Università degli Studi di Padova

University of Padua, Department of Civil, Environmental and Architectural Engineering
Master Thesis in Environmental Engineering

Life Cycle Assessment (LCA) for Hybrid (Wind/-Solar) Systems

Shirin Askari
ID 2081333

Supervisor
Prof. Hamid Sarlak
Dr. Megha Gupta, Postdoc
Technical University of Denmark (DTU)

Internal Supervisor
Prof. Alessandro Manzardo
University of Padua

Academic Year 2024/2025

Contents

Approval

This thesis has been prepared at the Department of Wind and Energy Systems at the Technical University of Denmark (DTU), Department of Civil, Environmental and Architectural Engineering in UNIPD, Dipartimento di Ingegneria Civile, Edile e Ambientale (ICEA) in partial fulfillment of the Master of Science degree in Environmental Engineering, MSc Eng.

In the process of writing and refining this thesis, I utilized AI-based tools to help improve the clarity, coherence, and overall quality of the text. It is assumed that the reader has a basic knowledge in the areas of statistics. The use of AI was limited to enhancing the readability of the document and did not influence the academic integrity or the originality of the findings.

Shirin Askari – 2081333

Signature

Date

Abstract

The increasing urgency to address climate change and the depletion of fossil fuel reserves require the transition to sustainable energy solutions. This thesis explores the optimization and environmental assessment of hybrid power plants (HPPs) that combine a wind and solar system for reliable and efficient electricity production. Focusing on a case study in Denmark, the research employs the **HyDesign tool** for techno-economic optimization and **a Python-based tool** for Life Cycle Assessment (LCA).

The study evaluates multiple configurations of hybrid systems that integrate photovoltaic (PV), wind turbines and battery storage. Key objectives include:

1. **Optimization of system size and capacity:** Optimization of system size and capacity: Using HyDesign to minimize the Levelized Cost of Electricity (LCOE) while maximizing the NPV/CAPEX ratio.

2. **Life Cycle Assessment:** A custom Python-based LCA framework was developed to assess environmental impacts from raw material extraction to end of life. The tool supports both the ReCiPe 2016 and IMPACT 2002+ methods for comprehensive impact characterization across multiple environmental categories.

3. **Economic and environmental balance:** Provide insight into the feasibility of hybrid systems through techno-economic and environmental indicators.

The results contribute to understanding the potential of hybrid systems to enhance energy security and reliability in Denmark, a country recognized for its progressive renewable energy initiatives. By addressing the intermittency of renewable energy sources, this research supports the deployment of sustainable hybrid power solutions.

Acknowledgements

I would like to express my deepest appreciation to my supervisors, whose guidance and support have been invaluable throughout this thesis. Their expertise and encouragement have not only shaped the outcome of this work but also significantly contributed to my personal and professional growth.

Professor Alessandro Manzardo, Department of Civil, Building and Environmental Engineering - ICEA, and Associate Researcher in the field of footprint and sustainability assessment, Department of Industrial Engineering, University of Padova.

Associate Professor Hamid Sarlak, Department of Wind and Energy Systems, Technical University of Denmark (DTU).

Dr. Megha Gupta, postdoctoral researcher, Renewable Plants in Energy Systems, Division of Wind Energy Systems, DTU.

This work would not have been possible without their commitment and insights, and I am sincerely grateful for the opportunity to have worked under their supervision.

1 Introduction

1.1 Background

In recent decades, the extensive use of fossil fuels to meet the demands of heating, electricity, and transportation in developed countries has led to the release of large amounts of carbon, previously stored in natural reserves, into the atmosphere. If this trend continues and spreads to developing countries, humanity could face global climate change in the next century. The urgency to address this challenge, combined with limited fossil fuel supplies, has driven a growing focus on large-scale renewable energy solutions, particularly hybrid power plant systems that integrate solar and wind systems. Such systems present a valuable path to sustainable energy production and help counteract the impacts of global climate change [20].

High energy consumption rates, combined with insufficient supply from existing energy sources, have led to significant energy shortages. Traditional large-scale power generation relies on conventional energy sources that are both limited and unevenly distributed across the Earth's crust. The rapid depletion of fossil fuels such as coal, oil, and gas has made this issue worse and significantly impacted the environment by increasing CO_2 levels, which contributes to global warming. Therefore, there is an urgent need to use renewable energy sources. However, a key challenge with these sources is their dependence on environmental conditions, such as wind speed and solar irradiance.

As a result, individual renewable energy sources often struggle to provide a steady power supply because their availability can vary greatly. To overcome this challenge, various renewable sources, including wind, solar, hydro, biogas, and fuel cells, can be integrated into hybrid systems, offering a more reliable and environmentally friendly energy solution. These renewable sources are classified as distributed energy resources, and their generation is referred to as distributed generation [30], as illustrated in Fig. 1.1.

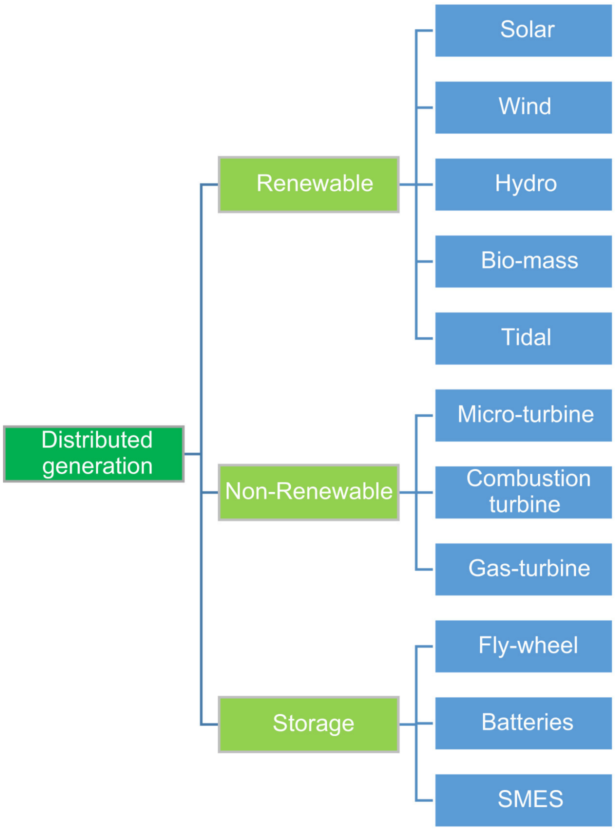


Figure 1.1: Distributed generation. [30].

A hybrid system is defined as the integration of two or more renewable or non-renewable energy sources. The specific hybrid system we focus on combines wind energy and photovoltaic (PV) technology.

Hybrid power plants (HPPs) build on this idea by combining different types of electricity generation at a single connection point to the grid. They often include wind and solar power, as well as battery storage systems. This setup allows excess energy produced when demand is low to be stored in batteries, which can then be used when demand is high. HPP technology facilitates the large-scale adoption of renewable energy while ensuring grid stability, making it an essential approach to achieving sustainable energy solutions.

The primary aim of this thesis is to conduct a comprehensive Life Cycle Assessment (LCA) for a hybrid power plant, focusing on the environmental impacts associated with its various components and operational phases. To achieve this, I will optimize the sizing of the hybrid power plant using the HyDesign tool, which enables the integration of multiple renewable energy sources, such as wind and solar. This tool supports both the evaluation of specific plant designs and general sizing optimization, based on user-defined objective functions—such as minimizing the Levelized Cost of Energy (LCOE) or maximizing Net Present Value (NPV) relative to capital expenditure (CAPEX). The optimization will consider key factors including energy output and economic performance to ensure an efficient and balanced system design.

Following the optimization phase, I will utilize SimaPro to model the LCA component of the project. SimaPro is a robust tool for assessing the environmental impacts throughout the life cycle of the hybrid power plant, from resource extraction to end-of-life disposal. By integrating the insights gained from the sizing optimization with the LCA results, this research aims to provide valuable recommendations for enhancing the sustainability and efficiency of hybrid power plants.

1.2 Problem Statement

The global average surface temperature has already risen by 1.2°C above pre-industrial levels, and 2023 was marked by extreme weather events like heatwaves and droughts. These events have strained energy systems by decreasing hydro and thermal power supply while increasing demand for cooling. CO_2 emissions also reached a record high of 37 gigatonnes in 2022. Various future scenarios predict different emissions pathways, from the Stated Policies Scenario (STEPS), which anticipates emissions leveling off, to the Announced Pledges Scenario (APS) and Net Zero Emissions (NZE) Scenario, which envision significant reductions by 2050 [2].

The continuous rise in global temperatures poses a severe threat to ecosystems and human life. Current policies project temperature increases approaching 2°C by mid-century, leading to potentially severe climate disruptions. Stronger climate actions could help slow this rise, while aiming for net-zero emissions offers hope for a more sustainable future.

Given the increasing challenges of climate change, a transition to Renewable Energy Sources (RES) such as solar and wind power is essential. Fossil fuels are the primary source of greenhouse gas emissions, contributing significantly to global warming and environmental degradation. Shifting to renewable energy is vital for reducing carbon emissions, stabilizing the climate, and securing a healthier future for generations to come [15].

This thesis focuses on the optimization of hybrid power plant (HPP) design, combining wind and solar energy, to achieve a balance between energy production and minimal environmental impact.Hybrid power systems offer the flexibility to balance the variable outputs of renewable sources such as solar and wind by integrating energy storage systems and, if needed, backup power sources. This improves overall system reliability and enhances energy security. By optimizing the size of HPPs, the goal is to design systems that maximize the use of renewable energy while minimizing the overall carbon footprint

As demand for electricity continues to grow, implementing flexible energy solutions—such as batteries, electrolyzers, and hydrogen-based storage systems (H_2X)—can ensure a reliable power supply even when renewable sources fluctuate. Transitioning to renewables not only addresses climate challenges but also conserves natural resources and protects ecosystems. Embracing wind and solar energy as part of a hybrid solution can support a sustainable and resilient energy future.

1.3 Objectives

This thesis aims to enhance the integrated planning and environmental evaluation of hybrid renewable energy systems through the following objectives:

- **Techno-economic optimization:** To optimize the configuration and sizing of a hybrid power plant using the HyDesign tool, targeting the minimization of Levelized Cost of Electricity (LCOE) and maximization of the NPV/-CAPEX ratio. This ensures both cost-effectiveness and financial viability for investment decisions.
- **Comprehensive environmental assessment:** To develop and apply a Python-based Life Cycle Assessment (LCA) framework tailored to wind, photovoltaic (PV), and battery systems. The framework evaluates environmental impacts across all life cycle stages—manufacturing, transportation, and end-of-life—using both ReCiPe 2016 and IMPACT 2002+ characterization methods.
- **Region-specific case study in Denmark:** To apply the integrated techno-economic and environmental model to a real hybrid power project located in Nørhede-Hjortmose, Denmark. The analysis considers local wind and solar resource conditions, manufacturer locations, and logistics routes to generate context-specific insights into the feasibility, emissions profile, and system performance.
- **Visualization and decision support:** To present the results through interactive, component-level emission breakdowns, facilitating stakeholder understanding of emission hotspots and trade-offs, and supporting sustainable planning and policy decisions.

1.4 Scope and Limitations

This thesis presents a comprehensive assessment of the Nørhede-Hjortmose hybrid power plant (HPP) located in Ringkøbing, Denmark, through both techno-economic and environmental lenses. The study utilizes the *HyDesign* tool developed by DTU for system sizing and scenario simulation, followed by a custom-built Python-based Life Cycle Assessment (LCA) framework to quantify emissions across all major life cycle stages: Manufacturing, Transportation, and End-of-Life (EOL).

The scope includes:

- Evaluation of four HPP design configurations under fixed and variable capacity constraints.
- Integration of component-level inventories for wind turbines, photovoltaic (PV) systems, and battery storage.
- Calculation of manufacturing emissions using material-specific factors derived from publicly available sources (e.g., NREL, IEA PVPS, IMO).
- Estimation of transportation emissions based on geographic distances and transport mode selection (truck, rail, ship).
- Modeling of end-of-life emissions considering recycling, landfill, hazardous, and incineration pathways.
- Impact assessment using ReCiPe 2016 and IMPACT 2002+ methods across multiple environmental categories.

However, the study is subject to several limitations:

- **Database access:** Due to restricted access to commercial LCA databases such as Ecoinvent or SimaPro, emission factors were sourced from literature and technical reports, which may lack consistency or full regional specificity.
- **Assumptions in transportation:** Transport distances are based on estimated routes and manufacturer locations, which may not reflect the actual logistics chain.
- **Simplified EOL modeling:** The end-of-life treatment allocation is material-based and does not account for detailed local waste management infrastructure or emerging recycling technologies.
- **Limited operational data:** The system's operational phase was excluded from environmental analysis due to minimal emissions and the lack of site-specific operational datasets.
- **Tool validation:** While the custom Python framework is modular and flexible, it has not undergone formal validation against standardized LCA software tools like SimaPro or GaBi.

Despite these limitations, the integrated framework and site-specific approach provide meaningful insights into the environmental trade-offs of hybrid power systems and can support future research or policy decisions aimed at sustainable energy planning.

1.5 Thesis Structure

This thesis is organized into the following chapters:

- **Chapter 1 – Introduction:** Introduces the motivation behind hybrid renewable energy systems, their role in addressing climate change, and the need for integrated techno-economic and environmental assessments. It also outlines the research objectives, problem statement, scope, and methodology overview.
- **Chapter 2 – Literature Review:** Provides an overview of renewable energy technologies including wind and solar systems, hybrid system configurations, Life Cycle Assessment (LCA) methodology, and previous studies on techno-economic and environmental evaluations.
- **Chapter 3 – Methodology:** Describes the tools and methods used for techno-economic modeling and environmental assessment. This includes the HyDesign tool for hybrid system optimization and the custom Python-based LCA framework developed for emissions analysis across manufacturing, transportation, and end-of-life stages.
- **Chapter 4 – Case Study:** Presents the application of the methodology to the Nørhede-Hjortmose hybrid power plant in Denmark. It includes input data, sizing scenarios, simulation results, and environmental evaluation based on Life Cycle Inventory (LCI) and Impact Assessment (LCIA).
- **Chapter 5 – Results and Discussion:** Analyzes and interprets the techno-economic and environmental results. Discusses system performance, emissions breakdown, environmental hotspots, and design trade-offs between configurations.
- **Chapter 6 – Conclusion and Future Work:** Summarizes the main findings, highlights methodological limitations, and proposes recommendations for future research on hybrid renewable energy systems and LCA improvements.

2 Literature Review

2.1 Hybrid Power Plant Concepts

2.1.a Renewable Energy and Climate Change

All societies depend on energy services to fulfill fundamental human needs, such as lighting, cooking, heating, transportation, and communication, as well as to support productive processes. For sustainable development, it is essential that energy services are both secure and environmentally responsible. Achieving sustainable social and economic growth requires reliable and affordable access to the energy resources necessary to supply these critical services. This can involve adopting diverse strategies based on different stages of economic development. To minimize environmental harm, energy services must produce minimal environmental impact and low greenhouse gas (GHG) emissions. Currently, however, fossil fuels account for 85% of primary energy driving global economies, contributing to 56.6% of all human-made GHG emissions [29].

In 2008, renewable energy (RE) sources made up approximately 12.9% of the global primary energy supply, which totaled 492 exajoules (EJ), according to the IEA (2010a). Biomass was the largest RE source, contributing 10.2%, with around 60% of biomass energy being used for traditional cooking and heating, particularly in developing regions. However, the use of biomass for modern energy applications was also rising significantly. Hydropower contributed another 2.3%, while other renewable sources together made up 0.4% of the total RE supply, as shown in Figure 2.1 [29].

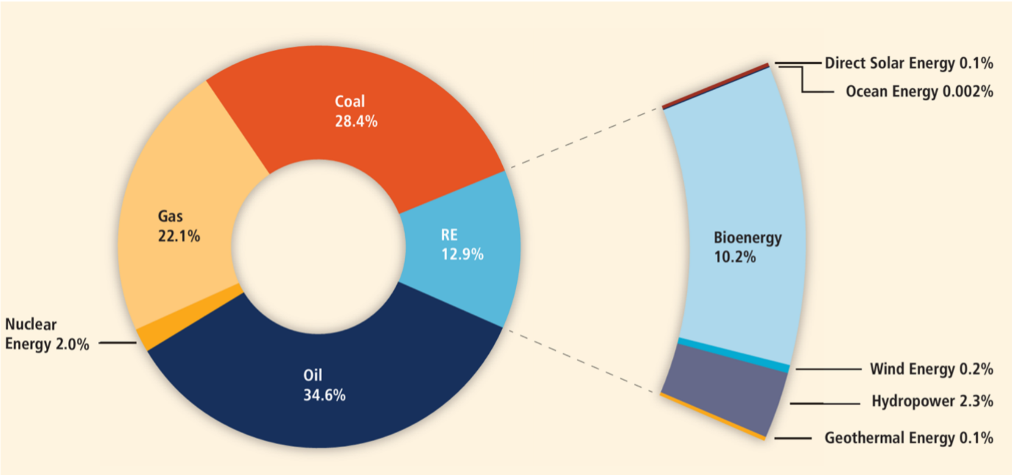


Figure 2.1: Distribution of energy sources in global primary energy supply for 2008 (492 EJ). Modern biomass represents 38% of the total biomass share.[1].

2.1.b Wind Energy

Wind energy has substantial potential for reducing greenhouse gas (GHG) emissions in both the short and long term, making it a key resource in the global effort to combat climate change. Wind energy systems can generally be categorized into onshore and offshore types. Onshore wind energy involves wind turbines installed on land, typically in open areas with high wind resources, whereas offshore wind energy comprises turbines located in bodies of water, where wind speeds are often stronger and more consistent [4]. In 2023, the global wind energy market grew faster than in previous years. As seen in Figure 2.2, global wind power capacity increased by 116.6 GW—a 50% rise from 2022—bringing the total to 1,021 GW. This represents a 13% growth rate, showing the rapid expansion of renewable energy sources. The onshore wind sector made a large contribution, setting a record with 105.8 GW added, increasing the total onshore capacity to 945 GW [31]. This growth was driven by policies in the Asia-Pacific region, particularly in China. However, North America saw a 16% drop in onshore installations, mainly due to slower growth in the United States.

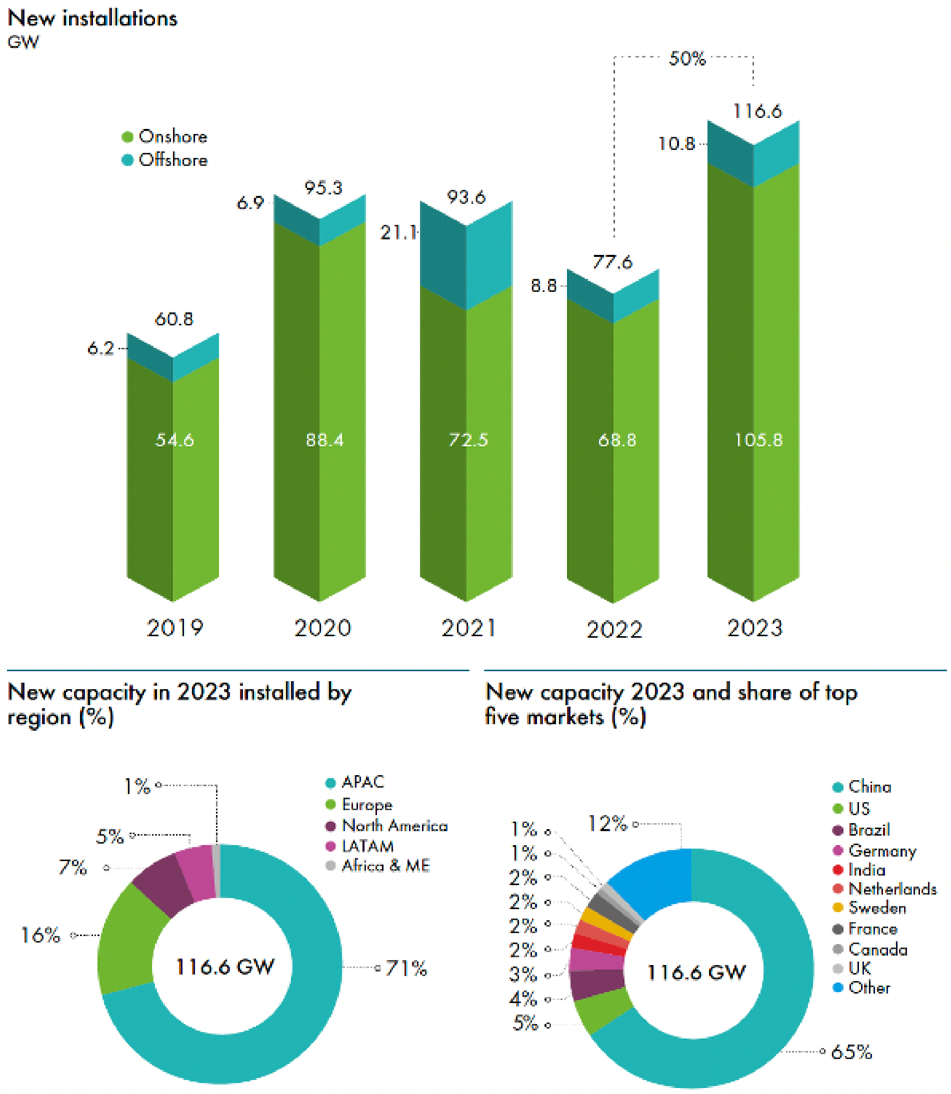


Figure 2.2: Overview of the Global Wind Energy Market in 2023. This figure shows the overall market trends and highlights major developments in the wind energy sector [31].

Offshore wind system also grew in 2023, with an addition of 10.8 GW—the second-highest annual increase in the sector. Figure 2.3 shows Europe's commitment to offshore wind, highlighted by Denmark's completion of the Vesterhav Syd and Nord offshore wind projects in the North Sea. These projects, fully operational by early 2024, demonstrate Denmark's focus on expanding offshore wind capacity alongside other European installations . European installations.Regionally, the Asia-Pacific region held the largest market share at 71% , with most of the growth in China and India, which saw a combined increase of 15% . Europe came in second, adding 18.3 GW, including a record 16.2 GW from the EU-27 countries, though its global share dropped by 9% . North America retained third place, despite the U.S. having its lowest installation levels since 2014. Brazil's record installations kept Latin America in fourth place with a 5% share of the global market.The top five countries for new wind installations in 2023 were China, the U.S., Brazil, Germany, and India, with India moving up in the rankings. Together, these countries accounted for 80% of global installations, with China leading the increase. By the end of 2023, China, the U.S., Germany, India, and Spain held 72% of the world's wind capacity, as illustrated in Figure 3.3.[31].

Figure 2.3: Status of the Onshore Wind Market in 2023. This figure details the current state of the onshore wind market, reflecting regional trends and recent developments within the sector. [31].

2.1.c Solar Energy Technologies (SETs)

Solar energy is one of the most abundant and sustainable energy resources available, providing significant potential for both short-term and long-term climate change mitigation. By harnessing solar energy, we can meet global energy demands while reducing greenhouse gas emissions. The rapid advancement of solar technologies offers diverse applications capable of fulfilling various energy service needs. Among the most prominent solar technologies are photovoltaic (PV) systems, concentrating solar power (CSP) systems, and solar chimneys [11].

Photovoltaic (PV) Systems: PV systems convert solar radiation directly into electricity via the photovoltaic effect—an interaction where incident sunlight excites electrons in a semiconductor material, generating an electric current. Modern PV technologies are primarily based on crystalline silicon (c-Si), which accounts for over 95% of the global market due to its high efficiency and scalability [48].

Recent innovations have led to the development of advanced architectures such as PERC (Passivated Emitter and Rear Cell), HIT (Heterojunction with Intrinsic Thin layer), and TOPCon (Tunnel Oxide Passivated Contact), with lab efficiencies approaching 26–27%. These improvements have significantly enhanced the performance of both residential and utility-scale solar installations.

PV systems are modular, low-maintenance, and easy to deploy in diverse settings, from rooftops and open land to integration in building materials (BIPV) or floating platforms (FPV). Their versatility and declining costs make them a central pillar of global clean energy strategies. Figure 2.4 provides a schematic illustration of a typical PV system setup.

Figure 2.4: photovoltaic (PV) system

Concentrating Solar Power (CSP) Systems: CSP systems use mirrors or lenses to concentrate sunlight onto a small focal point or line, producing high-temperature thermal energy. This heat is then used to drive a steam turbine or other heat engine connected to a generator. CSP is particularly effective in arid, high-irradiance regions such as deserts and offers the significant advantage of thermal energy storage, enabling power generation even during periods without sunlight.

These systems can be designed with molten salt storage, parabolic troughs, solar towers, or dish-engine configurations. With appropriate investment and supportive energy policy, CSP technology has the potential to supply over 20% of the global electricity demand by 2050. Figure 2.5 illustrates the basic principle and components of a CSP plant.

Figure 2.5: Concentrating Solar Power (CSP) system using a central receiver and thermal energy storage.

Solar Chimneys: Solar chimneys work by using solar energy to heat air within a tall structure, creating an updraft that drives a turbine connected to a generator. This innovative technology harnesses solar thermal energy and can be implemented on a large scale to generate electricity, contributing to a diverse energy mix.

Solar energy technologies (SETs) offer substantial environmental benefits compared to conventional energy sources, primarily due to their minimal air emissions and waste production. They are considered nearly clean and safe, with the added potential for standalone applications that support ecosystem protection and remote monitoring. SETs also provide socio-economic advantages, including diversified energy supply, job creation, and reduced dependency on fuel imports. However, it's important to acknowledge that no project is entirely free from environmental impact, which can vary by site, often relating to visual and noise pollution. These impacts are typically minor and can be mitigated through best practices and advanced technologies. Investors, developers, and permitting authorities must prioritize environmental considerations during planning. Conducting an Environmental Impact Assessment (EIA) can effectively estimate potential impacts and suggest mitigation measures, leading to better project design and public acceptance. [11].

2.1.d Why Hybrid Power Plants?

The rapid development of hybrid power plants that combine photovoltaic (PV) solar systems and wind energy has emerged as a solution to the challenges posed by the intermittent nature of these renewable sources. These hybrid plants enhance reliability and efficiency in electricity production by integrating both solar and wind energy, which are inherently variable and dependent on environmental conditions.

To ensure that electricity is produced precisely when needed, it is essential to develop specialized hybrid power plants. These plants can incorporate energy storage systems to store excess energy generated during peak production times or combine solar and wind energy with advanced control mechanisms to optimize output.

Developers are exploring various configurations for hybrid systems, including:

- **PV solar systems combined with wind turbines:** This configuration allows for simultaneous harnessing of solar and wind energy, maximizing energy generation throughout the day and across different weather conditions.
- **Wind turbines integrated with battery storage:** This setup ensures that excess energy generated during windy periods can be stored and utilized when energy demand is high or wind conditions are low.
- **Advanced control systems to optimize energy output:** By employing sophisticated algorithms and technologies, these systems can manage the energy produced by both PV and wind sources, ensuring a stable and reliable energy supply.

Hybrid power generation systems effectively leverage the strengths of solar and wind energy to mitigate their weaknesses [41].

2.2 Design Approaches for Hybrid Systems

Designing hybrid renewable energy systems involves a multidisciplinary approach that combines energy resource assessment, component selection, system sizing, and control strategies. The objective is to achieve an optimal balance between system cost, reliability, and environmental impact. Several tools and methodologies have been developed to assist in this process, ranging from rule-based heuristics to advanced optimization algorithms.

In this thesis, the HyDesign tool—developed by the Technical University of Denmark (DTU)—is used as the core platform for techno-economic design and sizing of hybrid systems [13]. HyDesign enables both fixed and variable capacity design scenarios through a nested optimization structure [42]:

It integrates techno-economic constraints including component costs, degradation penalties, and grid limitations.

Several common design configurations explored in literature and applied in this study include:

- Wind-PV hybrid systems with and without battery storage
- Wind-PV-Battery systems
- Power-to-X (PtX) integration for green hydrogen

These configurations are tested in the case study using the same geographic and economic context. The resulting techno-economic performance metrics are used to guide the environmental assessment in the next phase of the study.

2.3 Life Cycle Assessment

Life Cycle Assessment (LCA) is a standardized analytical tool used to evaluate the potential environmental impacts associated with all stages of a product's life—from raw material extraction and manufacturing to transportation, usage, and end-of-life disposal [16]. This "cradle-to-grave"[27] perspective makes LCA particularly valuable in assessing energy systems that span complex global supply chains and long operational lifetimes.

Unlike traditional evaluation methods that focus on a single life phase (such as operational emissions), LCA provides a holistic view that encompasses both direct and indirect environmental effects. In the context of electricity production, inputs include primary energy sources, materials, and infrastructure, while outputs involve secondary energy (electricity), emissions, and waste.

The standardized LCA framework is defined by ISO 14040 and ISO 14044 [26, 27].

Several impact assessment methodologies have been developed for the LCIA stage. In this thesis, both ReCiPe 2016 [21] and IMPACT 2002+ [28] are employed. ReCiPe 2016 translates LCI results into both midpoint indicators (e.g., climate change, ozone depletion) and endpoint damage categories (human health, ecosystems, resources) [21]. IMPACT 2002+ integrates midpoint and damage categories into a single harmonized framework, useful for comparative sustainability assessments.

LCA plays a crucial role in supporting policymakers, engineers, and investors by revealing environmental trade-offs that are often invisible in cost-based evaluations alone [12]. When combined with techno-economic analysis, LCA enables a more comprehensive sustainability assessment of renewable energy systems.

2.4 Previous Studies on LCA of Hybrid Power Plants

Numerous studies have applied Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) methods to evaluate the environmental and economic impacts of renewable energy systems. These analyses are especially relevant for wind and solar technologies, where the majority of emissions occur during manufacturing and end-of-life stages rather than operation. Through detailed modeling, LCA allows researchers to identify high-emission components, assess material recovery potential, and compare different system configurations and technology choices.

Many studies also integrate economic indicators through LCC analysis, offering a combined view of environmental performance and cost-effectiveness. This is particularly valuable in decision-making processes for policymakers and project developers aiming to meet both sustainability and financial goals.

The table below summarizes key research findings from a wide range of LCA and LCC studies on wind, solar, and hybrid energy systems.

Table 2.1: Summary of Life Cycle Assessment Studies in renewable energy.

Ref.	Method	Software/Tool	Key Findings
[32]	LCA of Energy and CO_2 Emissions in Wind Turbines	Process Analysis, Hybrid	Energy and CO_2 intensities depend on production methods and materials. Larger turbines have lower intensities.
[33]	Economic and Environmental Analysis of Wind Turbines	Monte Carlo Simulation	Wind turbines have lower CO_2 and SOx/NOx emissions than fossil fuels. Viability varies by location.
[36]	LCA of Wind Turbine	CML Method	Manufacturing impacts arise from steel production. Recycling reduces overall environmental impact.
[45]	LCA of Wind Turbines	Not specified	Larger turbines (4.5 MW) have lower energy intensity due to economies of scale.
[41]	LCA of Hybrid (Solar & Wind) Systems	Hybrid Power Systems Design	Hybrid systems enhance energy reliability and allow surplus feed-in.
[18]	LCA for Wind, Hydraulic, and Solar Energy	SimaPro 7.0	Increased renewable integration lowers CO_2 emissions. Country-specific outcomes vary.
[34]	LCA of Wind Power	SimaPro 7.1	Denmark's mix of coal, CHP, and wind affects marginal production based on demand.
[47]	LCA of Concentrated Solar Power (CSP) Technologies	LEAP, MARKAL, GAMS	CSP shows high potential for emission reductions. Technological advancements reduce costs by 2050.
[37]	LCA of Solar Chimneys	Hybrid-Approach Model	Solar chimneys suit arid regions with low water needs and payback periods of 2-3 years.
[49]	LCA with Design Alternatives	SimaPro with Ecoinvent v2.2	Thermal Energy Storage (TES) in CSP reduces greenhouse gas emissions and improves efficiency.

Ref.	Method	Software/Tool	Key Findings
[38]	LCC Model for Offshore Wind	Not specified	Comprehensive LCC model highlights cost reduction opportunities throughout lifecycle.
[3]	WISDEM for Wind Farm Cost Analysis	WISDEM, Python, OpenMDAO	Optimized wind farm designs lower costs and enhance economic viability.
[14]	LCA Onshore and Offshore Wind Energy	Siemens Wind Power data	Onshore turbines are more efficient, with lower CO_2 per kWh. Recycling reduces climate impact.
[7]	LCA of Wind and Solar	THEMIS, REMix	Variable Renewable Energy (VRE) systems show better climate performance but higher resource depletion.
[10]	Simulation and Optimization of Wind-Solar Hybrid System	Particle Swarm Optimization Algorithm	Hybrid systems reduce wind curtailment. Storage improves stability and economics.
[5]	LCA of Solar Power (CSP) Plant	ReCiPe method, IPCC 2013 method	TES enhances CSP performance and reduces reliance on grid electricity.
[8]	LCA of Solar Photovoltaic	E3-India Model	Recycling solar PV waste supports a circular economy. Subsidies needed for economic feasibility.
[6]	LCA of Wind Power	Multiple economic indicators	Analyzed cost composition for diverse wind farm types and settings.
[9]	Hybrid Renewable Energy Systems Techno-economic and Environmental Assessment	HOMER Pro and SimaPro	Studied 11 HRES combinations. Lowest LCOE (0.319 $/kWh) achieved with PV/WT/BAT/CONV/DG.

3 Methodology

3.1 Research Methodology

This study employs a two-stage methodological framework that integrates techno-economic modeling and environmental life cycle assessment (LCA) to evaluate a hybrid power plant (HPP) composed of wind turbines, photovoltaic (PV) panels, and battery energy storage systems (BESS). The overall approach includes:

- **Stage 1 – Techno-economic optimization:** Conducted using the HyDesign tool, developed by DTU, to determine the optimal configuration of the HPP in terms of capacity and design layout.
- **Stage 2 – Environmental assessment:** A custom Python-based Life Cycle Assessment (LCA) model is used to quantify environmental impacts throughout the life cycle. While the model is not formally validated against platforms like SimaPro, it is informed by emission factors and parameters sourced from scientific reports, articles, and other credible references.

This dual-phase strategy allows for balancing economic feasibility with environmental sustainability, and for making informed design decisions based on site-specific inputs.

3.1.a Hybrid Power Plant Design (Hydesign)

HyDesign is an open-source tool developed by DTU, designed to simulate and optimize the configuration and operation of hybrid systems consisting of wind turbines, solar PV, and battery energy storage systems (BESS).

The optimization consists of two levels:

- **Outer sizing optimization:** Adjusts the capacities of wind, solar, and battery systems to maximize Net Present Value over Capital Expenditure (NPV/-CAPEX) or minimize Levelized Cost of Electricity (LCOE).
- **Inner EMS optimization:** It determines the optimal hourly power dispatch between generation sources, energy storage systems, and connected loads, balancing supply and demand while minimizing operational costs, maximizing system efficiency, and ensuring reliable performance across all time steps.

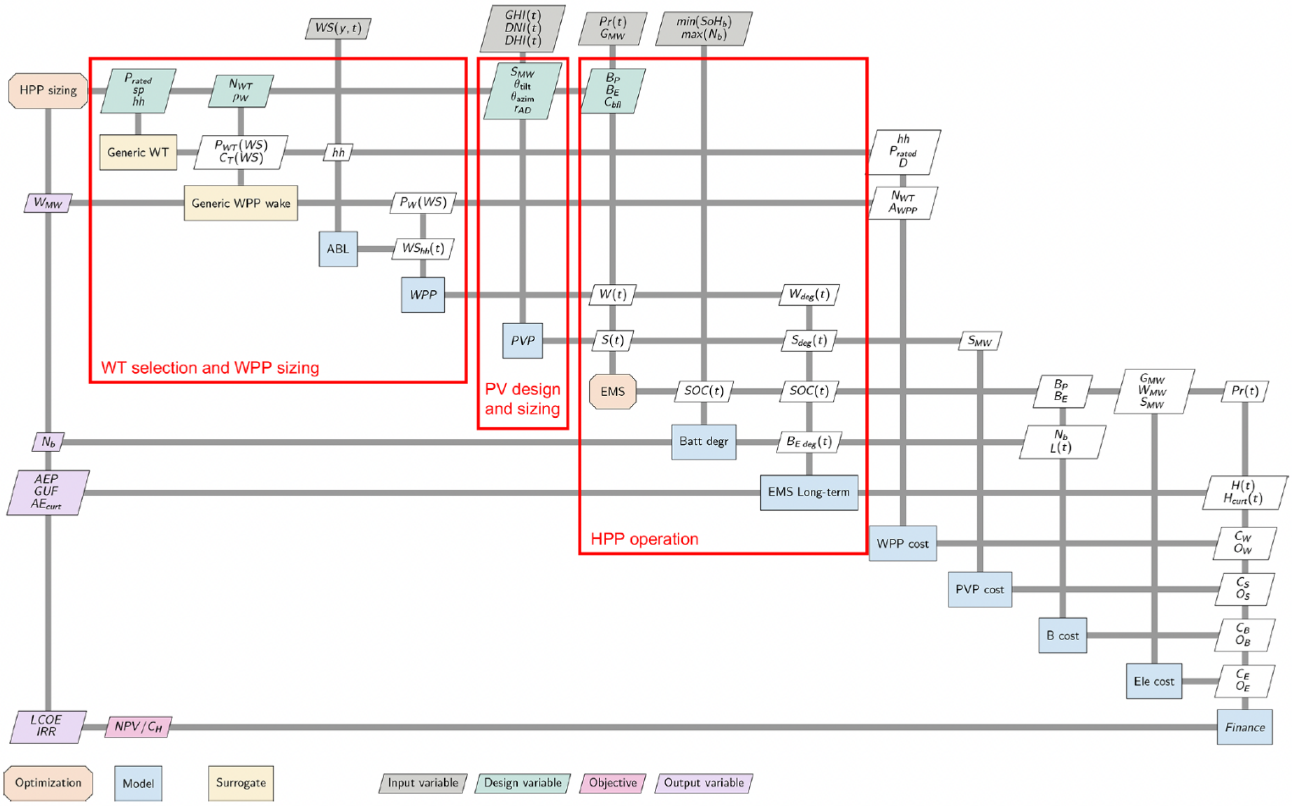


Figure 3.1: HyDesign's extended optimization structure for hybrid power plants. This diagram outlines wind and PV sizing, EMS dispatch, and financial flows across the model.[43].

How HyDesign Is Run in Practice?

To run HyDesign for a specific HPP configuration, the user begins by evaluating a basic system setup. This is done in a Python cell where key sizing parameters for wind, solar, and battery components are defined:

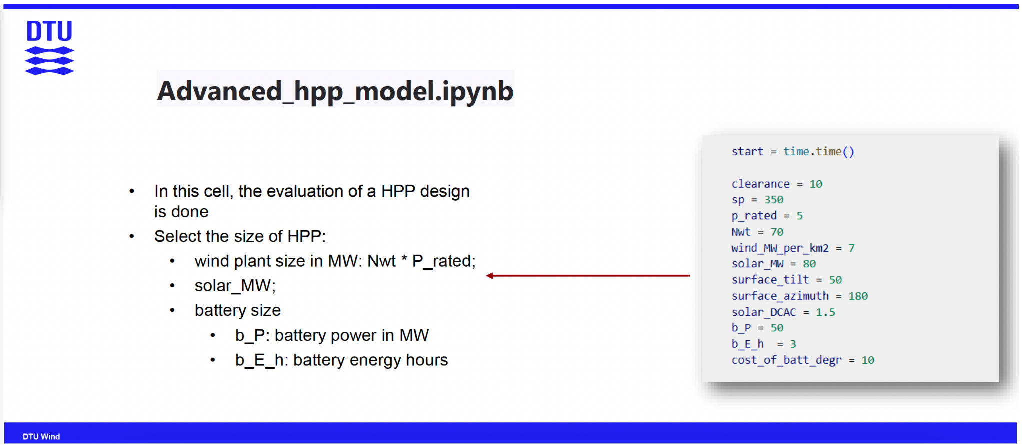


Figure 3.2: Parameter setup for HPP evaluation in HyDesign (input)[43]

Once the system size is set, HyDesign performs the evaluation of the HPP design using these inputs. If the results are suboptimal,Figure 3.3 (poor NPV/-CAPEX), the tool moves to sizing optimization Figure 3.4 by adjusting these parameters.

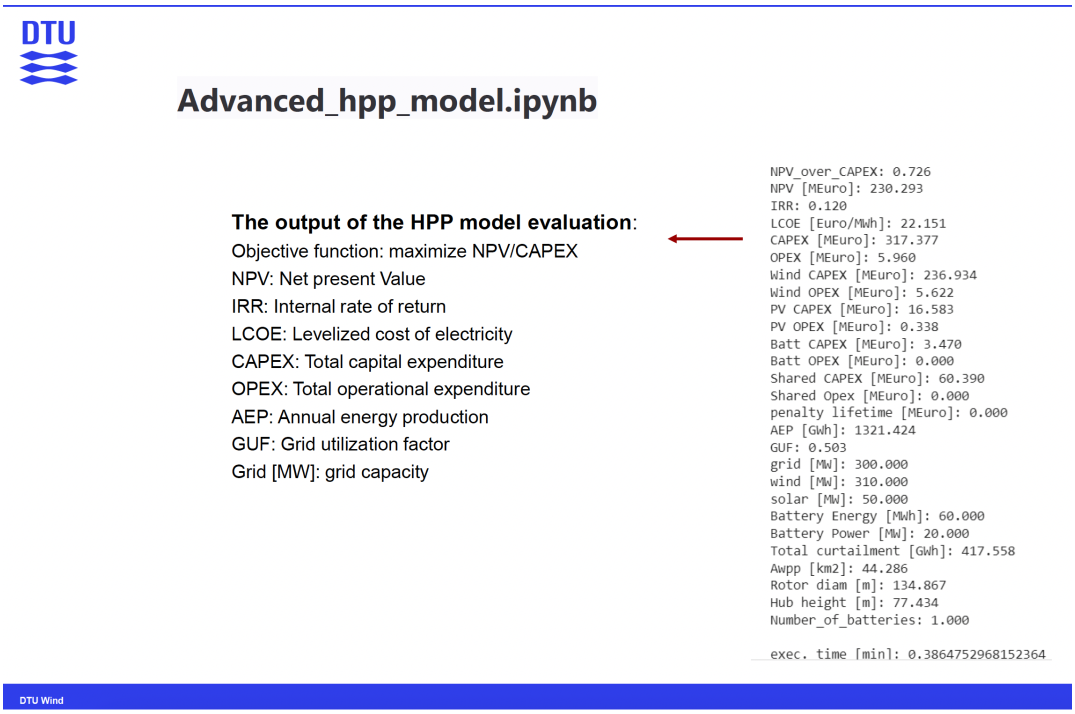
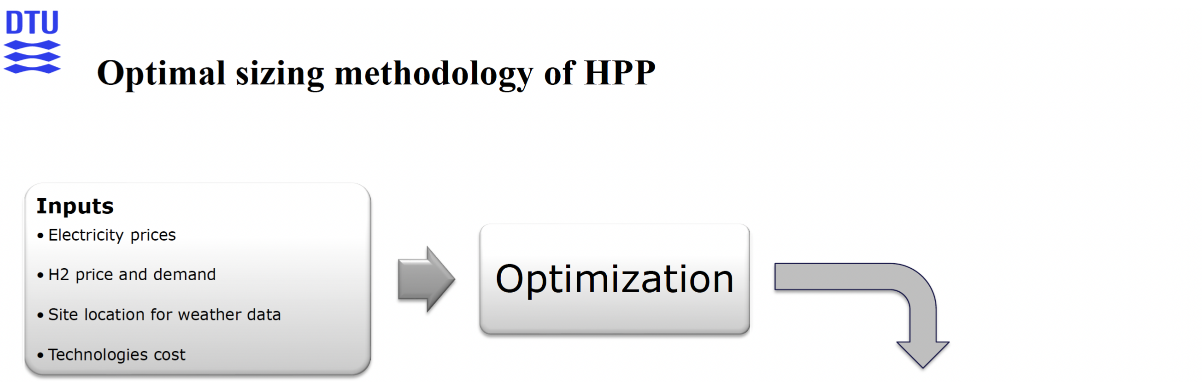


Figure 3.3: HPP evaluation in HyDesign (output)[43]

The model then computes the following indicators:

- **NPV**: Net Present Value
- **IRR**: Internal Rate of Return
- **LCOE**: Levelized Cost of Electricity
- **CAPEX**: Capital Expenditures
- **OPEX**: Operational Expenditures
- **AEP**: Annual Energy Production
- **GUF**: Grid Utilization Factor



Output (Design Variables)				Output
Wind	Solar	Battery	P2H	Finance model
Rotor diameter, hub height	AC power	Power rating	Electrolyzer capacity	NPV/CAPEX
Area of land	Surface tilt angle	Energy storage Capacity	H2 storage capacity	IRR
Rated power	Surface azimuth angle			LCOE, LCOH
Number of wind turbines				AEP, AHP
Wind power density				Number of batteries

Figure 3.4: HyDesign input parameters and manual configuration in Sizing HPP Model[43].

The optimization seeks to minimize the Levelized Cost of Electricity (LCOE) or maximize the Net Present Value per Capital Expenditure (NPV/CAPEX):

$$\min_{x} \begin{cases} -\frac{NPV}{CAPEX}(x) \\ LCOE(x) \end{cases} \tag{3.1}$$

The vector of design variables is:

$$x = \{hc, sp, P_{\text{rated}}, NWT, \rho_W, SMW, \theta_{\text{tilt}}, \theta_{\text{azim}}, r_{AD}, BP, BE_h, C_{bfl}\}$$

- hc: Hub height (m) – affects wind exposure and power output.

- sp: Specific power (MW/m^2) – ratio of rated power to rotor area.
- P_{rated}: Rated turbine power (MW).
- NWT: Number of wind turbines.
- ρ_W: Wind plant power density (MW/km^2).
- SMW: Installed solar capacity (MW).
- $\theta_{\text{tilt}}, \theta_{\text{azim}}$: Tilt and azimuth angles of PV modules.
- r_{AD}: PV DC/AC inverter ratio.
- BP: Battery power capacity (MW).
- BE_h: Battery energy storage capacity (MWh).
- C_{bfl}: Penalty cost for battery fluctuation.

System Submodels

Wind Energy Model

Wind power output is calculated using:

$$P_{WT}(WS) = NWT \times P_{\text{rated}} \times (1 - WL(WS)) \tag{3.2}$$

Where $WL(WS)$ denotes wind wake losses estimated from surrogate modeling.

Solar PV Model

PV output is modeled as:

$$P_{PV} = SMW \times \eta_{PV} \times f(\theta_{\text{tilt}}, \theta_{\text{azim}}) \tag{3.3}$$

Where η_{PV} is module efficiency and f represents orientation correction.

Battery Degradation Model

Battery lifetime degradation is modeled by:

$$f_d = \sum_{j=1}^{n_R} (S_{DoD,j} + S_{tc,j}) \cdot S_{SoC,j} \cdot S_{T_c} \tag{3.4}$$

With S_{DoD}, S_{tc}, S_{SoC}, and S_{T_c} capturing depth-of-discharge, calendar aging, state-of-charge, and thermal degradation.

Energy Management System (EMS)

The EMS optimization maximizes energy market revenue:

$$\max \sum_{t} (P_r(t) \cdot H(t)) - l - l_b \tag{3.5}$$

Where $P_r(t)$ is electricity price, $H(t)$ output power, and l, l_b are penalties for peak-hour mismatch and ramping.

Cost Modeling

Capital Expenditure (CAPEX)

The total capital expenditure is calculated as:

$$C_{\text{CAPEX}} = C_W + C_S + C_B + C_{\text{grid}}$$

This formula represents the aggregated investment needed to establish the hybrid power plant (HPP). The term C_W refers to the cost of wind turbines, including the procurement, transportation, foundation works, and installation of turbine hardware and related electrical systems. C_S captures the expenses associated with solar photovoltaic (PV) installation, such as PV modules, inverters, support structures, wiring, and installation labor. C_B accounts for the cost of the battery energy storage system (BESS), covering battery cells, battery management systems, enclosures, power electronics, and safety systems. Finally, C_{grid} represents the infrastructure costs for connecting the hybrid system to the main grid, including substations, transmission lines, SCADA systems, and grid compliance equipment. These components collectively define the upfront investment required to construct a fully operational HPP. [39]

Operational Expenditure (OPEX)

The operational expenditure over the plant's lifetime is defined as:

$$C_{\text{OPEX}} = C_{\text{fixed}} + C_{\text{variable}}$$

Here, C_{fixed} includes recurring annual costs that are largely independent of system output, such as scheduled maintenance, system inspections, administrative costs, insurance, and site leasing fees. In contrast, C_{variable} represents the operational costs that fluctuate based on the amount of energy generated and usage patterns. This includes expenses such as component wear and tear, unscheduled repairs, cleaning of solar panels, battery replacements, and inverter servicing.

Together, these ensure the continued functionality and reliability of the hybrid power plant over its operational life.

Total Cost

The overall lifetime cost of the hybrid power system is the sum of the capital and operational expenditures:

$$C_{\text{total}} = C_{\text{CAPEX}} + C_{\text{OPEX}}$$

This total cost metric is essential for comparing different system configurations in techno-economic analysis. It provides a comprehensive view of both upfront investment and long-term operational burdens, supporting more informed decisions in system design and optimization.[39]

3.1.b Life Cycle Assessment of the Hybrid Power Plant

Life Cycle Assessment (LCA) is a well-established methodological framework used to quantify the environmental impacts associated with every stage of a product's life cycle—from the extraction of raw materials and manufacturing processes to distribution, usage, and end-of-life treatment [16]. This comprehensive "cradle-to-grave" approach [27] is especially suited for evaluating energy systems with complex supply chains and extended lifespans.

In contrast to conventional evaluation techniques that often focus on a single life stage—such as emissions during operation—LCA offers an integrated assessment that captures both direct and indirect environmental burdens. When applied to electricity generation, it considers inputs like energy resources, materials, and infrastructure, and accounts for outputs such as electricity, emissions, and waste.

The framework for conducting an LCA is standardized under ISO 14040 and ISO 14044 [26, 27].

Various Life Cycle Impact Assessment (LCIA) methodologies have been established for interpreting inventory data. In this thesis, both ReCiPe 2016 [21] and IMPACT 2002+ [28] are utilized. ReCiPe 2016 facilitates the translation of inventory data into midpoint indicators (e.g., climate change, ozone layer depletion) as well as endpoint damage categories (e.g., human health, ecosystems, resource availability) [21]. On the other hand, IMPACT 2002+ offers a unified framework that combines midpoint and endpoint indicators, making it particularly useful for comparative environmental evaluations.

LCA serves as a valuable decision-support tool for policymakers, engineers, and investors by highlighting environmental trade-offs that are often overlooked in purely economic assessments [12]. When integrated with techno-economic analysis, LCA contributes to a more complete and informed evaluation of the sustainability of renewable energy technologies.

4 Case Study(Nørhede-Hjortmose-Denmark)

Renewable energy technologies are not completely carbon-free when considering their entire life cycle. It is important to evaluate their environmental impacts before planning new power plants.[13].

This case study focuses on the Nørhede-Hjortmose hybrid renewable energy park located in Ringkøbing, Denmark. The wind farm section includes **22 Vestas V112-3.3 MW turbines** (totaling 72.6 MW), while the solar power plant has a **capacity of 132 MW**, sufficient to power approximately **42,000 households**. The park is owned by *AURA Energi*, *Møllelauget Nørhede-Hjortmose Vindkraft I/S*, and *Encavis AG*, with operation handled by *Vestas Wind Systems*. Although the wind section became partially operational in 2013, the entire system is expected to be fully functional by 2026.

The site location is at a latitude of 56, longitude of 8, and an altitude of 17.0 meters above sea level. The solar panels used are monocrystalline silicon modules, optimized for high irradiance conditions and installed without tracking systems.

4.1 HyDesign-Based Sizing Scenarios

To evaluate the techno-economic feasibility of the Nørhede-Hjortmose hybrid power plant, four configurations were simulated using the HyDesign tool [44]. The site is located near Ringkøbing in western Denmark. As seen in the map (Figure 4.1), this region offers strong wind conditions and ample open land, making it suitable for the development of hybrid renewable energy.

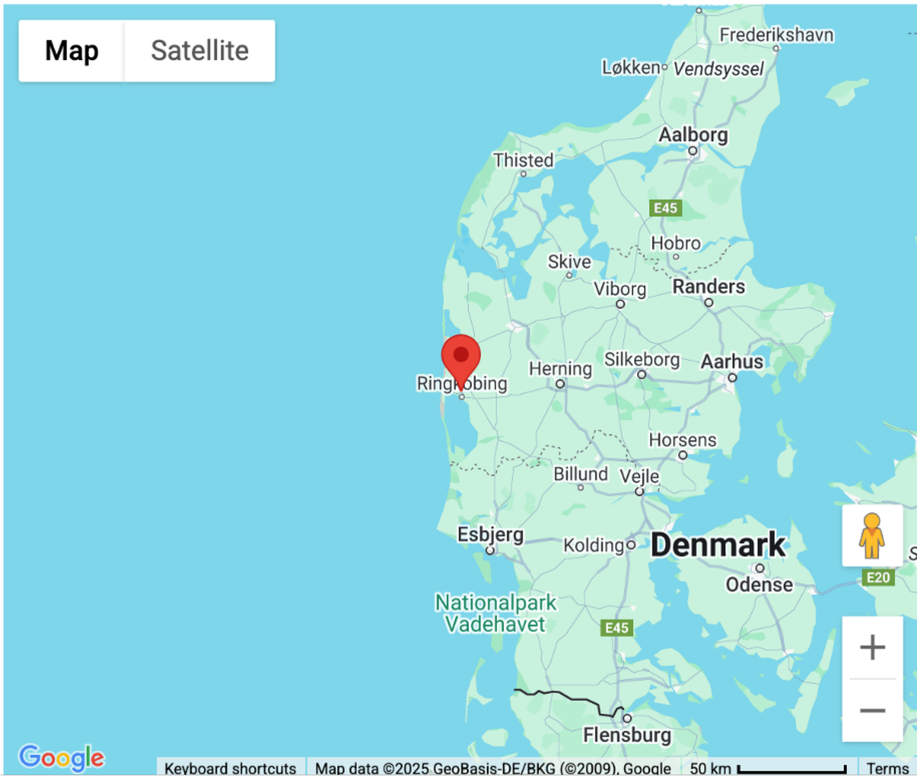


Figure 4.1: Nørhede-Hjortmose hybrid power plant site near Ringkøbing.

Figure 4.2: Hybrid power plants at Nørhede-Hjortmose.

Configuration 1: Fixed System with Battery Storage

In Configuration 1, several system parameters were initially fixed to allow a baseline comparison. The grid interconnection limit was set at 150 MW. The selected wind turbine had a rated power of 3.3 MW, and a total of 22 turbines were installed, resulting in a wind farm capacity of 72.6 MW. The solar photovoltaic (PV) component was sized at 132 MW. Additionally, a battery energy storage system (BESS) was incorporated, providing 80 MW of discharge power and 3 hours of storage duration, corresponding to 240 MWh of energy storage capacity.

The number of batteries required throughout the project lifetime (two replacements),rotor diameter (144.943 meters) and hub height (116.471 meters) were determined by HyDesign during the system sizing optimization process.

Table 4.1: Configuration 1 – System Setup

Parameter	**Value**
Location	Denmark (loc14) - Config 1
Grid [MW]	150
Rated Power P_{rated} [MW]	3.3
Number of Turbines (NWT)	22
Wind Capacity [MW]	72.6
Solar Capacity [MW]	132
Battery Power [MW]	80
Battery Energy [h]	3
Battery Energy [MWh]	240
Number of Batteries Used	2
Rotor Diameter [m]	144.943
Hub Height [m]	116.471
Plant Area [km^2]	14.516
NPV/CAPEX	0.648
Total Curtailment [GWh]	92.554
GUF	0.341

The inclusion of battery storage reduced curtailment significantly to 92.554 GWh and improved the Grid Utilization Factor (GUF = 0.341). However, due to the additional capital and replacement costs associated with the battery system, the overall economic performance was modest, with a NPV/CAPEX ratio of only 0.648.

Configuration 2: Fixed System without Battery Storage

In Configuration 2,system parameters such as the grid capacity (150 MW), wind turbine rated power (3.3 MW), number of turbines (22), total wind capacity (72.6 MW), and solar capacity (132 MW) were fixed similarly to Configuration 1.

The major difference in this configuration was the removal of the battery energy storage system (BESS). The rotor diameter (134 meters) and hub height (126 meters) were optimized by HyDesign .

Table 4.2: Configuration 2 – System Setup

Parameter	**Value**
Location	Denmark (loc14) - Config 2
Grid [MW]	150
Rated Power P_{rated} [MW]	3.3
Number of Turbines (NWT)	22
Wind Capacity [MW]	72.6
Solar Capacity [MW]	132
Battery Power [MW]	0
Battery Energy [h]	0
Battery Energy [MWh]	0
Number of Batteries Used	0
Rotor Diameter [m]	134
Hub Height [m]	126
Plant Area [km^2]	14.52
NPV/CAPEX	0.812
Total Curtailment [GWh]	145.83
GUF	0.331

By eliminating the battery, capital expenditures (CAPEX) were significantly reduced, leading to a marked improvement in the economic indicator (NPV/-CAPEX = 0.812). However, the absence of energy storage capacity caused a higher level of curtailed energy (145.83 GWh) and slightly lower grid utilization (GUF = 0.331) compared to the battery-supported system.

Configuration 3: Variable System without PtG

In Configuration 3, the only fixed parameter was the grid connection limit (150 MW), while all other system specifications—including wind turbine sizing, number of turbines, and solar PV capacity—were treated as variable and optimized by HyDesign.

A larger wind turbine model rated at 9 MW was selected, reducing the required number of turbines to 15. This resulted in a total installed wind capacity of 135 MW. The solar PV capacity was independently optimized to 134 MW based on resource availability and cost-effectiveness criteria. No battery energy storage system (BESS) or Power-to-Gas (PtG) facilities were included in this configuration.

The rotor diameter (178.661 meters) and hub height (125.33 meters) were selected through HyDesign's optimization.

Table 4.3: Configuration 3 – System Setup

Parameter	**Value**
Location	Denmark (loc14) - Config 3
Grid [MW]	150
Rated Power P_{rated} [MW]	9
Number of Turbines (NWT)	15
Wind Capacity [MW]	135
Solar Capacity [MW]	134
Battery Power [MW]	0
Battery Energy [h]	0
Battery Energy [MWh]	0
Number of Batteries Used	0
Rotor Diameter [m]	178.661
Hub Height [m]	125.33
Plant Area [km^2]	22.899
NPV/CAPEX	0.817
Total Curtailment [GWh]	512.144
GUF	0.422

Although energy curtailment rose significantly to 512.144 GWh due to larger installed capacities, the economic performance slightly improved with an NPV/-CAPEX ratio of 0.817. Moreover, the Grid Utilization Factor (GUF) increased to 0.422, indicating a better alignment between generation profiles and grid export capabilities despite the higher surplus energy.

Configuration 4: Variable System with PtG Integration

In Configuration 4, only the grid export limit (150 MW) was kept fixed, while the sizing of the wind farm, solar PV installation, and Power-to-Gas (PtG) electrolyzer capacity were variable and optimized using HyDesign.

This scenario introduced a large-scale hydrogen production component through

PtG technology. A 9 MW rated wind turbine model was selected, with the number of turbines significantly increased to 45, resulting in a substantial installed wind capacity of 405 MW. The solar capacity was optimized to 204 MW. No battery energy storage system was included.

A dedicated electrolyzer capacity of 188 MW was installed to convert surplus renewable electricity into hydrogen. Additionally, a hydrogen storage system (HSS) was included, designed to handle 3169 kg of hydrogen.

Table 4.4: Configuration 4 – System Setup

Parameter	Value
Location	Denmark (loc14) - Config 4
Grid [MW]	150
Rated Power P_{rated} [MW]	9
Number of Turbines (NWT)	45
Wind Capacity [MW]	405
Solar Capacity [MW]	204
Battery Power [MW]	0
Battery Energy [h]	0
Battery Energy [MWh]	0
PtG Capacity [MW]	188
Hydrogen Storage (HSS) [kg]	3169
Plant Area [km^2]	47.36
NPV/CAPEX	1.698
Total Curtailment [GWh]	3510.9
GUF	0.384

Despite a significant increase in total curtailment (3510.9 GWh) due to large renewable overproduction, the integration of PtG led to a remarkable improvement in financial performance. The NPV/CAPEX ratio reached 1.698—the highest among all configurations—highlighting the strong potential of hydrogen production to enhance hybrid renewable system profitability. The Grid Utilization Factor (GUF) slightly decreased compared to Configuration 3 but remained at a reasonable level (0.384), showing effective utilization of the fixed grid capacity even with the expanded generation assets.

4.2 LCA-Based Environmental Evaluation

Life Cycle Assessment (LCA) is a standardized method, as described by ISO 14040 and 14044 [26, 27], for evaluating the environmental impacts of a product, process or system. It involves four essential stages:

4.2.a Goal and Scopes

This study applies Life Cycle Assessment (LCA) to evaluate the environmental impacts of a hybrid power plant (HPP) integrating wind and solar photovoltaic (PV) technologies, with optional battery energy storage. The analysis is based on the Nørhede-Hjortmose renewable energy plant located in Ringkøbing, Denmark, which includes 22 Vestas V112-3.3 MW wind turbines (72.6 MW total) ,a 132 MW PV system and 240 MWh Battery system.

The goal of this LCA is to quantify the life cycle environmental impacts associated with the manufacturing, transportation, and end-of-life treatment of the major system components. The system boundaries include upstream and downstream processes relevant to these three life cycle phases.

Functional Unit

The functional unit for this LCA study is defined as: 1 MWh of grid-delivered electricity from a hybrid power plant in Nørhede-Hjortmose over a 25-year lifespan.

System Boundaries

The system boundary of this study adopts a cradle-to-grave perspective, encompassing all relevant stages from raw material extraction to end-of-life (EoL) disposal. The system is divided into **foreground** and **background** processes to ensure clarity and methodological consistency.

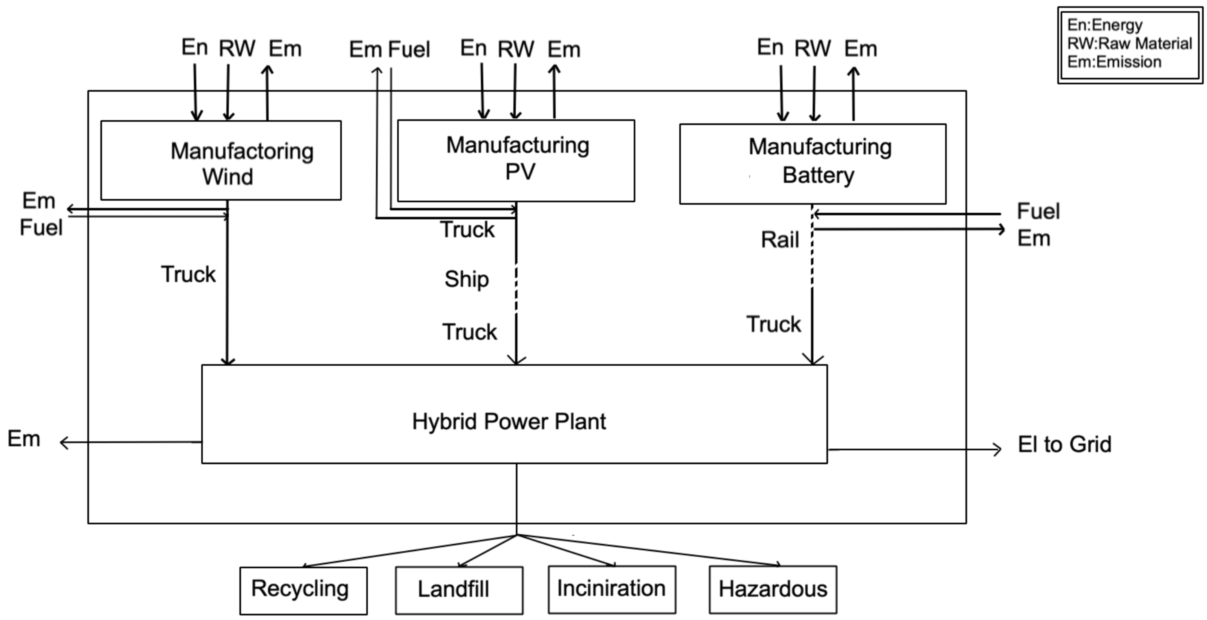


Figure 4.3: System boundary of the hybrid power plant including wind, solar PV, and battery systems.

As illustrated in Figure 4.3, the **foreground system** includes the main life cycle stages that are directly modeled in this study:

- **Manufacturing:** This stage represents one of the most emission-intensive phases of the hybrid power plant's life cycle. It encompasses the complete production process of key subsystems—wind turbines, photovoltaic (PV) modules, and battery energy storage systems (BESS). Each subsystem involves distinct components and materials, with unique environmental implications.

  For **PV systems**, manufacturing includes the fabrication of solar panels—primarily based on crystalline silicon technology—as well as the production of balance-of-system (BOS) components such as aluminum mounting structures, copper wiring, inverters, and transformers. The process is highly energy-intensive, especially during the purification of silicon and wafer production, contributing significantly to upstream greenhouse gas (GHG) emissions.

  For **wind energy systems**, the manufacturing process involves large-scale structural components including turbine blades made from composite materials (e.g., fiberglass and epoxy resin), steel towers, cast iron nacelles, and internal generators. These components require substantial quantities of raw materials such as steel, copper, balsa wood, and rare earth elements.

The high mass and volume of these items result in considerable energy consumption and emissions during raw material extraction, processing, and component assembly.

For **battery systems**, the manufacturing phase includes the production of electrochemical cells—commonly based on lithium iron phosphate (LFP) chemistry—as well as battery management systems, casing, and thermal control elements. Key materials include lithium salts, graphite, steel, copper, and high-performance polymers. The mining and refinement of critical minerals such as lithium and cobalt are particularly impactful in terms of environmental degradation and human toxicity categories.

Throughout all subsystems, the manufacturing stage accounts for the consumption of raw materials (RW), direct and indirect energy inputs (En), and the generation of emissions (Em), particularly in the form of carbon dioxide equivalents (CO_2-eq). These emissions are quantified using life cycle inventory data and emission factors sourced from publicly available databases and literature.

- **Transportation:** This stage involves the logistics and delivery of manufactured components—such as wind turbines, PV modules, and batteries—from their respective production sites to the hybrid power plant (HPP) installation site. Due to the considerable size and weight of many components, especially wind turbine towers, blades, and nacelles, transportation can contribute significantly to upstream life cycle emissions.

  Multiple transport modes are considered, including **truck**, **rail**, and **ship**, each associated with different emission factors (kg CO_2-eq per tonne-kilometer). Emissions for this stage are computed based on the selected transport mode, estimated travel distances, and the mass of each component. In particular, long-haul trucking—which is commonly used for the final leg of delivery—has been identified as a major contributor to transportation-related CO_2 emissions.

  For photovoltaic systems, the relatively lightweight nature of the components results in moderate transport emissions, whereas the wind subsystem, with its heavy and voluminous parts, dominates this category. Batteries, while compact, may be sourced from distant locations and require regulated shipping conditions, which can also elevate transport impacts. Accurate logistics modeling in this stage is critical for capturing realistic supply chain emissions.

- **End-of-Life (EoL):** The EoL phase encompasses the dismantling, separation, treatment, and disposal of system components once the HPP reaches the end of its operational lifetime. This stage considers four primary treatment routes: **recycling**, **landfilling**, **incineration**, and **hazardous waste handling**, each with its own environmental implications and recovery efficiencies.

For **PV systems**, common recyclable materials include aluminum frames, glass sheets, and silicon wafers. However, the presence of encapsulants and toxic substances can hinder full recyclability. **Wind systems** allow for high recovery of materials such as steel (from towers), copper (from electrical wiring), and cast iron (from nacelles), though the composite blades remain a recycling challenge due to thermoset resin content and fiber reinforcement. **Battery systems**, particularly lithium-ion variants, contain valuable and hazardous materials like lithium, copper, nickel, and electrolytes. These require specialized treatment pathways to recover useful fractions and avoid environmental contamination. Where possible, emissions from this stage are offset by the material recovery credits associated with recycling, which reduce the demand for virgin resource extraction.

The **background processes** encompass the upstream activities that indirectly support the system, such as fuel production, energy generation for manufacturing operations, and raw material extraction. Due to restricted access to commercial LCA databases (e.g., Ecoinvent, GaBi), emission factors for these background activities are sourced from peer-reviewed literature and public datasets including NREL, Fraunhofer ISE, IEA PVPS, and IMO reports.

4.2.b Life Cycle Inventory (LCI)

This study adopts a component-level LCI approach for each subsystem within the hybrid power plant (HPP), covering the photovoltaic (PV), wind, and battery energy storage systems. The scope includes upstream processes such as raw material extraction and processing, as well as component manufacturing. The data collection aligns with the system boundaries and functional unit defined in the Goal and Scope phase.

For the PV subsystem, Figure 4.4 provides a graphical breakdown of the module construction and associated material intensities. Table 4.5 quantifies the composition by weight, indicating that glass (67.5%) and aluminum frame (12.7%) dominate the system. Silicon-based solar cells, encapsulants, and backsheet materials also contribute notably. These material data are essential for estimating both embodied energy and emissions.

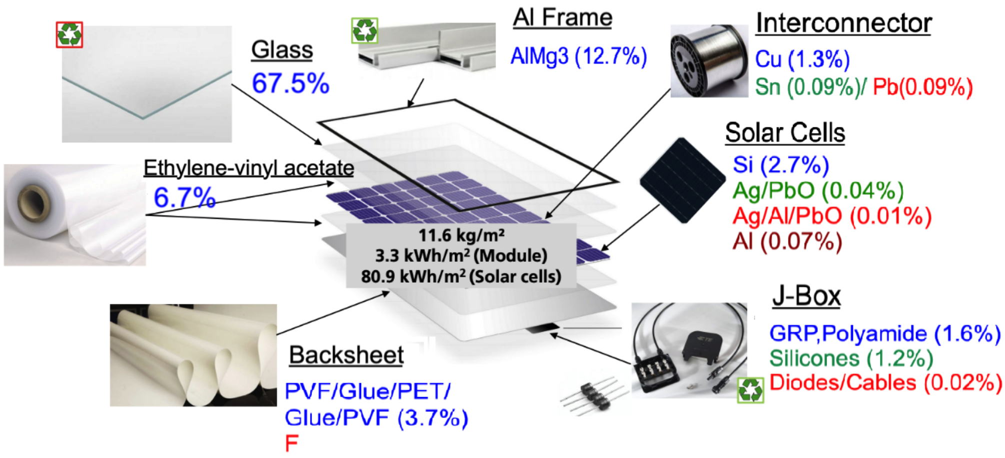


Figure 4.4: Material intensity table for a utility-scale PV system. [19].

Table 4.5: Material Inventory for Utility-Scale PV System

Component	Material	Mass Fraction (%)
Glass	Glass	67.5
Frame	Aluminum (AlMg3)	12.7
Encapsulant	Ethylene-vinyl acetate (EVA)	6.7
Backsheet	PVF/Glue/PET/Glue/PVF	3.7
Solar Cells	Silicon (Si)	2.7
	Ag/PbO	0.04
	Ag/Al/PbO	0.01
	Aluminum (Al)	0.07
Interconnector	Copper (Cu)	1.3
	Tin (Sn)	0.09
	Lead (Pb)	0.09
Junction Box (J-Box)	GRP/Polyamide	1.6
	Silicones	1.2
	Diodes/Cables	0.02

The material lists used in this study are based on reliable datasets from NREL (2020), Fraunhofer ISE (2024), and IEA PVPS (2020) [40, 23, 19, 22]. For the battery storage system, Table 4.6 provides a detailed breakdown of battery components by weight. Battery cells themselves comprise over 60% of the total mass, with additional contributions from the anode, cathode, case, and cooling systems. These data points are used to estimate embodied emissions from lithium, copper, graphite, and other specialized materials common to Li-ion battery chemistry.

Table 4.6: Mass distribution of battery components [22].

Battery weight	**253.0**	**kg (100%)**
Battery cell	152.3	kg (60.3%)
Anode	59.0	kg (23.6%)
Cathode	65.0	kg (26%)
Separator	3.3	kg (1.3%)
Electrolyte	24.0	kg (9.6%)
Cell container	1.0	kg (0.4%)
Battery case	81.0	kg (32%)
BMS	9.4	kg (3.7%)
Cooling system	10.0	kg (4.0%)

The LCI for the wind subsystem is based on average material intensities per megawatt (MW) of installed capacity. Figure 4.5 presents the material breakdown by subcomponent (e.g., nacelle, tower, blades), showing the dominant use of steel, cast iron, and composites in both onshore and offshore installations. These values are scaled based on the rated capacity of the Nørhede-Hjortmose wind farm (22 × 3.3 MW) to calculate total environmental loads.

	Component	Subassembly	Average Material Intensity (metric tonnes [t]/megawatt [MW]) of Current Wind Energy Technologies by Material Category: Steel	Cast iron	Other metals and alloys	Composites and polymers	Concrete	Road aggregate	Other materials
Land-Based Wind	Array and export cables	Total*			3.6	4.4			
	Foundation	Total*	20.8		1.0	<0.01	398.1		<0.01
	Roads	Total*						613.0	
	Substation	Total*	1.0	<0.01	0.2	0.1	0.6		0.2
	Turbine	Blades	0.3		<0.01	15.8			1.1
		Hub	4.8	2.5	0.2	0.1			<0.01
		Nacelle	17.0	6.3	3.8	1.0			0.3
		Tower	66.0		2.7	0.1			0.2
Offshore Wind	Array and export cables	Array cable	0.6		2.6	0.7			0.2
		Export cable	<0.01		0.5	0.5			0.1
		Onshore cable			<0.01	<0.01			
	Substructure	Monopile	144.5		4.9				
		Transition piece	51.5		1.8				
	Substation	Substation equipment	0.3		0.1	<0.01			0.2
		Support structure	7.0		0.2				
	Turbine	Blades	0.3		<0.01	10.4			0.9
		Hub	3.0	0.9	0.2	<0.01			<0.01
		Nacelle	11.5	7.8	2.6	0.7			0.4
		Tower	30.9		1.4	0.1			0.2

Figure 4.5: Material per MW for modern onshore and offshore wind power systems, Source: NREL (2021) [40].

A complete list of life cycle inputs and outputs for all three subsystems, covering raw materials, energy consumption, and emissions across manufacturing, transportation, and end-of-life stages, is provided in **Appendix C** for reference and transparency.

4.2.c Life Cycle Impact Assessment(LCIA)

The Life Cycle Impact Assessment (LCIA) phase translates inventory results into potential environmental impacts. In this study, the primary focus is on quantifying greenhouse gas (GHG) emissions—expressed as carbon dioxide equivalents (CO_2-eq)—across all life cycle stages of the hybrid power plant (HPP), which comprises wind turbines, photovoltaic (PV) modules, and battery energy storage systems. Emission factors were applied to the inventory data using a Python-based LCA tool, enabling the calculation of CO_2-eq emissions by subsystem and life cycle stage. After the techno-economic optimization with HyDesign, the Nørhede-Hjortmose hybrid power plant was further assessed environmentally using a Python-based Life Cycle Assessment (LCA) framework developed for this study. The tool takes the capacities of each subsystem—wind, solar, and battery—as input, and generates component-level material inventories (weights and types). The goal is to assess the emission generated during the life of the system. Figure 4.6 shows the weight distribution of the system by component.

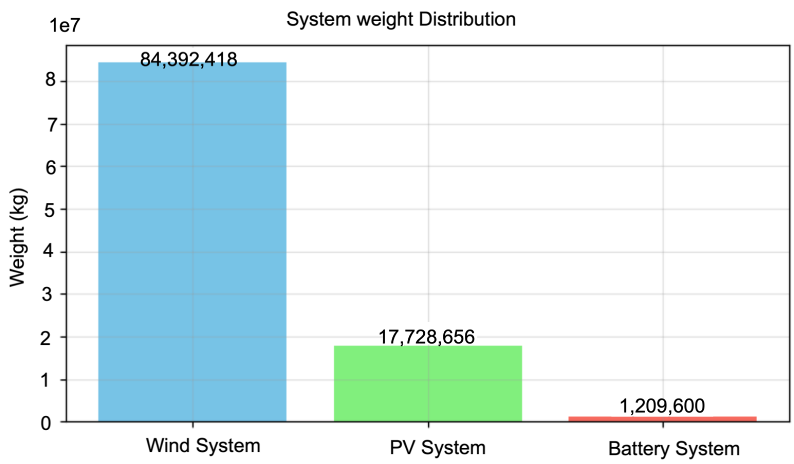


Figure 4.6: System weight distribution for wind, solar, and battery systems.

In the first step, based on inventories and emission factors, the manufacturing emissions were calculated. Due to limited access to commercial LCA databases most emission factors were derived from publicly available literature and sources . [25], NREL [46], Fraunhofer ISE [19], IEA PVPS [24], and battery LCA literature [17, 35].

In the second step, the user selects the location of the hybrid power plant (HPP) and manufacturing sites for each component of the subsytem. Using this information and the chosen transportation modes (truck, rail, ship), the tool calculates transport emissions based on actual distances. Figure 4.7 visualizes the selected manufacturers and routes.

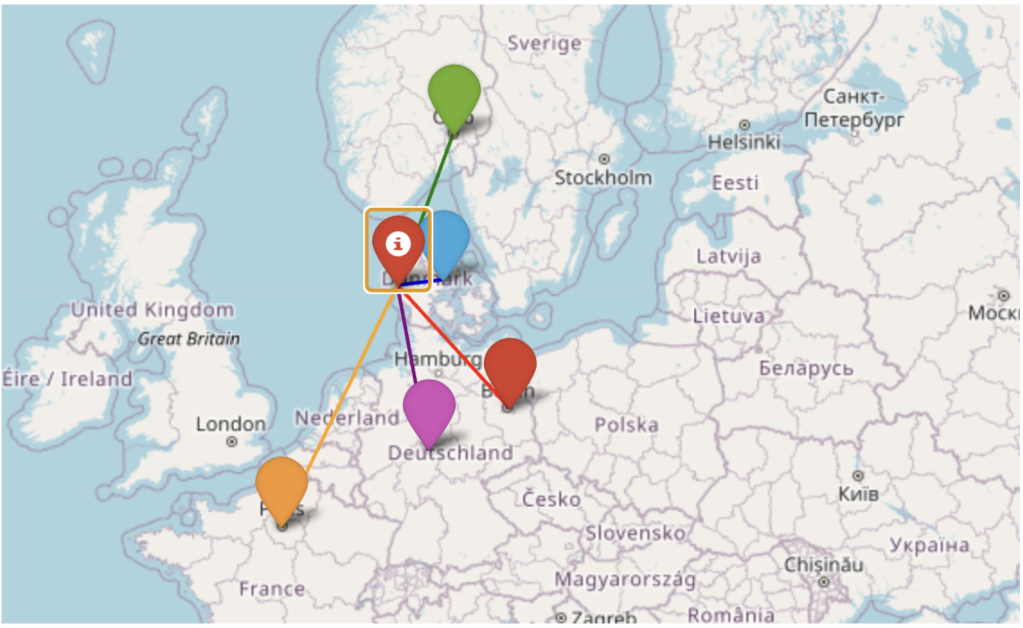


Figure 4.7: Transportation routes from manufacturers to the HPP site.

The pie chart Figure 4.8 breaks down the emissions by transport mode. Truck transportation accounts for the highest share (87.9%), followed by rail (6.9%) and ship (5.2%), highlighting the dominance of road freight in the hybrid system's supply chain. The bar chart Figure 4.9 quantifies emissions by individual components, showing that wind turbines contribute the majority of transport-related CO_2 emissions due to their size and mass.

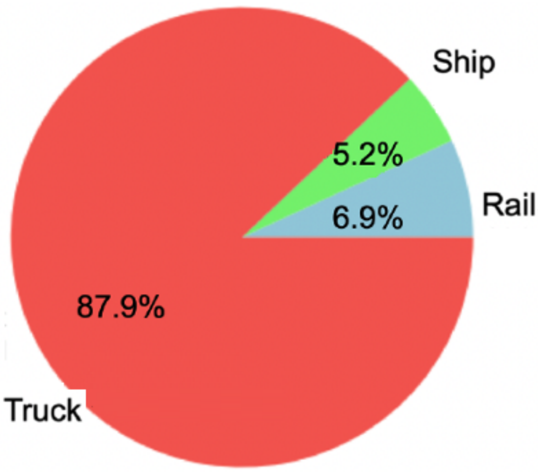


Figure 4.8: emissions by transport mode.

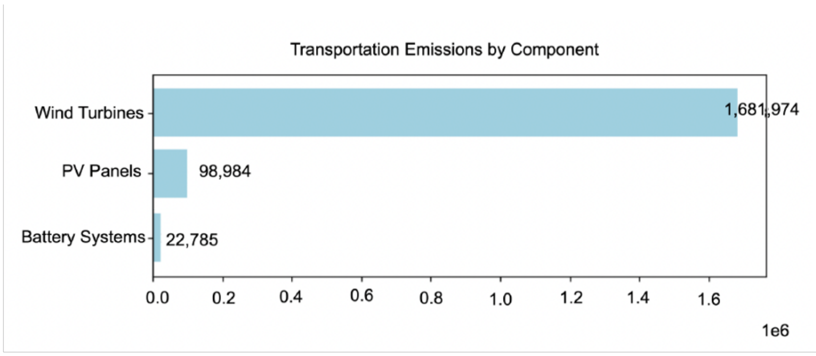


Figure 4.9: Transportation emissions by component (kg CO2-eq).

In manufacturing stage ,as shown in Figure 4.10,the bar chart quantifies the total manufacturing emissions by system, highlighting that wind turbines alone account for more than half of all emissions in this stage. This is consistent with their higher steel and concrete content and larger infrastructure demands compared to PV modules and batteries.

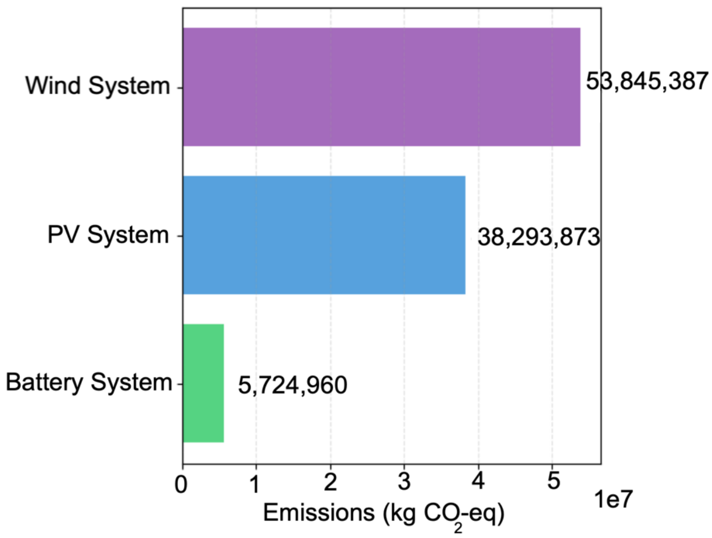


Figure 4.10: Manufacturing emissions by system (kg CO2-eq).

The pie chart 4.11 provides a proportional view of the manufacturing emissions. Wind turbines represent 55.0% of the total, while PV systems contribute 39.1% and battery systems account for only 5.8%. These shares are directly influenced by system capacities and the material intensity of each component.

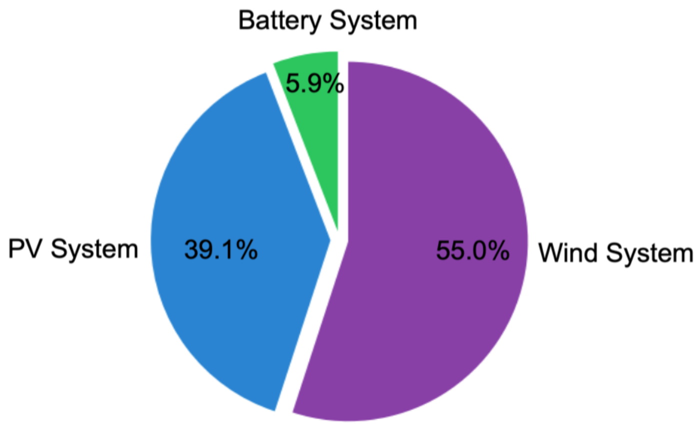


Figure 4.11: Percentage breakdown of manufacturing emissions by system.

Finally, in the end-of-life stage, each material is assigned to one or more treatment methods including recycling, landfill, hazardous, or incineration. Emissions are then calculated using method-specific emission factors. Figure 4.12 displays component-level EOL emissions and the distribution of disposal methods.

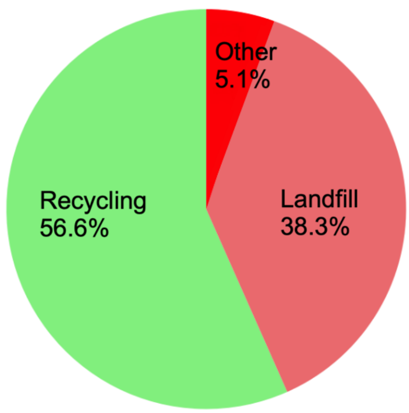


Figure 4.12: End-of-life emissions.

The overall life cycle emissions for each system—wind, solar (PV), and battery—are summarized in Figure 4.13. This stacked bar chart breaks down total emissions into three distinct stages: manufacturing, transportation, and end-of-life (EOL).

As shown, the wind subsystem exhibits the highest total emissions at approximately 57.7 million kg CO_2e, followed by the PV system at 38.9 million kg CO_2e, and the battery system at 5.8 million kg CO_2e. Notably, manufacturing is the dominant contributor across all systems, with transportation and EOL stages representing smaller shares.

These results reflect the substantial mass and complexity of wind turbine components, which require significant raw materials such as steel, concrete, and fiberglass. For PV systems, emissions are primarily tied to silicon wafer production and module assembly. Battery systems contribute the least emissions, owing to their relatively lower material weight and simpler transport logistics in this case study.

This figure provides a consolidated view of the total environmental footprint of each subsystem and underscores the importance of focusing emission reduction strategies on the manufacturing stage, where the largest gains can be made.

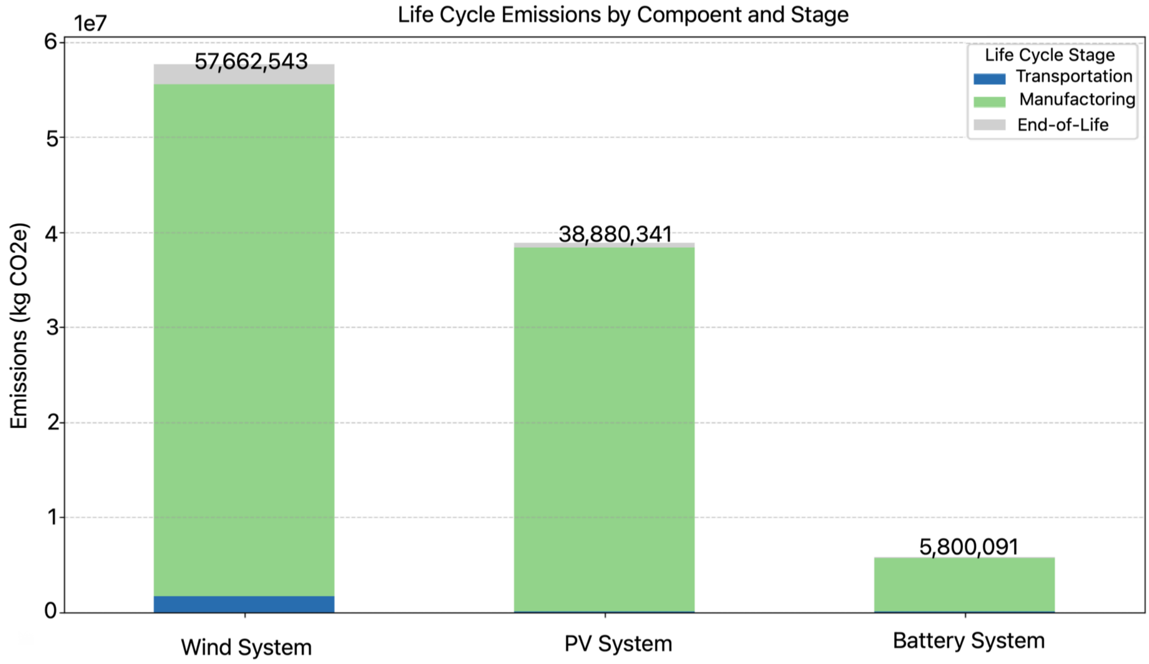


Figure 4.13: Total Life Cycle Emissions-(kg CO2-eq).

While this study emphasizes CO_2-eq due to data constraints, the Python tool also estimates additional midpoint categories from the ReCiPe 2016 and IMPACT 2002+ methodologies. These include land use, resource depletion, human toxicity, and others. Due to higher uncertainty in non-climate categories, these results are treated as indicative only. To provide a broader environmental perspective, Figure 4.14 illustrates the life cycle impacts for wind, PV, and battery systems across ReCiPe 2016 midpoint categories.

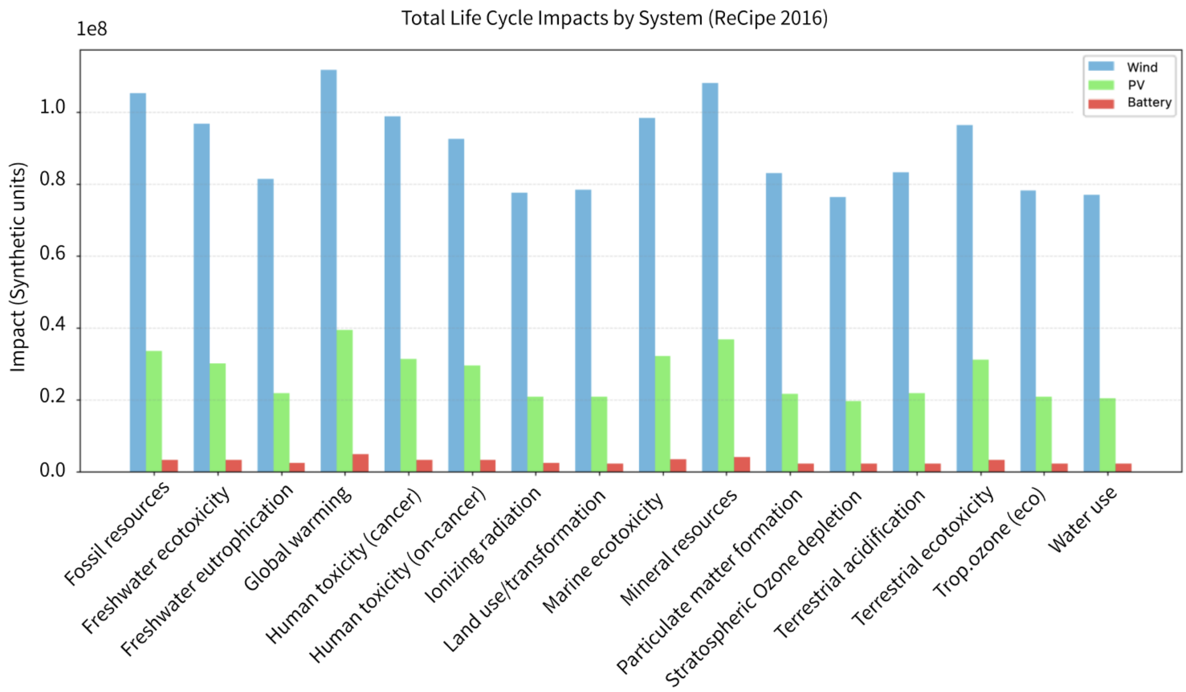


Figure 4.14: Life cycle impact comparison by system using ReCiPe 2016 midpoint impact categories.

As seen in the chart, the **wind subsystem** shows the highest impact across nearly all categories, including:

- Fossil resource depletion
- Global warming
- Mineral resource use
- Particulate matter formation
- Human toxicity (cancer and non-cancer)
- Ionizing radiation
- Land use transformation

These impacts stem from the large quantities of steel, concrete, and composites required, as well as transport-related emissions due to heavy and bulky components.

The **PV subsystem** has moderate impacts, particularly in:

- Freshwater and marine ecotoxicity
- Terrestrial acidification and ecotoxicity

- Tropospheric ozone formation

These are attributed to aluminum, copper, and silicon extraction and the high energy demand of PV manufacturing.

Despite being the smallest system in terms of energy capacity, the **battery subsystem** contributes to:

- Human toxicity
- Metal depletion
- Ionizing radiation

These are linked to the mining and processing of lithium, cobalt, and graphite, as well as low recycling rates at EOL.

For detailed numerical data on emissions per system and life cycle stage, refer to **Appendix C – LCI Emission Tables for Hybrid Systems**.

4.2.d Interpretation

The analysis shows that the **wind subsystem** is the most dominant in terms of total life cycle environmental impact. This is evident across several midpoint categories including climate change, fossil resource use, human toxicity, and mineral depletion. The primary cause is the extensive infrastructure associated with onshore wind turbines, especially the use of steel in towers and concrete in foundations. The high mass of these materials, combined with long transportation distances, results in significant embedded emissions during both manufacturing and delivery stages. Additionally, the large nacelle and composite blades add further emissions, particularly in the end-of-life phase where composite recycling remains limited.

The **photovoltaic (PV) subsystem** contributes moderate impacts across most categories. Emissions are primarily concentrated in the upstream manufacturing phase, especially during the energy-intensive purification of silicon and the production of aluminum frames. While PV systems have relatively lower mass compared to wind, the embodied energy in wafer production and mounting infrastructure makes them significant contributors in the categories of freshwater ecotoxicity, marine ecotoxicity, and metal depletion. However, their relatively high recyclability at end-of-life—particularly of glass and aluminum—offers some offsetting benefits.

The **battery subsystem**, although much smaller in terms of installed capacity, contributes disproportionately in several high-impact categories such as human toxicity, ionizing radiation, and resource scarcity. These impacts are closely linked to the extraction and processing of lithium, cobalt, and nickel for cathode materials, as well as graphite and copper for anodes and current collectors. Despite accounting for only a fraction of the total system mass, the environmental footprint per MWh of storage is high, especially due to low recycling rates and the hazardous nature of certain battery components. End-of-life emissions remain substantial, particularly when recycling infrastructure is not optimized.

Life Cycle Stage Comparison

From a life cycle stage perspective, **manufacturing** is by far the most emission-intensive phase for all subsystems. It accounts for over 70% of total CO_2-eq emissions in the case of wind and PV, and nearly 85% for the battery system. These emissions are closely tied to raw material production, electricity use during processing, and industrial-scale fabrication.

Transportation contributes between 5–15% of total emissions, depending on subsystem and distance to site. In the case of wind turbines, the size and mass of components like towers and blades amplify the role of transportation, especially when marine and long-haul road freight are used. While PV and battery components are lighter, global supply chains still introduce considerable emissions, particularly when shipping is used.

The **end-of-life (EOL)** phase plays a dual role: it introduces emissions through waste handling (landfilling and incineration), but also allows for partial emissions offsets through material recovery. Wind turbines show the highest recycling potential in steel components, whereas PV modules offer high glass and aluminum recovery. Batteries are more challenging—although recycling technology exists, only about 50% of lithium and 30–40% of other valuable metals are currently recoverable in practice. The environmental burden of residual waste and hazardous fractions (e.g., electrolyte and cathode residues) remains a concern.

5 Results and Discussion

5.1 Techno-Economic Performance

The techno-economic evaluation using the HyDesign tool revealed how different system configurations influence the financial feasibility of the hybrid power plant (HPP). Configurations 1 and 2, which maintained fixed capacities for wind and solar but differed in battery integration, provided a direct comparison between systems with and without storage. Configuration 1, which included an 80 MW battery system with 3 hours of storage, achieved a NPV/CAPEX ratio of 0.648. In contrast, Configuration 2, which eliminated the battery system, improved the economic outcome to an NPV/CAPEX ratio of 0.812.

Configurations 3 and 4 involved variable system sizing, allowing wind, solar, and hydrogen capacities to be optimized according to techno-economic criteria. Configuration 3, without hydrogen integration, further improved the NPV/-CAPEX ratio to 0.817, while Configuration 4, which incorporated a 188 MW Power-to-Gas (PtG) electrolyzer, achieved the highest economic performance with a NPV/CAPEX ratio of 1.698. This confirms that hydrogen integration can significantly enhance the financial returns of hybrid systems, especially when surplus renewable generation is high.

Across all configurations, trends showed that increasing the flexibility of system sizing and integrating sector-coupling technologies such as PtG can yield better economic performance, despite the associated increases in plant size, complexity, and energy curtailment.

5.2 Environmental Results

The environmental analysis focused on three key stages: manufacturing, transportation, and end-of-life (EOL). Manufacturing emerged as the dominant contributor to total life cycle CO_2-equivalent emissions for all subsystems.

Wind turbines accounted for approximately 55% of manufacturing emissions due to the large quantities of steel, concrete, and fiberglass used. Solar PV modules contributed around 39%, while battery systems added about 6% to the total manufacturing emissions.

Transportation emissions were dominated by truck transport, representing nearly 88% of the logistics-related CO_2 emissions. Components such as wind turbine blades and towers, which are bulky and heavy, were major contributors to transport emissions.

At the end-of-life stage, recycling rates varied depending on material type. Steel and aluminum achieved relatively high recovery rates, while composite materials such as fiberglass had lower recycling potentials. Landfilling and hazardous disposal methods contributed additional emissions, particularly from non-recyclable components.

Overall, the total life cycle emissions were highest for the wind subsystem (57.7 million kg CO_2-eq), followed by the solar subsystem (38.9 million kg CO_2-eq), and the battery subsystem (5.8 million kg CO_2-eq).

5.3 Comparison of Configurations

A number of trade-offs were identified when comparing different system designs:

- **Curtailment vs. Economic Performance:** Removing the battery improved economic outcomes but increased curtailment, as observed between Configurations 1 and 2.
- **Material Intensity vs. Energy Yield:** Larger turbines (in Configurations 3 and 4) improved grid utilization and economic performance, but increased material demand and environmental footprint.
- **PtG Integration:** The addition of a hydrogen system (Configuration 4) provided the highest economic benefit, but came at the cost of a larger land area (47.36 km^2) and extremely high curtailment (3510.9 GWh).

These findings emphasize that optimization must balance multiple objectives: minimizing costs, reducing emissions, and efficiently utilizing resources and land.

5.4 Limitations and Uncertainties

While the combined techno-economic and environmental analysis provides important insights, several limitations must be acknowledged:

- **Database Constraints:** Emission factors were sourced from open literature instead of commercial LCA databases like Ecoinvent, limiting precision.
- **Simplified Operational Phase:** Due to minimal emissions during system operation and lack of long-term operational data, this phase was excluded.
- **End-of-Life Modeling:** Recycling rates and disposal methods were based on generalized literature values rather than site-specific waste management practices.

Despite these limitations, the framework developed offers a transparent, reproducible, and insightful evaluation of hybrid renewable energy systems.

6 Conclusion and Future Work

6.1 Conclusion

This thesis studied how to design and evaluate a hybrid power plant (HPP) made of wind turbines, solar panels (PV), and battery storage (BESS). Two tools were used: the HyDesign software for system optimization, and a Python-based model to calculate environmental impacts using Life Cycle Assessment (LCA).

The economic analysis showed that the way we size the system and combine the components has a big effect on costs and benefits. Systems with fixed designs that included large batteries were more expensive. In contrast, systems where wind, solar, and hydrogen production were optimized (like Configuration 4) performed much better financially, reaching the highest NPV/CAPEX ratio of 1.698.

The environmental analysis focused mainly on CO_2 emissions from three stages: manufacturing, transportation, and end-of-life. Wind turbines were the largest source of emissions, followed by solar panels and then batteries. Transport emissions were mostly caused by trucks, showing that choosing nearby suppliers could reduce impacts. Batteries only added a small share of emissions but their cost-effectiveness depended a lot on how much curtailment they helped avoid.

Different designs showed important trade-offs between cost, energy loss (curtailment), land use, and environmental impact. This means that system design always needs careful planning to balance technical, economic, and environmental goals.

Although this study faced some limits — like not using full commercial LCA databases and using some estimated data — it still built a clear and practical framework to assess hybrid renewable systems.

6.2 Future Work

In this project, the developed Life Cycle Assessment (LCA) tool evaluates the environmental impacts of three major subsystems in hybrid renewable systems: photovoltaic (PV) panels, wind turbines, and battery energy storage. However, a major direction for future work is to expand this tool to include Power-to-X (P2X) technologies, such as hydrogen, ammonia, and methanol production. These technologies are already modeled in the HyDesign optimization framework, including different types of energy storage, and integrating them into the LCA tool would allow for a more comprehensive environmental assessment of advanced hybrid power systems.

Another area for future exploration is related to hybrid power plant (HPP) sizing. In this thesis, the system sizing was based on participation in a single market scenario. However, in real-world applications, HPPs may participate in multiple energy markets, such as electricity spot markets, balancing markets, and hydrogen trading markets. Future work can include a sensitivity analysis to investigate how market-specific participation strategies affect the optimal system configuration. This would improve the understanding of how economic drivers and energy policies influence the environmental and financial performance of hybrid renewable systems.

Bibliography

[1] International Energy Agency (IEA). *World Energy Outlook 2010*. Distribution of global energy sources and biomass data. Paris, France: OECD/IEA, 2010.

[2] International Energy Agency (IEA). *World Energy Outlook 2023*. p. 158. OECD/IEA, 2023.

[3] National Renewable Energy Laboratory (NREL). "WISDEM for Wind Farm Cost Analysis". In: *Renewable Energy Systems* 19 (2015), pp. 341–359.

[4] Maureen Hand (USA). "Advances in Wind Energy". In: *Renewable Energy Journal* 12 (2011), pp. 33–45.

[5] Gemma Gasa et al. "Life Cycle Assessment of Solar Power (CSP) Plant". In: *Journal of Environmental Sustainability* 29 (2022), pp. 123–138.

[6] Junbo Liu et al. "Life Cycle Assessment of Wind Power". In: *Journal of Energy Economics* 33 (2023), pp. 281–294.

[7] Peter Berrill et al. "Life Cycle Assessment of Wind and Solar Energy Systems". In: *Journal of Renewable Energy Economics* 22 (2016), pp. 61–72.

[8] Prabhu et al. "Life Cycle Assessment of Solar Photovoltaic". In: *Environmental Policy Reports* 21 (2022), pp. 55–72.

[9] Roy et al. "Hybrid Renewable Energy Systems Techno-economic and Environmental Assessment". In: *HOMER Pro and SimaPro Reports* 45 (2024), pp. 341–355.

[10] Zeyu Ding et al. "Simulation and Optimization of Wind-Solar Hybrid System". In: *Renewable Energy Journal* 34 (2019), pp. 445–460.

[11] Dan Arvizu. *Solar Energy: Challenges and Opportunities*. pp. 55–70. Wiley, 2011.

[12] Simon Aumonier. “Life Cycle Assessment of Renewable Energy Systems”. In: *Energy Systems Journal* 5 (1998). A comprehensive study on environmental impacts, pp. 345–358.

[13] Paul Barraqué. *The impact of CO2 optimization in Hybrid Power Plant sizing*. Tech. rep. Supervisors: Mikkel Friis-Møller, Juan Pablo Murcia Leon, and Rujie Zhu. DTU Wind & Energy Systems, Technical University of Denmark, July 2024. URL: https://www.wind.dtu.dk.

[14] Alexandra et al. Bonou. “Life Cycle Assessment (LCA) Onshore and Offshore Wind Energy”. In: *Siemens Wind Power Reports* 28 (2016), pp. 97–110.

[15] Mathiesen BV. “Renewable Energy Systems for a Sustainable Future”. In: *Renewable Energy Journal* 45.1 (2012), pp. 23–33.

[16] Mary Ann Curran. *Life Cycle Assessment Handbook: A Guide for Sustainability*. pp. 10–25. Wiley, 2013.

[17] Linda Ager-Wick Ellingsen, Bhawna Singh, and Anders Hammer Strømman. “The Size and Range Effect: Life Cycle Assessment of Electric Vehicles”. In: *Journal of Industrial Ecology* 18.1 (2014), pp. 132–144. DOI: 10.1111/jiec.12072.

[18] F. et al. Foidart. “Life Cycle Assessment (LCA) for Wind, Hydraulic, and Solar Energy”. In: *Applied Energy* 87 (2010), pp. 3244–3251.

[19] Fraunhofer ISE. *PV-Module Materials and Components. Slide 41*. https://www.ise.fraunhofer.de/en.html. Mass fraction of substance in relation to total module mass of 11.6 kg/m^2. 2024.

[20] J. Gerber. *Renewable Energy and Climate Change*. p. 11. New York: Springer, 2014.

[21] Mark A. J. Huijbregts et al. “ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level”. In: *The International Journal of Life Cycle Assessment* 22 (2017), pp. 138–147. DOI: 10.1007/s11367-016-1246-y.

[22] IEA PVPS Task 12. *Environmental Life Cycle Assessment of Residential PV and Battery Systems*. Battery component breakdown. 2023. URL: https://iea-pvps.org.

[23] IEA PVPS Task 12. *Life Cycle Inventories and Assessments of Photovoltaic Systems*. 2020. URL: https://iea-pvps.org.

[24] IEA PVPS Task 12. *Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems*. https://iea-pvps.org/wp-content/uploads/2020/01/IEA-PVPS_Task_12_LCI_LCA.pdf. IEA PVPS Report T12-19:2020. 2020.

[25] International Maritime Organization. *Emission Reports and Lifecycle Data*. https://www.imo.org/. Accessed April 2025. 2024.

[26] ISO. "Environmental management—Life cycle assessment—Principles and framework". In: *ISO 14040:2006* (2006).

[27] ISO. "Environmental management—Life cycle assessment—Requirements and guidelines". In: *ISO 14044:2006* (2006).

[28] Olivier Jolliet et al. "IMPACT 2002+: A new life cycle impact assessment methodology". In: *The International Journal of Life Cycle Assessment* 8.6 (2003), pp. 324–330. DOI: 10.1007/BF02978505.

[29] Masayuki Kamimoto. *Renewable Energy Contributions in Global Electricity Markets*. p. 45–60. Springer, 2011.

[30] S. Krishna. "Distributed Generation in Energy Systems: Challenges and Prospects". In: *Energy Systems Journal* 3.4 (2015), pp. 234–245.

[31] Joyce Lee. "Global Wind Energy Market Trends". In: *Renewable Energy Report* 3 (2024), pp. 78–90.

[32] M. Lenzen and J. Munksgaard. "Life Cycle Assessment of Energy and CO_2 Emissions in Wind Turbines". In: *Renewable Energy* 27 (2002), pp. 207–222.

[33] E. Liberman. "Economic and Environmental Analysis of Wind Turbines Using Monte Carlo Simulation". In: *Energy Economics* 25 (2003), pp. 471–487.

[34] Henrik et al. Lund. "Life Cycle Assessment of Wind Power in Denmark". In: *Energy Systems Journal* 15 (2010), pp. 341–353.

[35] Guillaume Majeau-Bettez, Troy R. Hawkins, and Anders Hammer Strømman. "Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles". In: *Environmental Science Technology* 45.10 (2011), pp. 4548–4554. DOI: 10.1021/es103607c.

[36] E. et al. Martínez. "Life Cycle Assessment (LCA) of Wind Turbine". In: *CML Method Report* (2008), pp. 145–158.

[37] C. Mbohwa and F. Van Blommestein. "Life Cycle Assessment of Solar Chimneys". In: *Renewable Energy* 49 (2013), pp. 177–184.

[38] Megavind. "LCC Model for Offshore Wind". In: *Wind Energy Journal* 18 (2015), pp. 435–450.

[39] Juan Pablo Murcia Leon et al. "HyDesign: a tool for sizing optimization of grid-connected hybrid power plants including wind, solar photovoltaic, and lithium-ion batteries". In: *Wind Energy Science* 9 (2024), pp. 759–776. DOI: 10.5194/wes-9-759-2024. URL: https://doi.org/10.5194/wes-9-759-2024.

[40] National Renewable Energy Laboratory (NREL). *Life Cycle Inventory of Energy Systems: Wind Energy Technologies*. Table 6. 2020. URL: https://www.nrel.gov/docs/fy20osti/74538.pdf.

[41] Jozef Paska. "The Role of Hybrid Power Plants in Future Energy Systems". In: *Energy Systems Journal* 14 (2009), pp. 145–158.

[42] Lillian Elizabeth Peterson. *Multi-objective optimization for hybrid sizing and objective function development*. Master's thesis. Sept. 2024. URL: https://www.dtu.dk/.

[43] Lillian Elizabeth Peterson et al. "HyDesign: A tool for sizing optimization of grid-connected hybrid power plants with wind, solar, and battery storage". In: *Renewable Energy* (2024). Figure adapted from the HyDesign framework overview diagram. URL: https://www.windenergy.dtu.dk/english/topfarm/hydesign.

[44] Technical University of Denmark (DTU). *HyDesign – Hybrid Power Plant Sizing Tool*. https://topfarm.pages.windenergy.dtu.dk/hydesign/. Accessed April 17, 2025. 2024.

[45] B. Tremeac and F. Meunier. "Life Cycle Analysis of Wind Turbines". In: *Energy Policy* 37 (2009), pp. 1744–1751.

[46] U.S. Department of Energy (DOE), National Renewable Energy Laboratory (NREL). *Life Cycle Inventory of Energy Systems: Wind Energy Technologies*. https://www.nrel.gov/docs/fy20osti/74538.pdf. Table 6: Average Material Intensity of Current Wind Energy Technologies. 2020.

[47] P. et al. Viebahn. "Life Cycle Assessment of Concentrated Solar Power (CSP) Technologies". In: *Energy Policy* 39 (2011), pp. 4420–4430.

[48] S.N. Vodapally and M.H. Ali. "A Comprehensive Review of Solar Photovoltaic (PV) Technologies, Architecture, and Its Applications to Improved Efficiency". In: *Energies* 16.1 (2023), p. 319. DOI: 10.3390/en16010319. URL: https://doi.org/10.3390/en16010319.

[49] M. et al. Whitaker. "LCA with Design Alternatives for CSP Plants". In: *Journal of Environmental Assessment* 12 (2013), pp. 121–130.

List of Abbreviations

LCA	Life Cycle Assessment
HPP	Hybrid Power Plant
PV	Photovoltaic
WT	Wind Turbine
BESS	Battery Energy Storage System
PtG	Power-to-Gas
GHG	Greenhouse Gas
GUF	Grid Utilization Factor
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
NPV	Net Present Value
LCOE	Levelized Cost of Electricity
EOL	End of Life
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MJ	Megajoule
CO_2e	Carbon Dioxide Equivalent
kg	Kilogram
MW	Megawatt
MWh	Megawatt-hour
t/km	tonne-kilometer

Appendix A – Python-Based LCA Tool

This Python-based Life Cycle Assessment (LCA) tool is designed to estimate the environmental impacts—particularly CO_2 emissions—of a hybrid renewable energy system. The workflow follows these main stages:

Input stage: The user provides system parameters, including wind power plant capacity, solar power plant capacity, and battery energy storage capacity, through interactive sliders.

Transportation emissions calculation: Based on the selected component capacities and the geographic location of the nearest manufacturers, the tool calculates transportation-related CO_2 emissions using mode-specific emission factors (truck, rail, or ship).

Manufacturing emissions calculation: Using detailed material breakdowns for each subsystem (wind, solar, battery), the tool estimates the manufacturing emissions by applying appropriate emission factors for each material type.

End-of-life (EOL) emissions calculation: The tool estimates emissions associated with the disposal or recycling of system components, considering material-specific treatment methods.

Summary stage: Finally, the tool aggregates all CO_2 emissions across the life cycle stages and presents a total summary, giving the user a full picture of the system's environmental footprint.

This tool is modular, interactive, and designed to support decision-making by providing clear visualizations and breakdowns of emissions hotspots.

```

# --- Import required libraries ---
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
```

```
import ipywidgets as widgets
from IPython.display import clear_output, display
from geopy.distance import geodesic

# --- Load site and manufacturer data ---
sites = pd.read_csv('examples_sites.csv', sep=';')
manufacturers = pd.read_csv('manufacturers.csv')

# --- Select a site ---
SELECTED_SITE = 'Denmark_hybridization'
site_info = sites[sites['name'] == SELECTED_SITE].iloc[0]

# --- Setup system parameters ---
wind_capacity = widgets.FloatSlider(...)
pv_capacity = widgets.FloatSlider(...)
battery_capacity = widgets.FloatSlider(...)
transport_mode = widgets.ToggleButtons(...)

# --- Transportation emissions calculator ---
def determine_transport_mode(distance_km, from_country, to_country):
    if distance_km <= 200:
        return "truck"
    elif distance_km <= 500:
        return "rail"
    else:
        return "ship"

emission_factors = {"truck": 0.12, "rail": 0.03, "ship": 0.01}  # kg CO2-eq/tkm

# --- Example for calculating emissions ---
def calculate_transport_emissions(weight_tons, distance_km, mode):
    return weight_tons * distance_km * emission_factors[mode]

# --- Simplified weight analysis display function ---
def display_component_weights(component_df):
    grouped = component_df.groupby('component_name')['weight_kg'].sum()
    total = grouped.sum()
    for name, weight in grouped.items():
        print(f"{name}: {weight:.1f} kg ({weight/total*100:.1f}%)")

# --- Display setup ---
display(wind_capacity, pv_capacity, battery_capacity, transport_mode)

\vspace{1em}

# Run Manufacturing Emissions Analysis
```

```
manufacturing_button = widgets.Button(description="Calculate
    Manufacturing Emissions")
manufacturing_button.on_click(on_manufacturing_button_clicked)
display(manufacturing_button)

# Run End-of-Life Emissions Analysis
eol_button = widgets.Button(description="Calculate EOL Emissions",
    button_style='danger')
eol_button.on_click(on_eol_button_clicked)
display(eol_button)

# Run Total Life Cycle Assessment
lifecycle_button = widgets.Button(description="Calculate Total LCA",
    button_style='success')
lifecycle_button.on_click(on_lifecycle_button_clicked)
display(lifecycle_button)

# Run Full LCA with Impact Category Filtering
full_lca_button = widgets.Button(description='Run Full LCA',
    button_style='danger')
full_lca_button.on_click(on_full_lca_button_clicked)
display(full_lca_button)
```

Appendix B – Impact Categories in Life Cycle Assessment

This appendix provides an overview of the environmental impact categories used in two widely adopted Life Cycle Assessment (LCA) methods: ReCiPe 2016 and IMPACT 2002+. These categories help quantify various types of environmental damage caused throughout a product or system's life cycle.

ReCiPe 2016 Impact Categories

ReCiPe 2016 offers both midpoint and endpoint indicators. Midpoints refer to specific environmental mechanisms, while endpoints group these into broader damage areas.

Midpoint Categories and Definitions

- **Climate Change**: Greenhouse gas emissions causing global warming.
- **Ozone Depletion**: Breakdown of stratospheric ozone, increasing UV exposure.
- **Terrestrial Acidification**: Soil acidification from emissions like SO_2 and NOx.
- **Freshwater Eutrophication**: Phosphorus-driven algal blooms in freshwater bodies.
- **Marine Eutrophication**: Nitrogen-driven pollution affecting marine systems.
- **Human Toxicity**: Human health risks from chemical exposure.
- **Photochemical Oxidant Formation**: Ground-level ozone from air pollutants.

- **Particulate Matter Formation**: Health effects from $PM_{2.5}$ and PM_{10}.
- **Terrestrial Ecotoxicity**: Harm to land organisms from toxic substances.
- **Freshwater Ecotoxicity**: Chemical harm to freshwater species.
- **Marine Ecotoxicity**: Toxic threats to marine life.
- **Ionizing Radiation**: Exposure risks from radioactive emissions.
- **Agricultural Land Occupation**: Biodiversity loss from farming land use.
- **Urban Land Occupation**: Land taken by urban infrastructure.
- **Natural Land Transformation**: Conversion of natural land into developed land.
- **Water Depletion**: Freshwater use affecting local water availability.
- **Metal Depletion**: Use of scarce metallic resources.
- **Fossil Depletion**: Depletion of fossil fuel reserves.

Endpoint Categories

- **Human Health**
- **Ecosystem Quality**
- **Resource Scarcity**

IMPACT 2002+ Impact Categories

IMPACT 2002+ merges midpoint and endpoint approaches, linking specific emissions to broader areas of damage.

Midpoint Categories and Definitions

- **Human Toxicity**: Health impacts from chemical exposure.
- **Respiratory Inorganics**: Impacts from SO_2, NOx, and particulates.
- **Ionizing Radiation**: Long-term health effects of radiation.
- **Ozone Layer Depletion**: UV-related impacts from ozone degradation.
- **Photochemical Oxidants**: Ground-level ozone from VOCs and NOx.
- **Aquatic and Terrestrial Ecotoxicity**: Ecosystem effects of toxic substances.
- **Aquatic Acidification**: Water pH impacts from acid emissions.

- **Aquatic Eutrophication**: Nutrient runoff causing algal blooms.
- **Land Occupation**: Loss of habitat and biodiversity.
- **Global Warming**: CO_2-equivalent emissions.
- **Non-renewable Energy Use**: Use of fossil-based energy resources.
- **Mineral Extraction**: Depletion of non-renewable minerals.

Endpoint (Damage) Categories

- **Human Health**
- **Ecosystem Quality**
- **Climate Change**
- **Resources**

Appendix C – Life Cycle Inventory for Hybrid Power Plant

This appendix provides the detailed life cycle inventory (LCI) data used in the environmental assessment of the hybrid power plant. Values are presented per MW or MWh capacity, as applicable, and cover inputs (raw materials, energy) and outputs (emissions, recycled fractions).

1. Wind Turbine System (per MW capacity)

Stage	Type	Parameter	Unit	Quantity
Raw Material	Input	Steel	t/MW	109.9
		Concrete	t/MW	398.7
		Fiberglass composites	t/MW	21.3
		Copper	t/MW	2.7
Manufacturing	Input	Electricity	MWh/MW	80.9
	Output	CO_2-eq emissions	kg CO_2e/MW	794,770
Transportation	Input	Diesel (truck)	MJ/t-km	43.7
	Output	CO_2-eq emissions	kg CO_2e/MW	88,420
End-of-Life	Output	Recycled steel	% mass	85%
	Output	Landfilled composites	% mass	40%
	Output	CO_2-eq emissions	kg CO_2e/MW	32,150

2. Photovoltaic System (per MW capacity)

Stage	Type	Parameter	Unit	Quantity
Raw Material	Input	Industrial silicon	kg/kWp	8.2
		Aluminum alloy	kg/kWp	18.6
		Copper	kg/kWp	4.3
Manufacturing	Input	Electricity (cells)	kWh/m^2	80.9
	Output	CO_2-eq emissions	kg CO_2e/MW	536,420
Transportation	Input	Marine fuel (shipping)	g/t-km	12.7
	Output	CO_2-eq emissions	kg CO_2e/MW	42,380
End-of-Life	Output	Recycled glass	% mass	95%
	Output	Recycled silicon	% mass	85%
	Output	CO_2-eq emissions	kg CO_2e/MW	15,290

3. Battery System (per MWh capacity)

Stage	Type	Parameter	Unit	Quantity
Raw Material	Input	Lithium iron phosphate	kg/MWh	260
		Graphite (anode)	kg/MWh	232
		Copper	kg/MWh	48.3
Manufacturing	Input	Electricity	kWh/kWh	110
	Output	CO_2-eq emissions	kg CO_2e/MWh	87,500
End-of-Life	Output	Recycled lithium	% mass	50%
	Output	Hazardous waste	% mass	12%
	Output	CO_2-eq emissions	kg CO_2e/MWh	3,150

4. Transportation Overview

Stage	Type	Parameter	Unit	Value
Transportation	Input	Diesel (truck)	MJ/t-km	43.7
	Input	Marine fuel (shipping)	g/t-km	12.7
	Output	CO_2-eq emissions (Truck)	kg CO_2e/MWh	1,240
	Output	CO_2-eq emissions (Ship)	kg CO_2e/MW	42,380