy sources impede progress toward global decarbonization goals (Paredes-Canencio et al. 2024). Therefore, the conventional grid-based energy system faces the following issues in educational institutes:

1. Educational institutions are significant consumers of electricity, which contributes to an increase in the MD for commercial and industrial users, as illustrated in Figure 1.4. This results in substantial utility expenses,

typically amounting to 30.3 RM/kW, thereby elevating the overall utility costs for the educational institution.

2. A significant amount of energy is generated by burning fossil fuels such as oil, coal, and natural gas (as Malaysia's 97% energy is generated from fossil fuels), which contributes to GHG emissions, such as carbon emissions, to the environment.

3. The lack of comprehensive techno-economic-environmental analyses of grid-connected hybrid energy systems integrated with renewable energies in Malaysia poses a challenge in assessing the feasibility and sustainability.

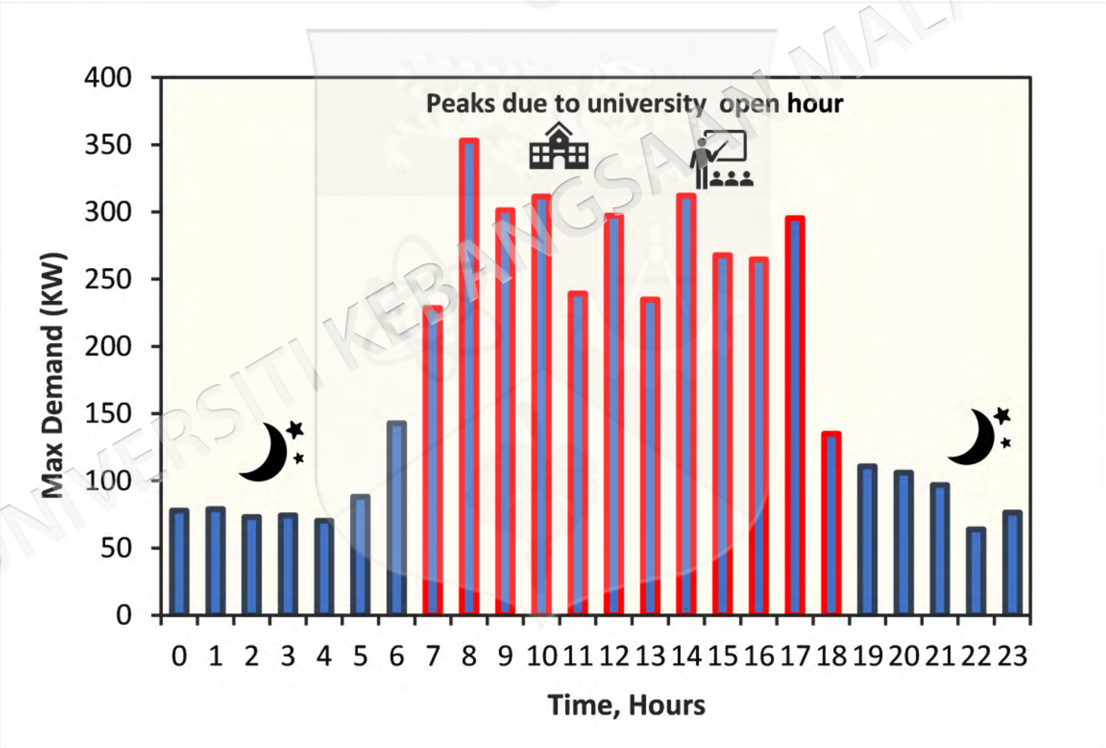

Figure 1.4 Typical MD of university faculty electrical load

1.3 OBJECTIVE OF RESEARCH

Typically, techno-economic-environmental analysis and the optimal design of grid-connected hybrid energy systems incorporating renewable energy sources can resolve the above issues. This study addresses the optimal sizing, design, and techno-economic and environmental analysis of grid-connected hybrid energy systems integrated with renewable energy sources on a university campus. The main objectives of this thesis are given below.

1. To optimally size and design grid-connected hybrid energy systems integrated with renewable energies for the university campus using computational tools.
2. To evaluate the techno-economic and feasibility analysis of grid-connected hybrid energy systems integrated with renewable energies for the university campus using computational tools.
3. To determine the amount of greenhouse gas emissions that can be reduced by transitioning to renewable energy sources.

1.4 SCOPE OF RESEARCH

This research focuses on the optimal design and comprehensive techno-economic and environmental evaluation of a grid-connected hybrid renewable energy system (HRES) for a university campus in Malaysia. The study aims to develop a practical, optimized hybrid energy configuration that integrates renewable energy sources, primarily solar photovoltaic, wind, fuel cells, and electrolyzers, with possible inclusion of battery energy storage and other technically feasible renewable components, while maintaining grid connectivity to ensure system reliability, flexibility, and continuous power supply. Due to Malaysia's limited wind potential, wind energy is not a primary focus of this study.

The scope of this research includes a detailed analysis of the campus electricity load profile, including academic buildings, laboratories, administrative offices, residential colleges, and other major energy-consuming facilities. Based on the load characteristics and available renewable resources, the hybrid system will be optimally sized and configured using HOMER and PVSyst. Technical performance indicators to be evaluated include total energy production, renewable energy fraction, system reliability, excess energy generation, and grid import-export interaction.

From an economic perspective, the study assesses key financial metrics, including net present cost (NPC), levelized cost of energy (LCOE), annual operating cost, return on investment, and payback period. The analysis also incorporates Malaysia's Net Energy Metering (NEM) scheme to evaluate potential cost savings and revenue from excess energy export. Sensitivity analysis will be conducted to examine the effects of variations in component costs, electricity tariffs, and load growth on overall system feasibility and robustness.

Environmental assessment within this scope includes quantifying greenhouse gas (GHG) emission reductions achieved by transitioning from conventional fossil-fuel-based grid electricity to renewable-integrated hybrid systems. The proposed configuration will be compared against the existing grid-dependent scenario to determine environmental benefits.

This research is limited to campus-level simulation-based modeling and optimization and does not involve physical system implementation, large-scale grid restructuring, or national policy formulation. Nevertheless, the findings are intended to provide practical, scalable, and evidence-based insights for renewable energy deployment in Malaysian higher education institutions.

1.5 ORGANIZATION OF THE THESIS

The thesis consists of five chapters. The details of the thesis organizations are as follows:

Chapter 1 presents the general introduction to the research work. It outlines the research background, highlighting the growing energy demand in educational institutions and the increasing need for sustainable, cost-effective integration of renewable energy on university campuses. This chapter further discusses the problem statement, research objectives, and the study's scope, thereby establishing the foundation and motivation for the present research.

Chapter 2 provides a comprehensive review of the literature on renewable energy technologies and hybrid renewable energy systems (HRES). It examines the potential of solar, wind, and hydrogen energy resources in the Malaysian context and reviews the implementation of grid-connected hybrid systems in institutional environments such as university campuses. In addition, techno-economic analysis approaches and commonly used optimization and simulation tools, including HOMER GRID, HOMER PRO, and PVsyst, are critically discussed. The chapter concludes by identifying the existing research gaps that justify the present study.

Chapter 3 describes the research methodology adopted in this work. It includes the site description of the selected university campus, meteorological data assessment, and electrical load profile analysis. This chapter further explains the configuration, modelling, and optimization of the proposed grid-connected hybrid renewable energy systems using HOMER GRID and HOMER PRO software tools. Detailed system design, component sizing, economic evaluation, sensitivity analysis, and environmental impact assessment are also presented. Additionally, PV system design and performance analysis are discussed in this chapter, carried out using PVsyst software.

Chapter 4 presents the simulation results obtained from the techno-economic analysis of the proposed hybrid renewable energy systems. The performance of different system configurations, including grid-connected photovoltaic (PV) systems with and without energy storage, and PV/wind/hydrogen-based hybrid systems, is analysed and compared using technical, economic, and environmental indicators. The results are discussed in terms of optimal system sizing, cost-effectiveness, energy production, and the potential for greenhouse gas emission reduction for university campus applications.

Finally, Chapter 5 summarizes the major findings and conclusions drawn from this research. It highlights the study's contributions to the field of hybrid renewable energy system optimization for institutional applications. Furthermore, recommendations for future research work and potential improvements in system implementation are provided to support sustainable energy planning in Malaysian higher education institutions.

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APPENDIX A

LIST OF PUBLICATIONS

1. **Iftiab Ahammed Sarker**, Mohd Salman, Rizwan Ullah, Shah Mohammad Mominul Islam, Mohammed Zeehan Saleheen, Mohd Shahbudin Masdar, Edy Herianto Majlan, Nurul Akidah Baharuddin, Zulfadly Anuar Taip, Rasyikah Md Khalid, "Techno-economic feasibility and optimal design of grid-connected PV system with energy storage: A case study for Malaysia's institutional" *Chemical Engineering Research and Design (2026)*, (index in ISI and Scopus Q2, IF: 3.9) (published).

2. **Iftiab Ahammed Sarker**, Mohd Salman, Rizwan Ullah, Shah Mohammad Mominul Islam, Mohammed Zeehan Saleheen, Mohd Shahbudin Masdar, Edy Herianto Majlan, Nurul Akidah Baharuddin, Zulfadly Anuar Taip, Rasyikah Md Khalid, "Techno-Economic Assessment and Designing of a Grid-Tied PV/Wind/Hydrogen Energy System for a University in Malaysia" *International Journal of Hydrogen Energy (2026)*, (index in ISI and Scopus Q1, IF: 8.3) (Accepted).