Introducing Advanced Comparative Life Cycle Assessment for Evaluating Environmental Conditions and Carbon Opportunity Costs of Energy Production Facilities

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***Abstract*—This study introduces an Advanced Comparative Life Cycle Assessment (LCA) model that refines the accuracy of environmental impact evaluations for renewable energy by integrating external factors like sea depth, solar irradiance, and wind speed. Traditional LCA approaches, which often overlook these critical variables, result in imprecise carbon footprint estimations. Developed with Python and incorporating libraries such as SciPy, Windrose, and pvlib, this model provides a nuanced analysis tailored to specific environmental conditions, particularly focusing on Korea. It aims to correct the shortcomings of existing LCA methods by factoring in regional variability, thereby offering more accurate assessments of carbon emissions and environmental impacts of renewable energy projects. This research facilitates informed decision-making in the renewable energy sector by improving the understanding of carbon footprints and supporting sustainable development policies. The study underscores the importance of considering local environmental conditions in the deployment of renewable energy technologies to achieve more sustainable and informed energy solutions.**

***Index Terms*—Life cycle assessment; Carbon opportunity cost; Renewable Energy; Environmental impact; Python-based modeling.**

I. INTRODUCTION

During the 29th Conference of Partics (COP) in Dubai in December 2023, the newly adopted "UAE Consensus" emphasized the urgency of transitioning from fossil fuels as an energy source by 2030 [1]. The consensus also included the commitments to triple the current global renewable energy supply, double the efficiency of energy use, and expedite the advancement of low-carbon technologies, with a particular focus on Carbon Capture, Utilization, and Storage (CCUS). Commencing in late 2018, there has been a subtle global surge in the development of new forms of energy, including Energy Storage Systems (ESS) and offshore wind farms, from various nations including Korea, European Unions, Austria, and the United States [2]. This trend has signaled a paradigm shift towards a renewable era, avoiding fossil fuel dependence; further, innovative transitions towards new platforms and technologies dedicated to power transactions are surely expected - getting closer to the ultimate goal of a carbon net-zero world by 2050.

The rest of the paper is structured as follows. In Section II, we examine the need for including external environmental factors in Life Cycle Assessments (LCA) of power generation. Section III details our methodology, describing the development of an Advanced Comparative LCA model and a Python-based environmental impact analysis model. Section IV outlines the expected outcomes, emphasizing the practical applications for stakeholders and policymakers in renewable energy. We conclude in Section V with a summary of our findings and their implications for sustainable energy practices.

II. SIGNIFICANCE

Drawing from current studies [3] [4], the assessment of energy production's efficiency and carbon emissions predominantly focuses on the power generation process of energy sources via the Life Cycle Assessment (LCA). Yet, such studies, many times, overlook crucial external environmental factors such as specific production circumstances, airflow, and irradiation. Moreover, in Peer-to-Peer (P2P) power trading scenarios, decisions are typically based solely on carbon emissions associated with the method of power generation [5]. As such, in the context of LCA, there exists a considerable potential for erroneous decision-making. For instance, in solar power generation, there has been a shortage of research to gather data on irradiation and to assess the environmental carbon opportunity cost - defined as the potential for CO2 emissions from the construction and operational processes of energy production facilities - in relation to power production alongside its carbon emission [6] [7]. Moreover, the ample number of studies oftentimes generalize the carbon emission of wind power to be 5 – 9g of CO2/kWh; yet, no differentiations were given either onshore or offshore [8].

On the other hand, other studies on offshore wind power suggest a carbon emission rate of approximately 6 g of CO2/kWh [8]. However, even such studies seldom consider variables such as water depth and wind speed within their LCA. In particular, under the nature of offshore wind power generation, installation depths significantly influence construction costs and carbon emissions [9]. Similarly, for solar power installations, the variability in radiation leads to uncertainty on the unit price and power production per unit of carbon emission. The installation of renewable power plants in locations that do not account for external environmental factors necessitates the evaluation of potential carbon emissions from replacement and repair processes [10]. However, these considerations are currently overlooked in existing LCA methodologies. This omission of external environmental factors could lead to

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substantial inaccuracies in the quantification of such actual carbon emissions. For a more precise assessment, this study consider not only the resources expanded on energy facilities but also the external environmental factors influencing their efficiency and impact.

III. Method

A. Development of the Advanced Comparative Life Cycle Assessment Model

Numerous previous studies and tools have been only developed to simply quantify the electricity yield of solar power installations, using local solar irradiance data. In this research, we are in the process of developing the Advanced Comparative Life Cycle Assessment model, which is an enhanced approach to the existing life cycle assessment, improving traditional methodologies by incorporating distinct environmental factors - sea depth, solar irradiance, and wind speed - to suit the various ecological locations in the context of Korea, as a prototype. The traditional methodologies approaches often overlook regional environmental variations - in terms of varying amounts of solar irradiance, and wind speed with varying altitude - potentially leading to inaccurate emission assessment in proportional relation to their different temporal efficiency of generation. By factoring in such locational variability and specificity, the proposed assessment provides a more precise quantification of environmental impacts and carbon emissions per unit of the electricity yield under diverse conditions, automating the carbon opportunity cost.

B. Python-Based LCA Model for Environmental Impact Analysis

Building on this foundation, our work has led to the development of a Python-based Life Cycle Assessment model. Utilizing Python as a scripting language, the model is intricately designed to provide a detailed analysis of the environmental impacts associated with renewable energy projects, with a special focus on construction costs and carbon emissions. The model integrates the SciPy library for its extensive applications in scientific and technical computing for sophisticated algorithms for numerical analysis. Additionally, by incorporating specialized libraries such as Windrose and pvlib, the model is uniquely equipped to model and study wind and solar power, respectively. As a prototype, the model stores backend data such as sea depth, average sunlight, and wind speed specific to Korea, intending to calculate the expected carbon emissions and installation costs for new renewable energy facilities based on their location. From the user interface, users can select various options like the power generation method and scale, materials for the power plant and its foundation, and the total amount of materials used. This allows for a comparison of carbon emissions and power efficiency with the backend Python calculation results, thereby providing a multifaceted approach to analyzing the environmental impacts of renewable energy projects.

This model, ultimately, aims to enhance the societal understanding of carbon footprints by processing inputs that include the specific characteristics and locality of renewable energy facilities, leveraging Korean public datasets to dynamically update environmental factors such as wind speed and solar irradiance based on location, and incorporating contemporary raw material import costs. By evaluating these parameters over a 20-year lifespan through complex unit conversions and theoretical calculations, the model delivers a comprehensive LCA.

IV. Expected Outcome

The purpose of the study extends beyond its technical aspects. The assessment model is aimed to provide useful environmental impact analysis by providing such valuable information accessible to a broader audience. Through this, the study aims to allow stakeholders to make informed decisions about renewable energy, and its resources in specific locales, thus, offering more accurate, localized, and environmentally conscious perspectives. Specifically, the function of the model is being proposed to be beneficial to the business sectors in renewable energy and to general users, especially in the context of P2P power transactions. It is designed for companies to employ this model to improve efficiency and carbon emissions of their energy production processes, while general users gain the ability to conveniently select electricity generators, based on their simple carbon emission values. Ultimately, this advancement in such perspectives must allow further sustainable development and aid informed policymaking, underling the benefits of this approach.

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