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Proceeding Paper

Lifecycle Sustainability and Waste Management in Nuclear Renewable Integrated Energy Systems †

Wai Yie Leong

Faculty of Engineering and Quantity Surveying, INTI International University, Nilai 71800, Negeri Sembilan, Malaysia; waiyie.leong@newinti.edu.my

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Abstract

The transition toward low-carbon energy systems requires sustainable integration of nuclear power and renewable energy technologies. Nuclear-renewable hybrid energy systems (NR-HES) combine the reliable baseload generation of nuclear reactors with the flexibility of renewable sources such as solar, wind, and hydroelectric power. These integrated systems have the potential to enhance energy security, reduce greenhouse gas emissions, and improve grid stability. However, lifecycle sustainability and waste management remain key challenges, particularly regarding nuclear fuel waste, renewable component disposal, and resource consumption across the entire energy system lifecycle. This study investigates lifecycle sustainability in nuclear-renewable integrated energy systems using life cycle assessment (LCA) and sustainability metrics. The research evaluates environmental impacts across the stages of resource extraction, infrastructure construction, energy generation, and decommissioning. Additionally, the study explores waste management strategies such as nuclear fuel reprocessing, geological disposal, and recycling of renewable infrastructure components. Results demonstrate that integrated nuclear-renewable systems can significantly reduce lifecycle carbon emissions while improving long-term resource efficiency and energy sustainability.

Keywords: nuclear; life cycle assessment; waste management; process innovation

1. Introduction

The global transition toward low-carbon energy systems has intensified due to increasing concerns about climate change and environmental sustainability. Fossil fuel-based energy systems remain the primary contributors to global greenhouse gas emissions, prompting governments and industries to seek cleaner and more sustainable alternatives [1]. Renewable energy technologies such as solar photovoltaic (PV), wind turbines, and hydropower have become widely adopted due to their minimal operational emissions and abundant natural resources [2]. However, renewable energy systems are inherently intermittent and depend heavily on environmental conditions such as sunlight availability and wind speed.

Nuclear power represents another low-carbon energy source capable of providing stable and reliable baseload electricity generation [3]. Unlike renewable sources, nuclear reactors can operate continuously for extended periods without interruption, making them an essential component of many national energy infrastructures. As a result, integrating

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nuclear power with renewable energy technologies has become an attractive strategy for achieving stable and sustainable energy systems.

Nuclear-renewable hybrid energy systems combine the advantages of both energy technologies by utilizing nuclear power for baseload generation and renewable sources for supplementary electricity production [4], Figure 1. Nevertheless, evaluating the sustainability of such integrated systems requires comprehensive lifecycle assessment. Lifecycle sustainability analysis examines environmental impacts throughout all stages of an energy system, including resource extraction, infrastructure construction, operation, waste management, and decommissioning [5]. This study focuses on evaluating lifecycle sustainability and waste management strategies in nuclear-renewable integrated energy systems.

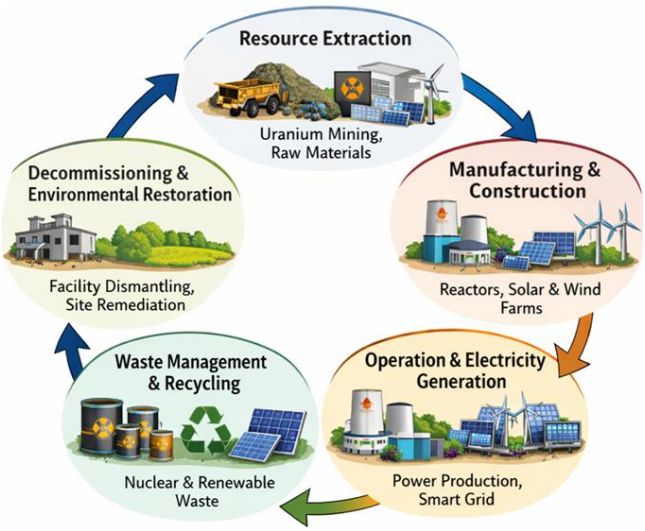


Figure 1. Lifecycle Framework of Nuclear-Renewable Integrated Energy Systems.

2. Literature Review

Numerous studies have examined the environmental impacts and sustainability performance of nuclear and renewable energy systems individually. Life cycle assessment (LCA) has become the most widely used analytical tool for evaluating environmental impacts across the entire lifecycle of energy technologies [5]. LCA considers various lifecycle stages, including raw material extraction, infrastructure manufacturing, energy generation, and waste disposal.

Research indicates that renewable energy technologies such as solar and wind have significantly lower lifecycle carbon emissions compared with fossil fuel power plants [2]. However, renewable energy infrastructure requires substantial material inputs including metals, rare earth elements, and composite materials. These materials must eventually be recycled or disposed of at the end of their operational lifecycle.

Nuclear power plants also exhibit very low lifecycle greenhouse gas emissions due to the absence of direct carbon emissions during operation [3]. Nevertheless, nuclear energy systems generate radioactive waste that requires long-term management and safe storage [6]. High-level radioactive waste from nuclear fuel cycles can remain hazardous for thousands of years, making waste management a critical component of nuclear sustainability.

Recent research has explored nuclear-renewable hybrid energy systems as a strategy to enhance energy system resilience and sustainability [4]. These hybrid systems can improve grid stability while reducing dependence on fossil fuel backup generation. Despite these advantages, relatively few studies have evaluated the lifecycle sustainability and waste management challenges associated with such integrated energy systems.

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3. Methodology

This study adopts a lifecycle sustainability assessment framework to evaluate environmental impacts and waste management strategies in nuclear-renewable integrated energy systems, Figure 2. The methodology combines life cycle assessment (LCA), lifecycle cost analysis, and waste management evaluation.

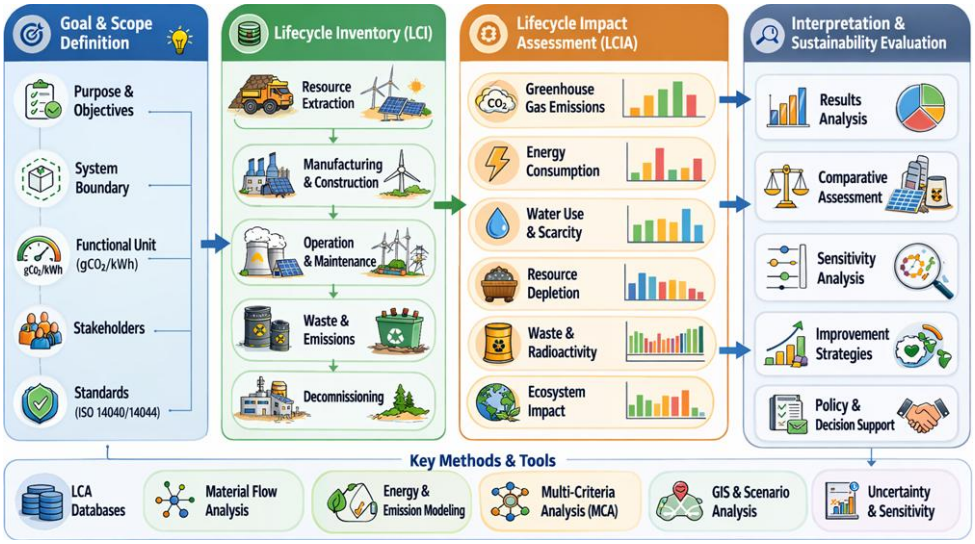


Figure 2. Lifecycle Sustainability Assessment Methodology for Nuclear-Renewable Energy Systems.

The LCA methodology follows ISO 14040 [5] and ISO 14044 [7] standards, which define four key phases: goal and scope definition, lifecycle inventory analysis, lifecycle impact assessment, and interpretation [5], Table 1. The system boundary is defined as a cradle-to-grave lifecycle covering the following stages:

(a) Uranium mining and nuclear fuel enrichment;
(b) Manufacturing of renewable energy infrastructure such as solar panels and wind turbines;
(c) Construction of nuclear reactors and renewable energy facilities;
(d) Electricity generation and system operation;
(e) Waste management and recycling processes;
(f) System decommissioning and infrastructure dismantling.

Table 1. Lifecycle Sustainability Assessment Indicators.

Indicator Category	Indicator	Unit	Description	Lifecycle Stage Evaluated
Environmental Impact	Lifecycle Greenhouse Gas Emissions	gCO_2/kWh	Total carbon emissions generated across the entire energy system lifecycle	Extraction, Construction, Operation
Environmental Impact	Water Consumption	L/kWh	Water used during fuel processing, power generation, and cooling operations	Operation
Environmental Impact	Land Use	m^2/MWh	Land area required for nuclear plants, solar farms, wind farms, and infrastructure	Construction, Operation

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Table 1. *Cont.*

Indicator Category	Indicator	Unit	Description	Lifecycle Stage Evaluated
Resource Efficiency	Energy Return on Investment (EROI)	Ratio	Ratio between energy produced and energy consumed during the lifecycle	Full Lifecycle
Resource Efficiency	Material Resource Consumption	kg/MWh	Quantity of metals, uranium fuel, rare earth elements, and structural materials required	Extraction, Manufacturing
Waste Management	Radioactive Waste Generation	kg/MWh	Amount of high-level and intermediate-level nuclear waste produced	Operation
Waste Management	Renewable Infrastructure Waste	kg/MWh	Waste generated from solar panels, wind turbine blades, and system components	Decommissioning
Economic Sustainability	Lifecycle Cost of Energy (LCOE)	USD/kWh	Total cost of electricity production including construction, operation, and disposal	Full Lifecycle
Social Sustainability	Energy Security Contribution	Index Score	Contribution of hybrid energy systems to national energy reliability	Operation
System Performance	Grid Stability Contribution	% Stability Improvement	Improvement in grid reliability due to hybrid nuclear-renewable energy integration	Operation

Lifecycle inventory data were obtained from energy databases and peer-reviewed literature sources [1–6]. Environmental indicators evaluated in this study include lifecycle greenhouse gas emissions, energy efficiency, water consumption, and waste generation.

Waste management analysis focuses on three major nuclear waste strategies: direct geological disposal of spent nuclear fuel, nuclear fuel recycling and reprocessing, and advanced partitioning and transmutation technologies [6]. Renewable infrastructure waste management is evaluated using circular economy strategies such as photovoltaic module recycling and wind turbine blade material recovery. A multi-criteria sustainability model is applied to compare environmental performance among different energy systems.

4. Results

The results of the lifecycle sustainability analysis demonstrate that nuclear-renewable hybrid energy systems significantly reduce environmental impacts compared with conventional fossil-fuel-based electricity generation, Figure 3. Nuclear energy provides stable baseload electricity with very low operational carbon emissions, while renewable energy sources contribute additional clean electricity during favorable environmental conditions.

The analysis indicates that hybrid nuclear-renewable systems achieve lifecycle carbon emissions between 15 and 30 gCO_2/kWh, which is substantially lower than fossil fuel systems, Table 2. Nuclear reactors contribute consistent low-carbon energy output while renewable technologies reduce reliance on fossil-fuel backup generation, Figure 4.

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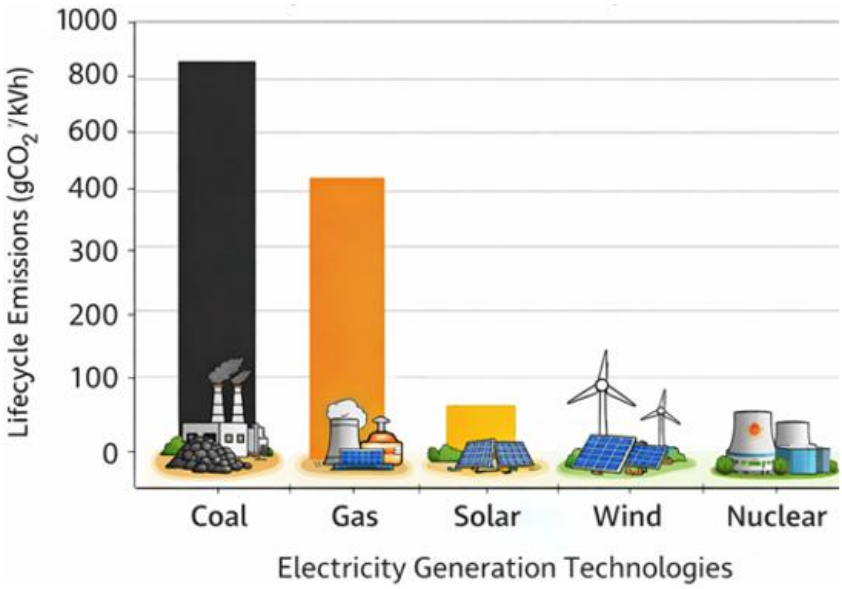


Figure 3. Lifecycle Carbon Emissions Comparison of Electricity Generation Technologies.

Table 2. Lifecycle Carbon Emissions of Electricity Generation Technologies.

Electricity Generation Technology	Lifecycle Carbon Emissions (gCO_2/kWh)	Major Emission Sources	Lifecycle Stages Contributing to Emissions	Environmental Impact Level
Coal-Fired Power Plant	820–1000	Coal combustion, mining operations, plant construction	Fuel extraction, combustion, transportation	Very High
Natural Gas Power Plant	400–500	Methane leakage, natural gas combustion	Fuel extraction, pipeline transport, electricity generation	High
Solar Photovoltaic (PV)	40–60	Manufacturing of PV modules, silicon processing	Manufacturing, installation, recycling	Low
Wind Energy	10–20	Turbine manufacturing, steel and composite materials	Manufacturing, transportation, installation	Very Low
Nuclear Power	10–15	Uranium mining, fuel enrichment, plant construction	Fuel cycle, construction, decommissioning	Very Low
Nuclear–Renewable Hybrid System	15–30	Infrastructure manufacturing, energy storage integration	Construction, operation, recycling	Very Low

Waste management results reveal that although nuclear waste is highly radioactive, the total volume produced is relatively small compared with other industrial waste streams. Deep geological repositories remain the most widely accepted solution for long-term nuclear waste storage [6]. Additionally, advanced nuclear fuel recycling technologies can significantly reduce waste volume while improving fuel utilization efficiency, Figure 5.

Renewable infrastructure waste presents additional sustainability challenges, particularly regarding photovoltaic panel disposal and wind turbine blade recycling. However, emerging recycling technologies and circular economy strategies can recover valuable materials and reduce environmental impacts [2].

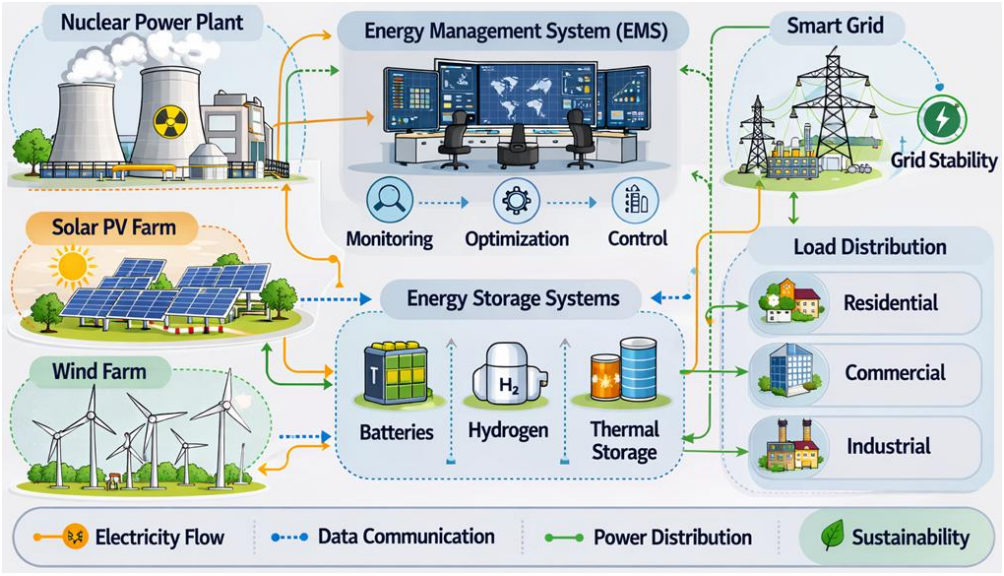


Figure 4. Integrated Nuclear-Renewable Hybrid Energy System Architecture.

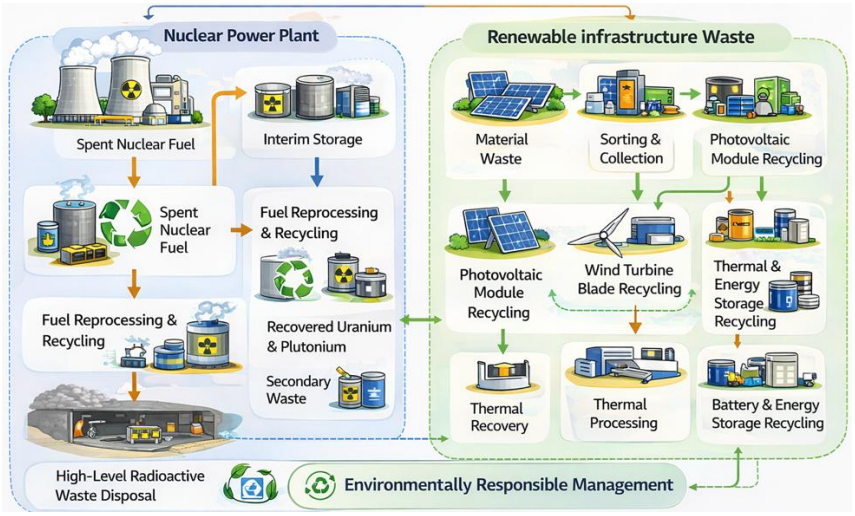


Figure 5. Nuclear and Renewable Waste Management Workflow.

5. Conclusions

This study examined lifecycle sustainability and waste management strategies in nuclear-renewable integrated energy systems using a comprehensive lifecycle assessment framework. The findings indicate that combining nuclear and renewable energy technologies significantly improves environmental sustainability while reducing lifecycle greenhouse gas emissions.

Hybrid nuclear-renewable systems provide reliable electricity generation while minimizing dependence on fossil fuel backup power plants. Although nuclear energy produces radioactive waste, effective management strategies such as deep geological disposal and advanced fuel recycling technologies can mitigate long-term environmental risks.

In addition, renewable infrastructure recycling strategies contribute to circular economy principles and reduce resource depletion. Overall, nuclear-renewable integrated energy systems represent a promising pathway toward achieving global decarbonization and sustainable energy development. Future research should focus on advanced waste treatment technologies, improved lifecycle monitoring methods, and integrated

policy frameworks to support the large-scale deployment of nuclear-renewable hybrid energy infrastructures.

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