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Towards a Standardized LCOE Calculation for Informed Decision-Making in Energy Policy and Investment: Application to the Colombian Context

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ABSTRACT

The Levelized cost of electricity - *LCOE* represents a constant cost per unit of generated electrical energy, resulting from the analysis of the total costs throughout the life cycle of a generation plant. Its widespread use, thanks to its simplicity of calculation and potential of standardization, has made it one of the primary criteria for comparing electricity generation technologies. However, in the pursuit of simplification and generalization, certain aspects associated with the socioeconomic context of the region, as well as accounting and financial concepts, are excluded due to externalities or incentives related to regulatory and fiscal policies. These exclusions affect the accuracy of *LCOE* and introduce uncertainty when using it as a criterion for investment decision-making or allocation of public resources for the development of renewable sources. This article proposes a clear and standardized methodology for calculating *LCOE*, which allows for a fair and precise comparison of renewable energy generation options in rural areas. It contributes to informed and transparent decision-making in the fields of energy policy and public investment for expanding electricity service coverage. The proposed methodology is based on the financial cash flow matrix to address variability sources in the calculation, considering the local context of the generation project.

Keywords: Levelized Cost of Electricity, Evaluation of Alternative Energy Projects, Incentives for Renewable Generation
JEL Classifications: Q42, P48

1. INTRODUCTION

The technological boom and the expectations of decreasing cost in renewable energy-based generation in the late 80's and early 90's raised concerns about how to evaluate the kWh produced by these sources using a general method that would allow for comparisons, particularly with conventional forms of electricity generation. As early as 1976, reference was made to "Life-cycle levelized cost of electricity" (Duggan et al., n.d.) for future costs comparison between coal and nuclear power plants. However, in the evaluation of generation technologies using different fuels, including renewables, the term "Relative Cost of Electricity Production" of the California Energy Commission – CEC (Ringer, 1984) was more commonly used. This term gradually transformed in their cost reports between 1981 and 1987 to what we know as Levelized Cost of Electricity – *LCOE* (Bemls and Deangells, n.d.).

In 1991, the International Energy Agency – IEA organized a workshop in Chateau Montebello, Canada, where experts extensively examined the issue and suggested a general methodology for calculating the cost of energy production. The results of this workshop were published in 1991 in the document "Guidelines for the Economic Analysis of Renewable Energy Technology Applications" (International Energy Agency - IEA,

1991) This document obtained a cost per *kWh* produced applying the Net Present Value – *NPV* to the annual cash flows of the generation system, using a somewhat lengthy calculation procedure. In 1995, an analysis of the IEA's calculation methodology (Coiante and Barra, 1995) was conducted, introducing improvements for simplification and standardization purposes. The improvements were based on the assumptions that: (i) Specific price increases can be modeled through generalized inflation; (ii) If the generation plant belongs to a public service, it is exempt from taxes; and (iii) The salvage value of the plant at the end of its useful life, as well as replacement, operation, and maintenance costs, are proportional to the investment value. However, the document recommends considering externalities associated with social and environmental costs when generation is based on fossil fuels.

In this same year (1995) the National Renewable Energy Laboratory - NREL publishes the document: "A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies" (Short et al., 1995) where the concept of *LCOE* is reaffirmed, as one of the metrics for decision making and comparative analysis of generation systems; this time, it was based on the Total Life Cycle Cost – *TLCC*, defined as the total cost of constructing and operating a power generation system throughout its lifespan, divided by the total energy generated from the system during that period. This definition implies that *LCOE* is often used as an alternative to the average price that the electricity generation system must receive in a market to achieve breakeven over its useful life.

From the NREL's calculation methodology to the present day, conceptual revisions (Aldersey-Williams and Rubert, 2019; Australia. Bureau of Resources and Energy Economics, 2012; Brown and Klein, 2016; Loewen, 2019; 2020; Matsuo, 2022; McCann, 2020) have been published, and different variations of *LCOE* have been proposed (Bruck and Sandborn, 2021; Dong et al., 2021; Geissmann, 2017; Nissen and Harfst, 2019; Tran and Smith, 2018; Ueckerdt et al., 2013; Wagner and Foster, 2011), along with applications to specific generation systems scenarios within a specific contexts (Bruck et al., 2018; Darling et al., 2011; Guo et al., 2023; IEEE Electron Devices Society et al., n.d.; Lotfi and Khodaei, 2016; Park et al., 2021; Patel et al., 2019; Pawel, 2014) The main objective has always been to maintain a simple model that allows the comparison of conventional and alternative electricity supply options. This always involves contrasting a renewable energy source with the conventional way of obtaining the same electricity from a fossil source or extending the distribution grid to rural areas. In fact, there are even annual publications with extensive bibliographic citation that showcase these comparisons of different technologies using this indicator (Energy Information Administration, 2020; Fraunhofer Institute for Solar Energy System, 2021; International Renewable Energy Agency, 2022; Lazard LTDA, 2021; NREL, 2022; The New Energy Outlook (NEO) Is BloombergNEF's Long-Term Scenario Analysis on the Future of the Energy Economy PRODUCT BLOG Want to Learn VIEW EXECUTIVE SUMMARY, n.d.). However, beyond the comparison of technological options for energy supply, a properly calculated *LCOE* has a great potential as a criterion for investment decision-making, in programs aimed at providing electricity access in rural areas or implemented distributed generation solutions, as promoted by energy planning and sustainable electricity service coverage agencies.

Based on the premise that the Financial Cash Flow - *FCF* is the best approach to capture the real total costs of a generation system, while also allowing for the inclusion of internationally recognized accounting rules and different regulatory and fiscal incentive policies, this study proposes a methodology for calculating the *LCOE* that aims to simplify the calculation process while enabling standardization and systematization in computational tools. The methodology takes into account the specific considerations of the context in which the electrification project is being developed. This article provides an in-depth review of current approaches to calculating LCOE, identifying key sources of variability and errors. It analyzes the impacts of different assumptions and input factors and presents a proposed methodological approach for LCOE calculation. The approach is validated through representative case studies and its implications for energy and investment decision-making are discussed.

2. METHODOLOGIES FOR CALCULATING THE LEVELIZED COST OF ELECTRICITY

The following section will review the most commonly employed *LCOE* calculation methodologies to contrast them with the *FCF*-based result. Subsequently, the proposed calculation methodology will consider prevalent regulatory policies, fiscal incentives, and public financing schemes.

While the simplicity of the LCOE calculation has contributed to its widespread acceptance, it is important to consider more specialized analyses and additional investment decision criteria. The following are some reasons that can introduce errors in the calculation process:

a. Failure to include all relevant costs throughout the project's lifecycle, including pre-installation, replacement, decommissioning, and final disposal costs, in addition to operation and maintenance expenses.
b. Use of inappropriate or inconsistent discount rates, which can significantly impact the LCOE calculation.
c. Neglecting the variability in energy production during the lifecycle, arising from factors such as demand behavior, equipment degradation over time, and climate-related fluctuations for renewable energy sources, which can affect the assumed constant capacity factor.
d. Disregarding differences in geographical and social contexts that can impact investment and operational costs, such as labor, materials, fuel supply, and community project management and operation.
e. Within the standardized approach aiming for comparability across projects and technologies, lack of understanding of the methodologies and assumptions used for *LCOE* calculation can result in outdated or imprecise calculations.

Despite being widely used for comparing electricity generation and energy storage technologies, none of the simple *LCOE* calculation methodologies have been standardized or universally accepted by the research community. When referencing *LCOE* values, it is essential to consider the specific considerations made by the authors in their calculations. The validity of *LCOE* is dependent on calculating it under the same conditions as the cost evaluations used as a basis. Factors such as energy resource availability, variability of renewable energy resources, demand variability and growth, system lifespan, discount rate differences, tax regime, fiscal policy incentives, and regulatory framework all impact the *LCOE* and must be considered.

Nevertheless, the *LCOE* has gained significant recognition among designers, researchers, and decision-makers due to its ability to encapsulate the entire project in a single parameter, answering the question: What is the minimum cost of electricity production required to recover the investment? However, the limitations stemming from its simple calculation method present challenges in determining the proper calculation approach. It is necessary to return to the fundamentals of the concept, where financial cash flow allows for the inclusion of all externalities and context-specific aspects of the project execution.

In its most basic definition, the *LCOE* is the sum of all costs incurred over the project's lifetime divided by the energy generated during that period. However, it is crucial to consider the concept of the time value of money, as financial mathematics does not allow for the direct addition of values from different years due to the cost of capital represented by an opportunity interest rate or discount rate. Thus, an annualized value or equivalent annual cost of all project expenses throughout its useful life needs to be approximated and calculated, divided by the average annual generation, as shown in the following equation (Eq. 1).

$$LCOE = \frac{Lifetime\,Cost}{Lifetime\,Electricity\,Generated} \cong \frac{Total\ Equivalent\ Annual\ Cost}{Average\ Anual\ Electricity\ Generation} \quad (1)$$

This approach can be avoided by considering that, to calculate an equivalent annual cost for a set of different costs in each year (non-uniform series), the figures for each year should first be brought to present value (at year 0), summed, and then distributed as a uniform series of annuities. When bringing the total costs of each year divided by the energy generated in that same year to present value, the most generalized form of *LCOE* calculation emerges. This involves dividing the Net Present Value – *NPV* of all costs by the "Present Value" – *PV* of the electricity generated, using the same discount rate employed in the numerator (Eq. 2).

$$LCOE = \frac{NPV\ Total\,Cost}{PV\ Electricity\,Generated} \quad (2)$$

Under the previous definition, the *LCOE* provides a single value that can be interpreted as the minimum price at which the energy generated by the power plant can be sold, in order for the Net present value of the generation project to be zero. If the selling price is lower than the *LCOE*, it means that the revenues will not meet the investor's expectations. On the other hand, if the selling price is higher than the *LCOE*, it will result in a higher profitability than the minimum expected by the investors, considering the Weighted Average Cost of Capital – *WACC* as the discount rate, which represents the investor's opportunity cost.

As shown in (Aldersey-Williams and Rubert, 2019), when considering a typical cash flow, where the investment is made at year *t=0* and is recovered through electricity generation from year *t=1* to year *t=n*, assuming that the project's life cycle ends at year *t=n*, the previous equation (Eq. 2) would transform into (Eq. 3):

$$LCOE = \frac{\sum_{t=1}^{n} \frac{C_t + O_t + V_t + F_t}{(1+d_r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+d_r)^t}} \quad (3)$$

Where:

- C_t: Capital cost annuity in the period *t* (Including replacement and decommissioning)
- O_t: Fixed operating and maintenance cost in the period *t*
- V_t: Variable operating and maintenance cost in the period *t* (Including fuel cost, carbon cost, taxes, etc.)
- F_t: Cost of financing in the period *t*
- E_t: Annual energy production in the period *t*
- d_r: Discount rate (in decimal form)
- t: Specific year of project lifetime
- n: Last year of project life cycle time

It is also important to clarify in the previous equation (Eq. 3), that when starting the summation from year 1, the capital costs associated with the investment (year *0*), equipment replacement or overhauls (specific year when they occur), and decommissioning (year *n*) must be converted into equivalent annual figures. Similarly, the project's financing costs should be converted into annual equivalents. To convert the investment costs and project financing (or any sum in Present Value – *PV* at year *t=0*) into Annuities – *A*, it is necessary to use the Capital Recovery Factor – *CRF* as shown in the following expression (Eq. 4).

$$A = PV * CRF = PV * \frac{d_r * (1+d_r)^n}{(1+d_r)^n - 1} \quad (4)$$

Considering the construction of the cash flow, when the present value *PV* pertains to financing costs, it is important to consider accounting standards and separate the loan payment represented by the annuity *A* into the Interest Charge and Principal Repayment components, as the former are tax-deductible while the latter is not. This will be explained further later on.

In the case of Decommissioning costs – *D*, which may include restoration costs (or any sum in future value *D* at year *t = n*), the annuity is calculated according to the following expression (Eq. 5).

$$A = D_{t=n} * \frac{d_r}{(1+d_r)^n - 1} \quad (5)$$

For any other sum that is not a uniform series composed of equal annuities *A* between year *t = 1* and year *t = n*, such as

Replacement Expenses – *RE*, it is recommended to first convert it into a present value *PV* using the following expression (Eq. 6), and then transform it into an annuity *A* using equation (Eq. 4).

$$VP = \frac{RE_{t=n}}{(1+d_r)^n} \tag{6}$$

From this point forward, the problem of calculating the *LCOE* consists of determining which costs are included in the numerator or how to incorporate all the costs associated with the project. There are many variations of this concept in the state of the art, which relate to the consideration of which capital expenditures – *CAPEX* are taken into account and their timing, the inclusion of tax rates and fiscal and regulatory incentives in operational expenditures – *OPEX*, as well as the choice of discount rate, such as the weighted average cost of capital – *WACC*. However, one of the major objections to the calculation of *LCOE* in this form lies in its denominator, as bringing the energy produced E_t to present value using the discount rate does not represent an actual cash flow. This, according to the rules of financial mathematics, could be considered inappropriate. In the review of the state of the art, criticisms of this concept proposed by Loewen in (Loewen, 2020) are of particular interest, where it is argued that as the discount rate and project lifespan increase, there are greater distortions in the value of *LCOE*, which disadvantages renewable energy sources compared to fossil fuels. In response to this issue, an alternative is proposed: the Present Value of the Cost of Energy – *PVCOE*, which divides the Total Lifecycle Cost - *TLCC* by the undiscounted sum of energy production. This would avoid the use of a discount rate d_r on the energy produced, as shown in equation (Eq. 4).

$$PVCOE = \frac{TLCC}{\sum_{t=1}^{n} E_t} \tag{7}$$

The *TLCC* being calculated as (Eq. 8):

$$TLCC = \sum_{t=1}^{n} \frac{C_t + O_t + V_t + F_t}{\left(1+d_r\right)^t} \tag{8}$$

In response to this criticism, Mac Cann, one of the consultants to the California Energy Commission who worked on several of the energy cost studies, published in (McCann, 2020) comments on Loewen's articles (in fact, in the same issue of (Loewen, 2020), in which he argues that the *LCOE* should be calculated by discounting both future cash flows and future energy production, and only in this way can a true value of *LCOE* be obtained. This is merely a conceptual and mathematical method consistent with the use of discount rates to compare investment options over time. He claims that the *PVCOE* method allocates initial costs annually in a way that does not sum up to the initial investment based on *NPV*, and such a result is inconsistent with basic economic and financial principles. He also asserts that instead of seeking a simple solution to compare resources with different lifespans, the correct approach is to chain a series of investments for two options that reach the same total lifespan for each option. In this way, the two *LCOEs* will be comparable.

On the other hand, NREL developed a simple calculation model for *LCOE*, generally applied to utility-scale and distributed generation (DG) renewable energy technologies, considering capital costs, operation and maintenance (O&M) costs, system efficiency, and fuel costs where applicable. Originally, this methodology does not include issues related to investment financing, incentives, taxes, depreciations, future replacement costs, among other aspects. It is necessary to include these issues in a more comprehensive analysis of the total costs of the generation project, using financial cash flow. For this purpose, NREL also provides the Cost of Renewable Energy Spreadsheet Tool – CREST (Gifford and Grace, 2009), which is more than just a spreadsheet containing economic and cash flow models designed to assess project economics, design cost-based incentives, and evaluate the impact of state and federal support structures on renewable energy. Returning to the more generalized model proposed in (NREL, n.d.), the simple *LCOE* is calculated using the following equation (Eq. 9):

$$sLCOE = \frac{OCC * CRF + F\,O\,\&\,M}{8760 * CF} + \left(FC * HR\right) + V\,O\,\&\,M \tag{9}$$

Where:
sLCOE: Simple Levelized Cost of Electricity
OCC: Overall Capital Costs per kW of generation capacity
FC: Fuel Cost
F O&M: Fixed Annual Operation and Maintenance Cost
V O&M: Variable Annual Operation and Maintenance Cost
CF: Capacity Factor or Plant Factor (in decimal form)
HR: Heat Rate (*kBTU/kWh*) or similar units in relation to energy rate
CRF: Capital Recovery Factor

NREL utilizes assumptions for calculating the *LCOE*, such as the useful life and the discount rate, which can be either real or nominal. The *CRF* enables the calculation of an annual equivalent value based on the present value of the investment, as equal annual figures over a time interval. Furthermore, equation (Eq. 6) shows that annual generation can be decomposed as the multiplication of the generation unit size by the capacity factor and the number of hours in a year (8760). This calculation approach is employed in an online tool referenced in (NREL, 2022).

This model is specifically used for generalized applications in renewable energy systems or small-scale fuel-based generation systems, aiming to make simple comparisons between the purchase price of electricity and the unit cost of implementing a generation project. Its simplicity implies that it only works with reference unit costs of investment and operation (*USD/MWh* or *USDcent/kWh*), requiring the definition of a scaling factor to account for economies of scale resulting from plant size. Additionally, it does not include costs related to investment financing, levies, or incentives, whether regulatory, tariff-based, or fiscal policy-related. However, NREL recognizes the straightforward nature and limitations of its methodology for *LCOE* calculation, and provides more detailed tools for technology comparison and future trends, such as the Annual Technology Baseline – ATB, which offers a set of tools for developing prospective analysis of different technologies (NREL, 2020).

In (Loewen, 2020) a comparison is conducted among different calculation methodologies proposed by NREL, CEC, Department of Energy and Climate Change of the UK - UK DECC, Bureau of Resources and Energy Economics – BREE of Australia, and Electric Power Research Institute - EPRI. This analysis aims to contrast these methodologies with the authors' own proposal, to provide a comparative analysis of the assumptions made in different models and the costs taken into account.

One of these models, the CEC model, could be considered the first to propose the concept. It is widely used and referenced, employing the concept of equivalent annual cost from equation (Eq. 10). It brings all costs per unit of generated energy $Cost_t$ to present value in the first component of the equation and then converts them into annual costs using the *CRF* in the second component of the equation. Similar to the previous NREL model, it has been implemented in a calculation tool. The general expression of the calculation of the *LCOE* of the CEC, taken from (Brown and Klein, 2016) is as follows (Eq. 10).

$$LCOE = \sum_{t=1}^{n} \frac{Cost_t}{(1+dr)^t} * \frac{dr*(1+dr)^t}{(1+dr)^t - 1} \quad (10)$$

In this expression, $Cost_t$ represents the costs of capital and financing, insurance costs, property taxes, fixed and variable costs of operation and maintenance, federal and state taxes, fuel costs, among others. Due to the interdependence of capital financing and taxes (the amount of financing cannot be estimated without knowing the taxes, and the taxes cannot be known until the amount of financing is known), simultaneous equations need to be solved using iterative methods. By employing the concept of equivalent annual cost, the investment typically made in year $t = 0$ is reflected in the costs from year $t = 1$ to $t = n$, thanks to the CRF in the second term of equation (Eq. 10).

Like the CEC, various governmental agencies responsible for energy planning and policies, as well as research institutes or non-governmental agencies, have developed calculation models and tools based on dividing the present value of total costs by the present value of electricity generated, as in equation (Eq. 2). This method of calculating the *LCOE* is the most widely employed in the state of the art. At this point, the differences among the various calculation proposals are based on the considerations taken into account within the costs and the simplifications made for the purpose of analysis and technology comparison. For instance, the Australian government's Bureau of Resources and Energy Economics – BREE has developed the Australian Energy Technology Assessment – AETA model (Australia. Bureau of Resources and Energy Economics., 2012) which has been in use since 2012 and incorporates environmental aspects related to carbon capture into operational costs – OM_t (Eq. 11).

$$OM_t = OPEX_t + CP_t * Em_t * NPO * \frac{CF_t}{100} * Hy + SC * \left(\frac{Em_t}{1 - \frac{EmCa_t}{100}} - Em_t \right) \quad (11)$$

Where:
$OPEX_t$: Operational Expenditures in year t (*AUD*)
CP_t: Carbon Price in the year *t* (*AUD/Ton* CO_2eq)
EM_t: Emissions in the year *t* (*Ton* CO_2eq/MWh)
NPO: Net Plant Output (*MW*)
CF_t: Capacity Factor in the year *t* (%)
Hy: 8760 hours per year (*h*)
SC_t: Sequestration Cost in the year *t* (*AUD*/Ton CO_2eq)
$EmCa_t$: Emissions Capture Rate in the year *t* (%)

Another example is the model of the Department for Business, Energy and Industrial Strategy – BEIS of the United Kingdom (Department for Business Energy and Industrial Strategy – BEIS, 2020), which is regularly employed in their reports to estimate costs and technical specifications for different generation technologies, aiming to include all costs in equation (Eq. 2). However, another highly cited exponent of this calculation methodology is the Fraunhofer Institute for Solar Energy Systems – ISE (Fraunhofer Institute for Solar Energy System, 2021), which, for calculating the *LCOE* of new generation plants, relies on the annuity method as a simplification of the *NPV* method. In this approach, the *CRF* is used in the numerator of the expression to annualize the total costs, while the denominator considers the average annual energy generated. Since this analysis is conducted for new plants, this value remains an estimate (Eq. 12).

$$LCOE = \frac{\left(I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+dr)^t} \right) * CRF}{\frac{\sum_{t=1}^{n} E_t}{n}} \quad (12)$$

Where:
I_0: Investment expenditure in the year *0*
A_t Annual total cost (fixed operating costs+variable operating costs+residual value/disposal of the power plant) in the year *t*

The *LCOE* calculation by Fraunhofer ISE represents a cost based on the project's own costs without including specific factors such as fiscal or regulatory incentives, tax rates, among others. This calculation using the annuity method in equation (Eq. 12) can be seen as a simplification of the *NPV* method, offering the advantage of lower computational effort. However, depending on the selected input parameters, significant deviations can occur. Nevertheless, its use as a comparison metric, where parameters like discount rates and project lifetime are equal for all generation systems, allows for observing the cost behavior of different technologies (Fraunhofer Institute for Solar Energy System, 2021).

3. INCENTIVES FOR THE INTEGRATION OF ALTERNATIVE ENERGY SOURCES

The transition to a low-carbon economy based on diversifying the energy mix with renewable resources is a top priority on the agenda of governments in several countries. In recent years, policies and incentives have been developed and consolidated both on the supply and demand sides. The aim is not only to integrate clean technologies in electricity generation but also to decarbonize the transportation sector, promote rational and efficient energy use, carbon capture, self-consumption, energy storage, and large-scale implementation of renewable generation projects. References such as (Kabel and Bassim, 2019; Shen et al., 2020; Wolsink, 2020) provide reviews and bibliometric analyses of different renewable energy policies, while in (Bardhan et al., 2019; Fuinhas et al., 2017a; 2017b; Izadian et al., 2013; Liu, 2019; Pathak and Shah, 2019; Zhu et al., 2020) offer more detailed regional or country-level analyses. This work will examine the incentives for the integration of alternative sources, given their importance in providing a more precise definition of *CAPEX* and *OPEX* in *LCOE* calculations. The proposed schematic by the Renewable Energy Policy Network - REN21 in their 2020 Global Status Report (REN21, 2020) will serve as the basis. According to REN21, policies for the development of alternative energy sources can be grouped into two categories that are independent of a country's economic and social development level: (i). Regulatory policies that provide incentives to economic operators who connect to the grid or produce electricity partially or entirely from renewable sources, and (ii). Fiscal incentives, including capital subsidies, investment or production tax credits, tax refunds and deductions, as well as direct public investment in the form of productive and competitive subsidies.

3.1. Regulatory Policies

The Organization for Economic Cooperation and Development - OECD, defines on its website "Regulatory policy is about achieving government's objectives through the use of regulations, laws, and other instruments to deliver better economic and social outcomes and thus enhance the life of citizens and business" (Organisation for Economic Co-operation and Development - OECD, n.d.). In 2004 Beck and Martinot (Beck and Martinot, 2004) summarized the main policies and barriers to renewable energy development, which can be oriented towards price setting, cost reduction through incentives, and market facilitation through public investments. The following are the most common regulatory policies found in the state of the art, applicable to distributed generation projects and renewable energy generation by public utility customers.

3.1.1. Feed-in tariff – FIT

This regulatory mechanism establishes prices for electricity injected into the grid by renewable generators (U.S Energy Information Agency, n.d.) *FITs* are usually paid by grid operators, energy retailers, or the market operator through a Power Purchase Agreement (PPA). The payment is guaranteed for a certain period of time, related to the project's economic life. There are variations of this concept, such as when the tariff is based on a fixed maximum number of hours of full-load renewable electricity production for which the *FIT* will be paid. *FITs* have proven to be one of the most successful incentives for promoting renewable energy (Lu et al., 2020). Many countries have support schemes for renewable energy sources where the *FIT* is established based on the *LCOE*, as it allows investors to recover their total costs and achieve a return on investment. However, *FITs* can also be determined through mechanisms such as auctions or avoided costs for the electric system. This tariff is generally tax-free and not considered as taxable income in financial accounting.

3.1.2. Net metering – NM

Net Metering enables customers with renewable energy generation capacity, typically solar PV on rooftops, to deliver excess electricity to the grid. They can later retrieve this energy from the grid when their renewable source is unavailable or when their energy demand exceeds their generation. This mechanism requires bidirectional meters to measure power flows. The key advantage of net metering is that it eliminates the need for energy storage systems, reducing investment and maintenance costs for the client. Under this regulatory mechanism, customers are billed only for their monthly net electricity consumption based on a defined tariff. The amount of electricity generated is subtracted from the amount consumed, often referred to as "running the meter backward." However, variations of this concept exist, such as "Buy all – Sell all," where the utility purchases all electricity generated by the net metered customer at a lower rate and sells all electricity consumed by the customer at a different rate (usually the same retail rate). Another variant is Net Billing, where the electricity delivered to the grid is offset by a predetermined value, measured as a tariff or a fixed amount (Lawson, 2019).

3.1.3. Carbon taxes and emissions trading system – CT and ETS

Another approach to promote clean technologies in electricity generation is to assign a higher price to carbon capture or non-emission than the cost of mitigation. Two instruments have been developed for this purpose: (i) Carbon Taxes – TC; and (ii) The Greenhouse Gas Emissions Trading System - ETS. These incentives have gained popularity in the regulatory policies of many countries, covering over 20% of global greenhouse gas emissions (Haites, 2018). With carbon taxes, the government sets a tax rate and specifies the sources subject to this tax. Companies emitting greenhouse gases are obligated to pay taxes proportional to their CO_2 equivalent emissions. In the case of ETS, it operates on the principle of "Cap-and-Trade" by establishing an emission allowance. The government imposes an emission cap on specified sources and distributes emission rights nearly equal to the limit. These rights are negotiable, creating a potential source of income. Like other taxes, carbon taxes generate public revenues while discouraging polluting behaviors. ETS, through auctioning emission rights, can also generate public revenues that can be utilized for climate and energy measures, tax reforms, debt repayment, social programs, or household compensation (International Carbon Action Partnership – ICAP, 2019).

3.2. Tax Incentives and Public Financing

Tax incentives encompass special exclusions, exemptions, deductions, or subsidies that provide preferential tax treatment, deferral of tax obligations, or special credits as part of green growth policies. These incentives are often included in public financing initiatives adopted by governments to reduce investment costs and encourage investor participation in renewable energy projects. The variations of tax incentives are numerous, as they depend on the tax laws and regulations of different countries.

These types of policies can have as many variations as tax laws and regulations exist in countries, proliferating not only in developed countries, but also in developing ones. In (Romano et al., 2017) an analysis of the effectiveness of green policies in stimulating investment in renewable energies reveals that different types of countries at different stages of development require tailored policies. For instance, direct government intervention is crucial in addressing environmental issues in developing countries, while in developed countries, the government assumes a regulatory role in managing existing policies. The following are common tax incentives and public financing measures used in the calculation of the *LCOE*:

3.2.1. Reduction of taxes – RT

Within the realm of tax incentives, special agreements aimed at reducing the tax burden are considered instrumental in supporting investments and the continuous operation of renewable generation systems. The primary tax incentives in this category include: (i) Income Tax Deductions, which allow taxpayers to subtract specific expenses or a percentage thereof from their gross income when calculating taxable income (tax liability), (ii) Accelerated Depreciation, which entails depreciating fixed assets at a faster rate during the initial stages of their useful life. This reduces taxable income early on, deferring tax obligations to later periods; and, (iii) Exclusion or Reduction of Value-Added Tax (VAT), Sales Taxes, Import Duties, or Emission Taxes through special tax regulations aimed at encouraging investment in renewable energy (Cox, 2015).

3.2.2. Production tax credit and investment tax credit – PTC and ITC

Tax incentives for producers of electricity from renewable sources are widely employed worldwide. The Production Tax Credit – *PTC* is granted either as a deduction from the taxable base or as a credit at a fixed rate per kilowatt-hour (kWh) from renewable sources. The *PTC* reduces income tax payments based on the amount of electricity produced. On the other hand, the Investment Tax Credit is based on the volume of capital investment (measured in monetary units). It allows individuals or companies to deduct a certain percentage of investment costs from their taxes once the installed equipment is operational (Goryunova, 2017). These *ITCs* are in addition to regular depreciation deductions, differing in that they offer a percentage deduction at the time of asset purchase.

3.2.3. Public financing – PF

In addition to the aforementioned tax measures, governments can implement measures to financially support the technological deployment of renewable energy through direct cash incentives based on performance, typically not requiring reimbursement. Examples of such measures include: (i) Rebates, which are usually applied after the purchase or installation of equipment and can be provided by utilities, financed by customer payments to these companies; (ii) Grants, which may be awarded by local governments, utilities, and non-profit institutions. They can be awarded before the installation of a technology (e.g., for research, development, and demonstration, business development, or feasibility studies) or after a system is fully operational. Grants can be combined with subsidized loans; and, (iii) Performance-based incentives, typically provided by utilities and funded through customer payments, aim to support renewable energy systems or improved energy efficiency based on performance. A small amount of money per kWh generated or saved is paid if established performance criteria are met (Cox, 2015; Goryunova, 2017). Within the concept of public financing for renewable energies, traditional financing strategies also play a role. With government policy support, investors can offer preferential interest rates, revolving loans, mortgage loans, grace periods for debt amortization, and access loans and other incentives through public-private partnerships and innovative financing approaches. For instance, green banks facilitate the "bundling" of financial incentives to support various phases or aspects of clean energy project deployment.

In (Organisation for Economic Co-operation and Development - OECD, n.d.) an example of including incentives in the calculation of the *LCOE* using the nomenclature of this article can be found in equation (Eq. 13).

$$COE = \frac{\sum_{t=1}^{n} \frac{C_t + OM_t + FC_t - PTC_t - D_t - T_t + Ry_t}{(1+dr)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+dr)^t}} \tag{13}$$

Where:
PTC_t: Production Tax Credit in the year *t*
D_t: Depreciation in the year *t*
T_t: Tax Levy in the year *t*
RY_t: Royalties in the year *t*

Below (Table 1) is an adaptation of Table 3 of REN21's Global Status Report 2020 (REN21, 2020), summarizing the presence

Table 1: Policies or incentives in 10 countries with the highest renewable power generation

Top ten	Country	Renewable power generation 2021 (TWh/year)	Regulatory policies			Fiscal incentives and public financing		
			FIT	NM	CT and ETS	RT	PTC and ITC	PF
1	China	1152,5	●			●	●	●
2	USED	624.5	●*	●*	●*	●	●*	●*
3	Germany	217.6	●		●	●	●	●
4	India	171.9	●*	●*	●	●	●	●*
5	Brazil	144.0		●		●	●	●
6	Japan	130.3	●		●	●		●
7	UK	116.9			●	●		●
8	Spain	95.8		●		●	●	●
9	Italy|	71.4	●	●		●	●	●*
10	France	62.8	●*		●	●	●	●

*Policy or incentive applied at sub-national level
Source: Adaptation of Table 3. Renewable Energy Targets and Policies in Renewables 2020 Global Status Report – REN21 (REN21, 2020)

Table 2: Structure of projected cash flow statement

Items		Year				
		0	1	2	3	*n*
+	Operating Revenues – *R*		X	X	X	X
+	Margin on Feed-in Tariffs – *MFIT*		X	X	X	
−	Operating and Maintenance Expenditures – *OM*		−X	−X	−X	−X
−	Fuel Costs – *FC*		−X	−X	−X	−X
−	Loan Interest Expenses – *LIE*		−X	−X	−X	
−	Depreciation – *D*		−X	−X	−X	−X
−	Amortization of Pre-operating Expenses – *APE*		−X	−X	−X	
=	Earnings Before Tax – *EBT*		X	X	X	X
−	Production Tax Credit – *PTC*		−X	−X	−X	
−	Investment Tax Credit – *ITC*		−X	−X	−X	
−	Other Income Tax Deductions – *ILO*		−X	−X	−X	
=	Taxable Operating Income – *TOI*		X	X	X	X
−	Income Tax – *T*		−X	−X	−X	−X
+	Other Non-Taxable Incomes – *ONTI* *		X	X	X	
=	Net Income – *NI*		X	X	X	X
+	Depreciation – *D* **		X	X	X	X
+	Amortization of Pre-operating Expenses – *APE* **		X	X	X	
+	Production Tax Credit – *PTC* **		X	X	X	
+	Investment Tax Credit – *ITC* **		X	X	X	
+	Other Income Tax Deductions – *OITD* **		X	X	X	
−	Investment Expenditures – *I*	−X				
+	Loan Received – *LR*	X				
−	Loan Principal Repayment – *LPR*		−X	−X	−X	
+	Salvage Value – *SV*					X
=	Net Cash Flow – *NCF*	−X	X	X	X	X

*e.g., Rebates, Grants, Subsidies. **Adjustment for expenditures not implying cash flows. Source: Authors

of the aforementioned incentives in the top 10 countries that generated the highest amount of electricity from renewable sources in 2021, according to the BP Statistical Review 2022 (BP, 2022). It can be observed that the most used incentives are related to tax burden reduction and support mechanisms for renewable generation projects.

4. PROPOSED METHODOLOGY FOR THE CALCULATION OF THE LCOE

We have already discussed the implications of using the *LCOE* beyond a mere comparison of renewable generation technologies. However, due to its definition, it is commonly employed to determine "Grid Parity" which refers to the condition where the cost of electricity generation from a particular source is equal to or lower than the general purchase price of electricity from the grid. It is also used to establish a "Fair Price" for energy in the context of Power Purchase Agreements (PPAs) or Performance-Based Contracts (PBCs), aiming to create equitable agreements for energy transactions.

Typically, *LCOE* calculation models aim to incorporate all costs associated with a project throughout its life cycle. This involves adding terms to the equation (Eq. 3) based on the present value of both costs and energy sales. In In a comprehensive analysis conducted by De Simón et al. (de Simón-Martín et al., 2022) they explore the concept of levelized cost in a broader energy context, covering various variants such as *LCOE* for conventional or alternative electricity systems, grid parity or fair price (*LCOE*), energy storage systems (*LCOS*), heat harnessing systems (*LCOH*), cooling systems (*LCOC*), and Levelized Cost of Exergy (*LCOEx*).

Table 3: Considerations in the *NCF* equation

Item in the equation	Case
E_t*(FIT−LCOE)	Disappears if no Feed-in Tariff is considered
D_t	Changes from the form of equation 20 to the form of equation 19, when there is no accelerated depreciation
PTC_t or ITC_t	Disappears if no Production Tax Credit or Investment Tax Credit is considered
$OITD_t$	Disappears if no special income tax deductions are made
$ONTI_t$	Disappears if no Rebates, Grants, Subsidies are given

Source: Authors

Table 4: Types of evaluation performed with the proposed methodology

Type	Criteria
1	Basic parameters used by existing methodologies without income tax or incentives
2	*LCOE* reported by international agencies or institutions for different technologies, following their criteria
3	Projects subjected to equal financial parameters, including accelerated depreciation, Feed-in Tariff and Investment Tax Credit (Accelerated depreciation during the first 5 years in straight line mode, *FIT* of 0,01USD/kWh for a period of 10 years, and *ITC* of 10%)
4	Similar to type 3 but with an additional loan component of 60% of the initial investment at a 10% effective interest rate over a 10-year period

Source: Authors

At its core, the proposed indicator derives an inequality shown in equation (Eq. 14), where all costs associated with the electricity generation project must be equal to or less than the revenues from energy sales, along with any additional benefits that can reduce investment and operating costs.

$$\sum_{t=1}^{n}\left[\frac{E_t*\overline{p_t}}{(1+dr)^t}+\frac{OR_t}{(1+dr)^t}\right] \geq \sum_{t-0}^{n}\left[\frac{CAPEX_t}{(1+dr)^t}+\frac{OPEX_t}{(1+dr)^t}+\frac{FC_t}{(1+dr)^t}+\frac{OC_t}{(1+dr)^t}\right] \quad (14)$$

Where:

$\overline{p_t}$: Annual average wholesale price in the year t

OR_t: Other revenues in the year t

OC_t: Other costs in the year t

In the equation mentioned above $\overline{p_t}$ represents the selling price or the price at which energy produced must be purchased from an alternative supplier, while OR_t encompasses indirect incentives or benefits. The left side of the equation represents the total discounted revenue over the project's lifespan, while the right side represents the total discounted costs of the power plant. Therefore, the discounted total annual revenues must at least cover the discounted total annual costs, which include capital expenditures, operation and maintenance expenses, fuel costs, and other expenses related to the power supply system. This analytical approach, known as "Discounted Cash Flow Analysis," will be utilized in the proposed methodology of this study.

Furthermore, to incorporate incentive and regulatory policies, as well as accounting and financial concepts in calculating the *LCOE*, Table 2 outlines the sequence of income and expenses in the annual cash flow projection within the financial evaluation of projects. It is important to note that, unlike a balance sheet, the *FCF* considers all cash inflows and outflows throughout the project's lifecycle. This is due to the impact of taxes on the annual cash balance, where tax-deductible costs, such as pre-operating expense amortization (recovering expenses incurred in the past) or depreciation (recognizing the wear and

Table 5: Specific parameters of NREL international projects

Concept	Solar - PV Dist. Res	Solar - PV Dist. Comm	Solar Utility PV	Wind Onshore	Wind Offshore	Geothermal
Plant capacity (*MW*)	0.05	0.30	23	50	30	35
Investment cost (*USD/kW*)	2.769.74	1.831.86	1.095.69	1.575.00	3.626.92	4.372.65
O&M (*USD/KW-year*)	24.20	18.36	19.87	43.56	128.27	135.23
Plant factor (*%*)	12.584	11.89	17.70	47.60	45.01	90.00
Shelf life (*year*)	30	30	30	30	30	30
Discount rate (*%*)	2.706	2.706	2.70	2.68	4.27	8.56
ITC (*USD/KW*)	276.97	183.19	109.57	157.50	362.69	437.26
Credit value (*USD/kW*)	1.661.84	1.099.12	657.42	945.00	2.176.15	2.623.59

Source: Adaptation of NREL (2020)

Table 6: Specific parameters of international projects by Fraunhofer institute

Concept	PV rooftop small	PV rooftop large	PV utility scale	Wind Onshore	Wind Offshore	Biopower
Plant capacity (*MW*)	0.005	0.1	2	2	3	0.05
Investment cost (*EUR/kW*)	1.200	800	600	1.500	3.100	2.000
Fixed O&M (*EUR/kW*)	30	20	15	30	100	80
O&M var (*EUR/KWh*)	-	-	-	0.005	0.005	-
Plant factor (*%*)	14.61	14.61	14.61	36.53	51.37	79.91
Shelf life (*year*)	25	25	25	25	25	30
Discount rate (*%*)	1.8	2.1	2.1	2.5	4.8	2.7
ITC (*EUR/KW*)	120	80	60	150	310	200
Credit value (*EUR/kW*)	720	480	360	900	1.860	1.200

Source: Adaptation of Fraunhofer Institute (2021)

Table 7: Specific Parameters of Lazard International Projects

Concept	PV Resident.	PV Rooftop	PV Comm.	PV Utility Cryst.	PV Utility Thin Fill	Wind Onshore	Wind Offshore	Geo thermal
Plant capacity (*MW*)	0.005	1.0	5	100	100	150	210	20.00
Investment cost (*USD/kW*)	2.800	1.750	1.600	1.100	1.100	1.100	2.350	3.920
Fixed O&M (*USD/kW*)	14	15	12	12	12	28.00	80.00	-
O&M var (*USD/KWh*)	-	-	-	-	-	-	-	0.024
Plant factor (*%*)	19	25	25	32	34	55	55	90%
Shelf life (*year*)	25	25	30	30	30	20	20	25
Discount rate (*%*)	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
ITC (*USD/KW*)	280	175	160	110	110	110	235	392
Credit value (*USD/kW*)	1.680	1.050	960	660	660	660	1.410	2.352

Source: Adaptation of Lazard (2021)

loss of value of an asset over time), do not actually involve any cash outflow. These values are deducted from net income before taxes and added back after taxes since they do not represent a cash outflow. Similarly, fiscal policy incentives like the Investment Tax Credit – *ITC* and the Production Tax Credit – *PTC*, along with other income tax deductions acting as incentives, are accounted for. Carbon Taxes - CT and the Emissions Trading System - ETS are considered within the operation and maintenance costs OM_t as defined in equation (Eq. 11).

The cash flow matrix provided in Table 2 encompasses all selected incentives at a general level. From this matrix, equations will be derived to represent the financial behavior of a renewable energy project throughout its lifecycle. Not all incentives are included in the cash flow of a specific project, as this depends on regulatory and public financing policies, as well as fiscal incentives specific to each country.

Table 8: Results of the evaluation in international projects

Technology	Type 1 A	Type 1 B	Type 2	Type 3	Type 4
NREL (*USD¢/kWh*)					
Solar - PV Dist. Res	14.53	14.53	15.09	15.85	19.27
Solar - PV Dist. Comm	10.40	10.40	10.92	11.17	13.56
Solar - Utility PV	4.75	4.75	4.96	4.71	5.67
Wind Onshore	2.98	2.98	3.03	2.65	3.16
Wind Offshore	8.75	8.75	9.27	8.97	10.06
Geothermal	6.90	6.90	7.63	6.85	7.03
Fraunhofer (*EUR¢//kWh*)					
PV rooftop small*	7.03	7.23	-	7.12	8.64
PV rooftop large*	4.80	4.95	-	4.68	5.67
PV utility scale*	3.60	3.71	-	3.37	4.11
Wind Onshore*	3.98	3.99	-	3.75	4.48
Wind Offshore*	7.49	7.51	-	7.50	8.33
Biogas*	10.12	10.14	-	9.80	10.19
Lazard (*USD¢/kWh*)					
PV Rooftop—Residential	16.20	-	15.10	17.38	18.46
PV Rooftop—C&I	7.98	-	7.50	8.16	8.60
PV Community	6.85	-	6.40	6.99	7.40
PV utility scale—Crystalline	3.82	-	3.60	3.57	3.80
PV utility scale—Thin Film	3.59	-	3.20	3.31	3.51
Geothermal	6.94	-	6.90	6.81	7.10
Wind—Onshore	2.85	-	2.80	2.32	2.45
Wind—Offshore	6.52	-	6.40	6.27	6.56

*Consider degradation of 0.5% in the annual energy generated. Source: Authors

Using a more generalized definition of *LCOE* based on the *NPV* (the minimum value at which the energy produced by the power plant can be sold to make the *NPV* of the generation project equal to zero), the first step is to establish the Net Cash Flow – *NCF* for each year. The *LCOE* is the unknown variable in this equation with *NPV=0*, requiring an iterative solution process. In this study, the iterative process utilized the complementary MS-Excel tool called "Solver."

$$\sum_{t=0}^{n} \frac{NCF_t}{(1+dr)^t} = 0;\ NCF_t = f(\bar{p}) \overset{when}{\rightarrow} \quad NPV = 0 \Rightarrow \bar{p} = LCOE \tag{15}$$

As an iterative process, it starts with a known or assumed value of *LCOE* based on similar projects in the context of development. The starting point is the Annual Operating Revenues (R), calculated as the product of *LCOE* and the annual energy generated by the power plant (Et). The equation to establish Rt is presented below (Eq. 16).

$$R_t = E_t * LCOE = NPO * CF_t * 8760 * LCOE \tag{16}$$

Where:
NPO: Net Plant Output (in energy units, e.g. *MWh*)
CF_t: Capacity Factor in the year *t* (in decimal form)

Note that equation (Eq. 15) associates the energy generated E_t with the Capacity Factor CF_t, which varies over time. This term not only considers the basic definition of the actual energy generated by a power plant in relation to its installed capacity or the percentage of the total generation capacity that a power plant utilizes in a specific time period but also takes into account the operational reality of most generation systems, where assets experience wear and a loss of useful life over time. Each item in the cash flow of Table 2 will be further explained.

When the Feed-in Tariff – *FIT* is included as an incentive, the income from energy sales R'_t would be the *FIT* value established by the government as an energy tariff (e.g., *USD/MWh*) multiplied by the energy produced (e.g., *MWh*). However, since the objective is to iteratively determine the *LCOE*, a margin called *MFIT* is used, which represents the difference between the *FIT* and the *LCOE*.

$$R'_t = E_t * LCOE + E_t * (FIT-LCOE) = R_t + MFIT_t = E_t * FIT \tag{17}$$

Table 9: Specific parameters projects in Colombia

Concept	Solar	Wind	Biomass	Geothermal
Plant Capacity (MW)	20	100	20	50
Cost to depreciate (*USD*)	31.600.000	115.000.000	10.000.000	25.000.000
Investment Cost (*USD*)	91.651.398	289.902.037	44.028.212	310.175.595
Maintenance (*USD*/year)	1.030.881	4.470.060	2.812.509	7.524.879
Plant Factor (%)	18.77	42.85	82.71	93.34
Energy Generated (*kWh*/year)	32.879.600	375.366.000	144.900.000	408.811.020
Shelf Life (years)	30	20	20	30
ITC (*USD*)	9.165.140	28.990.204	2.201.411	31.017.560
Credit Value (*USD*)	54.990.839	173.941.222	26.416.927	186.105.357

Source: Authors

In this case, the income from energy sales is obtained by multiplying the generated energy by the price agreed upon in the power purchase agreement *FIT*. If the *LCOE* is defined as the minimum value at which the energy produced by the power plant can be sold to make the *NPV* of the project zero, then the value of the *LCOE* should be equal to the *FIT*.

The Earnings Before Tax – *EBT* of the generation project (Eq. 18), is obtained by subtracting the tax-deductible expenses from the income received during the fiscal year from energy sales. As these values are part of the cash flow, they should be in monetary units (e.g., *USD* or *EUR*).

$$EBT_t = (R_t + MFIT_t)-(OM_t + FC_t + LIE_t + D_t + APE_t) \quad (18)$$

Where:
OM_t: Operating and Maintenance Expenditures in the year t (According to equation [Eq. 11])
FC_t: Fuel Cost in the year t
LIE_t: Loan Interest Expenses in the year t
D_t: Depreciation in the year t
APE_t: Amortization of Pre-operating Expenses in the year t

Table 10: Extension of case studies to the Colombian context

Guy	Characteristics
1	Takes into account the basic parameters used by existing methodologies without any tax rate or incentives
2	Evaluates the national project considering the income tax rate for the year 2019 (32% per year), as well as the incentives provided by Law 1715 of 2014 in Colombia
3 NREL	Subject only to the tax rate provided by NREL for the year 2017 since these projects are evaluated in that year, aiming to maintain consistent operating conditions for all projects
4	Applies the incentives provided by Law 1715 of 2014 in a qualitative manner (without specific values for Colombia), along with a Feed-in Tariff – *FIT* of 0.01 USD/kWh for a period of 10 years, an Investment Tax Credit (ITC) of 10%, and the possibility of using VAT or tariff deduction
5	Evaluates the projects in a financing case, considering a credit of 60% of the initial investment at an effective rate of 10% over a 5-year period using the ordinary annuity modality

Source: Authors

It is important to remember that each loan payment consists of two components: an Interest Charge and a Principal Repayment. The interest charge is a tax-deductible cost, while the principal repayment, which reduces the outstanding debt, should be calculated after taxes. Therefore, a "debt service" calculation is necessary. Through an iterative process, the interest and principal repayments are separated based on the loan payment (as an annuity), the initial loan balance, and the interest rate of the loan. The outstanding balance is updated for each payment period, and the interest is calculated based on it. Let At represent the annuity calculated using the *CRF*, OB_t be the outstanding balance at the beginning of period t, and ir be the loan interest rate. Then, the interest charge LIE_t will be calculated as follows (Eq. 19):

$$LIE_t = OB_t * ir \quad (19)$$

The loan principal repayment in period t will be (Eq. 20):

$$LPR_t = A_t\text{-}LIE_t \quad (20)$$

The process starts with an initial loan balance, which is the same as the loan received *LR* and is accounted for at the end of period *0* according to financial mathematics rules. This initial loan balance then becomes the outstanding balance at the beginning of period $t = 1$. By consecutively applying equations Eq. 19 and Eq. 20, we can calculate the outstanding balance at the end of period $t = 1$ (OB'_t) as a result of (Eq. 21):

$$OB'_{t=1} = OB_{t=1}\text{-}LPR_{t=1} \quad (21)$$

To continue the iterative process, outstanding balance must be updated at the beginning of the next period $t+1$, until the final balance of the lt period ($OB't_{=lt}$) that would be the loan term, is equal to zero (Eq. 22).

$$OB_{t=2} = OB'_{t=1} \quad (22)$$

This process ensures that loan obligations are met, and interest and principal amortization are paid appropriately.

Special attention should also be given to the term D_t in equation (Eq. 18), which represents depreciation, as it can be subject

Table 11: *LCOE* Results in projects in Colombia

Source	Concept	Type 5	Type 4	Type 2	Type 1	NREL	UPME	Energy Generated [*kWh*/year]
Solar	LCOE (*USD¢/kWh*)	27.32	25.57	28.11	22.18	22.18	21.68	32.879.600
	Annual Gross Revenue (*USD*)	8.985.864	8.409.319	9.243.507	7.292.695	7.292.695	7.130.598	
	Percentage change	19	13	21	0	0	−2	
Wind	LCOE (*USD¢/kWh*)	8.567	7.981	9.442	7.621	7.621	9.27	375.366.000
	Annual Gross Revenue (*USD*)	32.160.415	29.959.087	35.442.058	28.606.643	28.606.643	34.807.689	
	Percentage change	11	5	19	0	0	18	
Biomass	LCOE (*USD¢/kWh*)	8.31	8.1	9.2	8.4	8.4	7.89	144.900.000
	Annual Gross Revenue (*USD*)	12.044.692	11.742.374	13.339.102	12.185.430	12.184.641	11.438.406	
	Percentage change	−1	−4	9	0	0	−6	
Geothermal	LCOE (*USD¢/kWh*)	8.03	7.63	8.89	7.02	7.02	8.24	408.811.020
	Annual Gross Revenue (*USD*)	32.829.845	31.196.369	36.371.916	28.727.150	28.727.150	33.686.028	
	Percentage change	13	8	21	0	0	15	

Source: Authors

to incentives through tax reductions. In most cases, a constant depreciation rate is assumed throughout the project's lifecycle using the straight-line method. This method assumes that in year $t = 0$, when the asset is acquired, its book value is equal to the purchase price, and in year $t = n$, its value is the salvage value. Then, between year $t = 1$ and year $t = n$, the depreciation value is calculated using the following expression (Eq. 23):

$$D_t = \frac{IFA - SV}{n} \quad (23)$$

Where:
IFA: Initial Investment in Fixed Assets in the year 0 (*USD*)
SV: Salvage Value in the year *n* (*USD)*
n: Last year of project life cycle time

Other methods for calculating depreciation include the declining balance method and the sum-of-years-digits method, but the straight-line method is the most commonly used for financial reporting purposes. The Investment in Fixed Assets – *IFA* refers to investments in depreciable fixed assets such as machinery, control and measurement equipment, buildings, and other acquired assets that experience wear and tear over time until reaching a residual value or Salvage Value. At this point, it is important to clarify that, for simplicity's sake, *n* refers to the project's lifecycle time. However, when calculating depreciation on an individual asset basis, *n* would actually represent the useful life of an asset, which is the period of time during which an asset is expected to be useful and productive before it needs to be replaced.

On the other hand, when the incentive of Accelerated Depreciation exists, it is assumed that for a short period of time (typically 3-5 years), assets eligible for this incentive are fully depreciated within this timeframe, reducing their Salvage Value *SV* to zero. Therefore, Accelerated Depreciation would result from dividing the *IFA* by the depreciation time determined by the incentive (Eq. 24). Governments usually establish an annual depreciation factor df_t and specify which types of assets are eligible for this incentive.

$$D_t = IFA * \frac{df_t}{100} \quad (24)$$

These expenses can include other deductible additional costs, such as dismantling costs, which, depending on the tax regulations of each country, can be incurred in the year t=n or provisioned as an annualized series using the CRF. The treatment of these costs can be either before or after taxes, depending on the fiscal incentive policy.

Once the Earnings Before Tax - *EBT* is obtained, the next step is to calculate the Taxable Operating Income – *TOI* (Eq. 25), which represents the balance of income minus tax-deductible costs and serves as the basis for income tax payment. If there are any additional deductions due to renewable generation tax incentives, they should be applied to the *EBT*.

$$TOI_t = EBT_t - (ITC_t + PTC_t + OITD_t) \quad (25)$$

Where:
ITC_t: Investment Tax Credit in the year *t* (*USD*)
PTC_t: Production Tax Credit in the year *t* (*USD*)
$OITD_t$: Other Income Tax Deductions in the year *t* (*USD*)

As explained earlier, the Investment Tax Credit – *ITC* is calculated as a percentage of the investment and can be deducted over a specific period of time. On the other hand, the Production Tax Credit – *PTC* is calculated based on the energy produced multiplied by a fixed rate per kilowatt-hour (*kWh*). However, the specific concepts and variations of these incentives may differ depending on the country implementing them. Other Income Tax Deductions – *OITD* may also exist as deductions on the Net Income - *NI* with different schemes than those already presented, such as the *ITC* and *PTC*.

The Net Income - *NI*, which represents the accounting net profit, is obtained by subtracting the Income Tax – *T* from the Taxable Operating Income – *TOI* and subsequently adding the Other Non-Taxable Incomes - *ONTI*, which can also be subject to incentives (Eq. 26).

$$NI_t = TOI_t - T_t + ONTI_t = (1-itr) * TOI_t + ONTI_t \quad (26)$$

Where:
itr: Income Tax Rate (in decimal form)

Finally, to calculate the Net Cash Flow – *NCF* (Eq. 27), which represents the actual money inflows and outflows of the generation project, we start with the Net Income - *NI* and add expenses that do not generate cash outflows but are considered for tax purposes, such as *D*, *APE*, *PTC*, *ITC* and *OTD*. Additionally, we consider the Investment Expenditures *I* disbursed in year *0*, the Loan Received - *LR* which is a non-taxable income in year *0*, the Loan Principal Repayment – *LPR*, and the Salvage Value – *SV* taken into account in year *n* when accelerated depreciation is not applied.

$$NCF_t = NI_t + (D_t + APE_t + PTC_t + ITC_t + OITD_t) - I_{t=0} + LR_{t=0} - LPR_t + SV_{t=n} \quad (27)$$

By rearranging the equation (Eq. 22) and using the equations (Eq. 16, 18, Eq. 18, 22, Eq. 21, 23, Eq. 22) we can derive a generalized equation for the Net Cash Flow for each year, which is dependent on the value of the *LCOE* (Eq. 28).

$$NCF_t = (1-itr) * [E_t * LCOE + E_t * (FIT-LCOE) - OM_t - FC_t - LIE_t] + itr*DENC_t + ONTI_t - I_{t=0} + LR_{t=0} - LPR_t + SV_{t=n} \quad (28)$$

Where:

$DENC_t$: Tax-deductible expenses in the year *t* that not implying cash flows; calculated as (Eq. 29):

$$DENC_t = D_t + APE_t + PTC_t + ITC_t + OITD_t \quad (29)$$

Note that depending on the regulatory and fiscal policies of each country regarding the promotion of alternative energy sources, some terms may disappear or vary in equations (Eq. 28 and Eq. 29). Considerations in the NCF equation, are shown in Table 3.

The following equation (Eq. 30) provides an example for calculating the *LCOE* in the Colombian context by equating the *NPV* to zero over the *NCF*. In this scenario, there are four incentives for the development of non-conventional renewable energy sources, with two incentives related to *CAPEX* and the other two related to *OPEX*. The first set of incentives pertains to the exemption of import duties on equipment and the Value Added Tax - *VAT* on equipment purchase, assembly, and installation services. These incentives directly impact the value of the Initial Investment *I*. On the other hand, the incentives related to *OPEX* affect the cash flow from year $t = 1$ to year $t = 5$. They involve applying accelerated depreciation *D* as an expense deductible for income tax purposes, limited to a maximum annual depreciation rate of 20% of the asset's value (*IFA*). Additionally, there is a special deduction of 50% on income tax for the investments made (*I*).

$$\sum_{t=1}^{5} \frac{\left[E_t{*}LCOE - OM_t - FC_t - LIE_t\right]{*}\left(1-itr\right) + \left[0.2{*}IFA + APE_t + 0.1{*}I\right]{*}\left(itr\right) - LPR_t}{\left(1+dr\right)^t} + \sum_{t=6}^{n} \frac{\left[E_t{*}LCOE - OM_t - FC_t - LIE_t\right]{*}\left(1-itr\right) - LPR_t + SV_{t=n}}{\left(1+dr\right)^t} - I_{t=0} + LR_{t=0} = 0 \tag{30}$$

In equation (Eq. 26), all values except the *LCOE* are known, allowing for an iterative solution using the methodology proposed in this study, which utilizes the Solver function in MS-Excel to find the *LCOE* that satisfies the condition of *NPV* equal to zero.

To correctly apply the proposed methodology, it is assumed that the project's construction period is one year. If the duration is longer, it is unified using financial equivalence concepts at year *0*. This means that investment costs are accounted for in the year prior to project implementation. Factors such as depreciation or income tax deductions may not be considered throughout the project's entire lifecycle. Therefore, starting from the year following the end of asset's useful life (for depreciation) or the expiration of the income tax deduction benefit, these values are assumed to be zero. Other capital costs that do not follow a uniform series of annuities over the entire evaluation horizon, such as replacement costs, overhauls, and decommissioning costs, should be brought to year *0* and then converted into annuities from year *1* to year *n*. The tool was designed in a generalized manner, considering different incentives depending on each country's regulations. If an incentive does not apply, its value is assumed to be zero. Regarding debt service, the methodology includes a type of credit that allows for a single annuity with a maximum term of 15 years and an effective annual interest rate provided by the user. The fixed fee is taken into account in each period stipulated by the received credit.

It's important to note that the role of *LCOE* within the cash flow varies depending on the evaluated scenario. The two scenarios considered are:

4.1. Self-consumption Scenario

When calculating the *LCOE* for a self-consumption project, the result represents the cost at which the user produces energy. To demonstrate the savings achieved through replacement, it is necessary to compare this production cost with the cost of purchasing energy if the project were not operational.

4.2. Energy Sale Scenario

When calculating the *LCOE* for a project that sells energy to the grid, the result represents the unit cost that equals the opportunity cost. In other words, a sale price higher than the calculated *LCOE* results in an *NPV* greater than zero, indicating positive profitability for the project.

5. CASE STUDIES AND VALIDATION OF THE PROPOSED METHODOLOGY

To explore the effects of variations in the Levelized Cost of Electricity and validate the proposed methodology, an evaluation was conducted on international projects as reference, along with some projects from Colombia. These projects were subjected to different evaluation parameters to observe the behavior of the *LCOE* before considering external factors. To enhance the tool's applicability, four types of evaluations were developed, as listed in Table 4:

These evaluations aimed to make assumptions regarding:

a. Obtaining the same *LCOE* value calculated by both reference methodologies and the proposed methodology based on the same parameters.
b. Observing the *LCOE* variation by adopting base parameters and including tax rates and incentives within the cash flow.
c. Analyzing the individual impact of incentives on the *LCOE* value.

It is important to emphasize the variability and bias in data due to the effects of global markets and inflation caused by the pandemic. In this section of the study, focused on validation and comparative analysis, data from a pre-pandemic scenario will be employed. For the international context, the parameters adopted are provided by: the ATB DATA 2019 database from NREL, the report presented by Fraunhofer in 2018, and the *LCOE* analysis document provided by Lazard version 13.0. The projects within the Colombian context were derived from the technical documentation of the GeoLCOE v2.0 application belonging to the Mining and Energy Planning Unit – UPME of the Ministry of Mines and Energy of Colombia (Available at: http://www.geolcoe.siel.gov.co/#). These projects will undergo the cash flow described by the proposed methodology to verify that the obtained value falls within the standard international ranges.

5.1. Validation of the Methodology

The evaluated projects included photovoltaic solar power plants (residential, commercial, and large-scale), onshore and offshore wind, geothermal, and biomass. Tables 5-7 above presents the specific parameters of the international projects to be evaluated, where their common parameters for Evaluation Type 3 are: 25,7%

associated with income tax in the United States, an accelerated depreciation of 20% per year in straight line mode. Likewise, Table 8 four types of evaluation in which the different projects were submitted. Although the purpose is not to compare *LCOE* values by technology, similar technologies were included but with different operating parameters. It's important to note that projects of the same technology but from different entities should not be directly compared.

In Table 8 the first type of evaluation presents the values obtained by the proposed methodology (type 1-A) as well as those provided by the reports from different entities (type 1-B), demonstrating the validity of the methodology as the values obtained are consistent for each project. It should be noted that the projects from Lazard do not provide a theoretical value in this type of evaluation because they consider parameters such as the MACRS depreciation method and tax rates as a starting point. However, the general values for each project were used and presented in type 1-A. Additionally, the type 1-A values show a slight difference compared to type 1-B, as Fraunhofer introduces an annual energy degradation of 0.5%, whereas the methodology works with constant values without an inflationary scenario.

Within the second type of evaluation, only the *LCOE* values for each technology are presented, taking into account the externalities included by each entity. This type of evaluation aims to observe how certain considerations modify the value compared to the previous type. The Fraunhofer report does not include externalities in its evaluation and, therefore, they will not be considered in this type of evaluation.

Continuing with the validation results, the third type presents an *LCOE* subject to financial reference considerations adopted by the methodology, showing significant variations compared to types 1 and 2. This case is the most important in evaluating the proposed method. The use of various incentives in this analysis is employed to observe their scope or impact on the *LCOE* calculation. However, it does not imply that all incentives apply to the same project in real cases, as some may be specific to certain technologies or not applicable in a particular country.

There is an increase in *LCOE* in type 3 compared to type 1 for residential and community PV technologies in all three entities. This behavior is typical due to the high installation costs for these technologies, which are often not subject to tax rates since they are not projects for selling services.

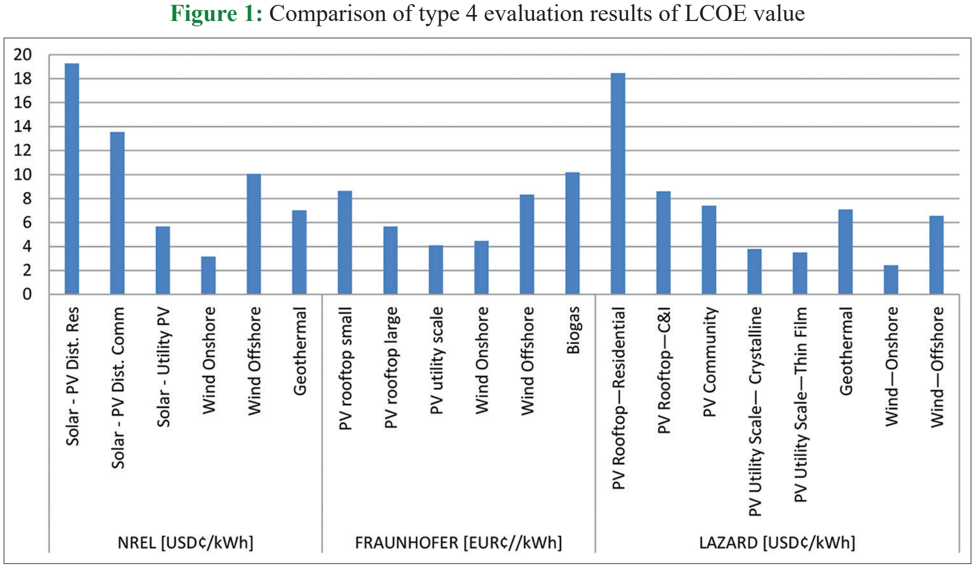
Finally, type 4 evaluation examines the impact of financing credits on the *LCOE* of a renewable energy project, although they are not always subject to the same conditions proposed in this evaluation (Figure 1).

5.2. Impact of Incentives on LCOE

Based on evaluation type 3, the impact on the *LCOE* value of two commonly used incentives, the Investment Tax Credit – *ITC* and the Feed-in Tariff - *FIT*, is analyzed. The projects from NREL will be used as a reference (Table 6). Other methods of incentivizing *LCOE* reduction, such as accelerated depreciation or income tax deductions, are not individually evaluated for these projects due to variations in their international usage, and thus would not yield significant results within the scope of this study. The following are some relevant results obtained in this work.

1. When evaluating the behavior of *LCOE* with respect to the *ITC* (Figure 2), a decrease is observed until a certain point where its impact on *LCOE* becomes negligible. This inflection point represents the percentage that the project requires to fully cover all costs associated with income tax over its lifetime. It is important to note that the *ITC* is closely related to depreciation since it modifies the taxable basis, which in turn affects the *ITC*. Additionally, as the investment percentage increases, the slope of the *ITC* becomes smaller, reaching a point where it contributes to each year of the project's lifetime. Beyond a specific percentage, the *LCOE* becomes less sensitive to further increases in the *ITC*. In real cases, *ITC* percentages are generally around 10%, as the objective of this incentive is to partially cover income tax in the initial years, which have the most significant impact during

Figure 1: Comparison of type 4 evaluation results of LCOE value

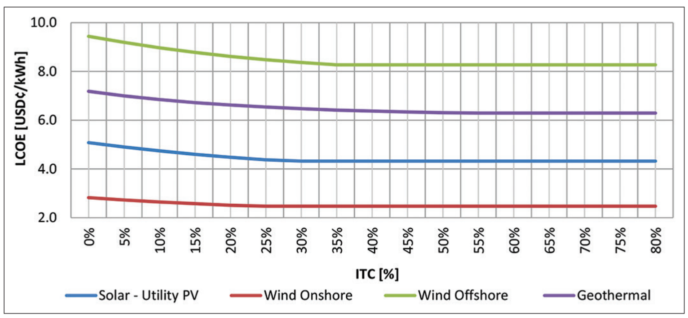


Source: Authors

project implementation. Furthermore, it is essential to highlight the significant role of investment and operation costs since the percentage at which *LCOE* stabilizes depends on them.

2. Incentives reflect significant changes in *LCOE*, but each incentive contributes with a different level of sensitivity in terms of its impact on cash flow. For example, in the case of the *FIT*, substantial changes in *LCOE* can be observed as it is influenced by two factors: the agreed-upon FIT value and the duration of the incentive contract. Figure 3 illustrates this behavior using contract periods ranging from 2 to 10 years for solar, wind, and geothermal projects from NREL, which serve as the basis for this comparison. It can be observed that the *FIT* results in reductions in *LCO*E, ranging between 2 and 3 USD¢/kWh, indicating a significant cash flow release from a financial perspective. This incentive holds great importance for power generation facilities with high capital expenditures (*CAPEX*), considering the extent of reduction it achieves. It should be noted that the technologies evaluated within the NREL projects also exhibit higher costs.

Figure 2: Behavior of the LCOE with respect to the ITC in international projects



Source: Authors

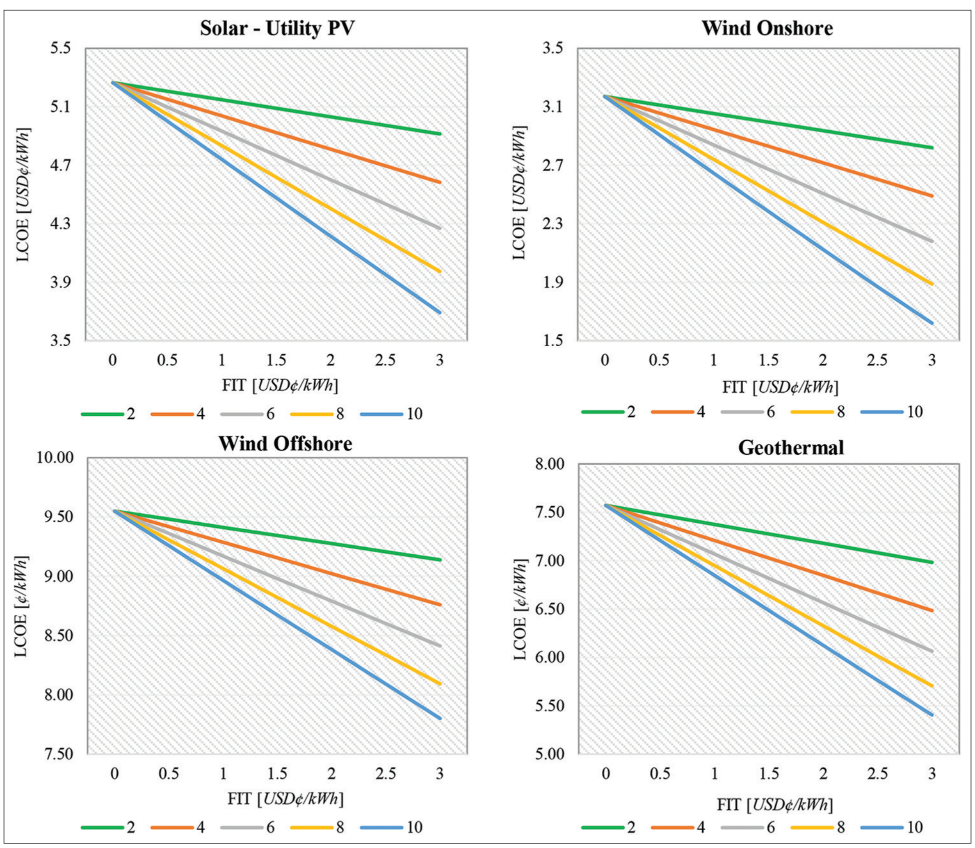
5.3. Application to the Colombian Context

As an additional case, a comparison and evaluation of the methodology for the Colombian context is presented, showing some variations depending on the incentives provided by Law 1715 of 2014 for Colombia. In this sense, project parameters found by the technical documentation of the Geo*LCOE* v2.0 application belonging to the UPME will be used. Table 9 specific parameters for the four national projects that will be evaluated. However, common parameters apply to all projects, such as a discount rate of 5.44%, an accelerated depreciation in a straight line in a period of 5 years, and a deduction of 50% of the liquid income in a period of 5 years. In the Biomass project, variable costs, and fuel costs of $608.580 USD and 5'098.408 *USD* respectively are considered. The value of dismantling and salvage will not be taken into account for any of the projects.

An evaluation and validation of the proposed methodology are conducted to explore the effects of *LCOE* variation for national projects, expanding the evaluations to five types (Table 10) that allow for different scenarios in the inclusion of externalities specific to the Colombian context.

Table 11 presents the results of the *LCOE* and annual gross revenues based on the type 1 evaluation. It aims to determine the

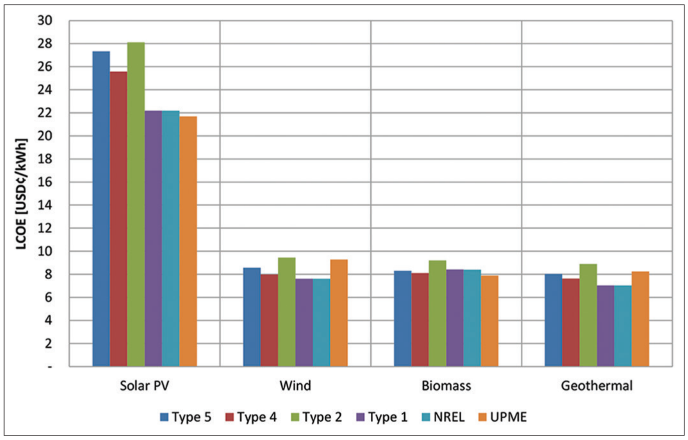
Figure 3: Behavior of the LCOE with respect to the FIT in some international projects



Source: Authors

percentage change of the *LCOE* in each evaluation. The NREL column shows values obtained using the method proposed by the NREL, while the UPME column presents the theoretical value proposed in the provided documentation. This table demonstrates significant variations in gross income, mainly attributed to annual operating income. Percentage variations are also observed compared to case 1. The calculations made in the base case and the NREL method show a variation of 0%, indicating that both methodologies yield the same *LCOE* value.

Figure 4: LCOE variation for each technology in national projects



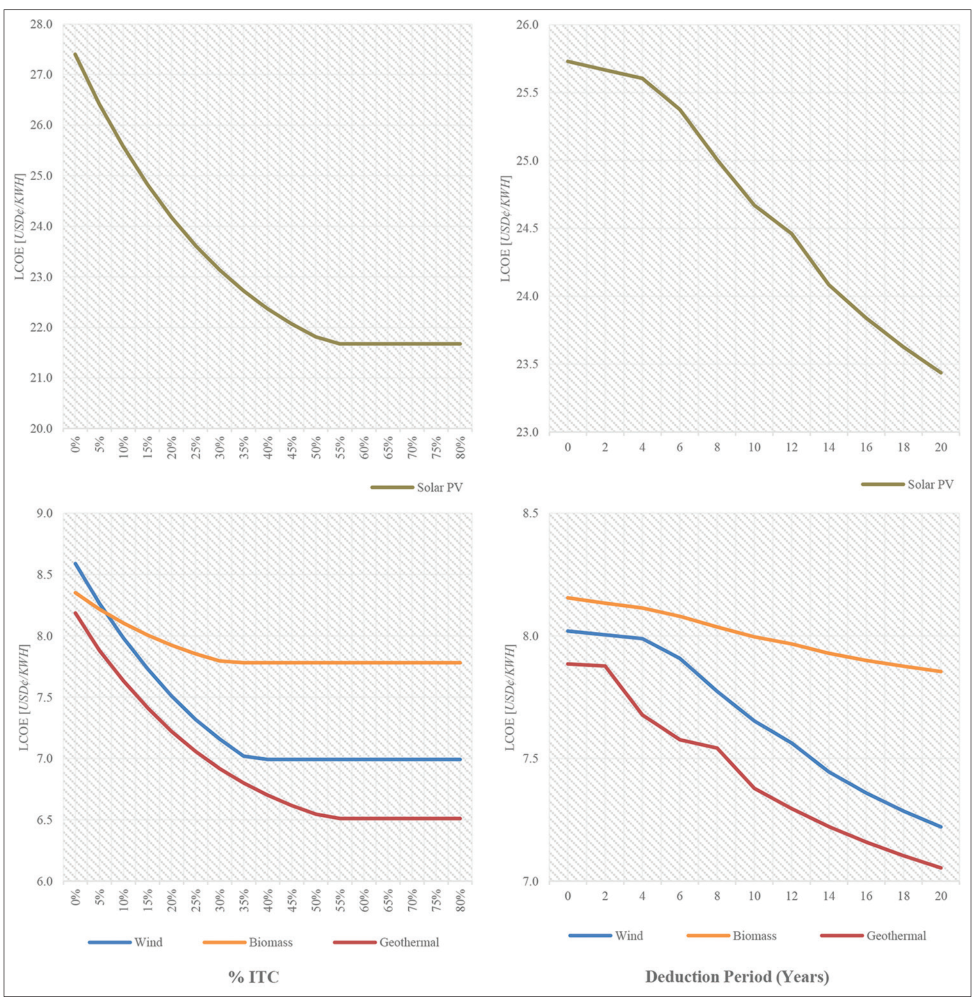
Source: Authors

From the previous table, it can be observed that each technology presents variations in *LCOE* according to the scenario, with minor variations ranging from 1% to 6%, and major variations up to 21%. However, it was expected that the variation would increase as more details were added. Surprisingly, the greatest variation occurs between type 1 and type 2 scenarios, and in the subsequent scenarios, the impact of incentives can partially or completely offset the effect of tax rates.

To fully compensate, significant impact incentives are required, but such cases are uncommon, and rarely result in an *LCOE* equal to or similar to the base scenario with incentives. It is worth noting that the *LCOE* obtained in the Colombian scenario and the value calculated by UPME show variations. This is due to differences in financial exercises, such as degradation value, discount rate, income tax, and some unspecified costs. Additionally, the proposed methodology works with real values, not current values.

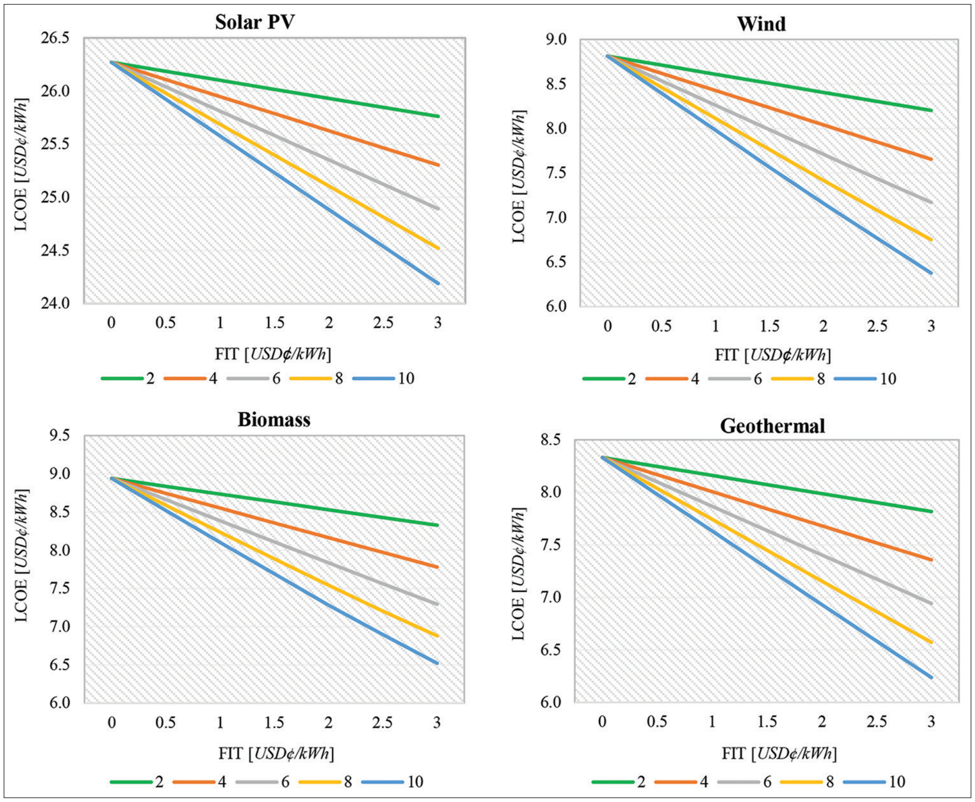
The high *LCOE* for solar PV technology in Colombia is noteworthy, especially in utility-scale cases like the one analyzed.

Figure 5: LCOE variation with respect to ITC and deduction time



Source: Authors

Figure 6: LCOE variation with respect to FIT national projects



Implementation costs for these projects are higher due to the lack of domestic companies capable of executing such large-scale projects. Consequently, the hiring of foreign personnel and technology becomes necessary for project development. Figure 4 illustrates the variation of *LCOE* for each technology in the Colombian context, while Figure 4 shows the variation of *LCOE* regarding the impact of each incentive (*ITC* and deduction years) on its cash flow.

The scope of the Investment Tax Credit is closely related to the initial investment and costs that affect the income tax value. The slope of the *ITC* decreases as the investment percentage increases, reaching a point where the *LCOE* shows no variation with further increases in the *ITC* percentage. At this point, the *ITC* value covers the total income tax that the project is obligated to pay throughout its useful life, rendering an *ITC* greater than the inflection point percentage unnecessary, and where its behavior becomes constant.

On the other hand, the variation of the *LCOE* is presented with respect to the impact that each incentive has on its cash flow (Figure 5). The scope of the Investment Tax Credit - *ITC* is closely related to the initial investment and to the costs that affect the value of the income tax. The slope of the *ITC* decreases as the percentage of the investment increases, and the time will come when the *LCOE* will not present any variation in the face of the increase in the *ITC* percentage. From this moment the value covers the entire income tax that the project is obliged to pay throughout its useful life, which implies that an *ITC* greater than the percentage established as a turning point is unnecessary, and where its behavior becomes constant.

According to the previous graph, a slight decrease in *LCOE* is observed concerning the deduction period and income tax percentage. One of the reasons behind this behavior is the deductible costs. This incentive is directly linked to income tax, implying that a lower income tax value results in a smaller deduction and, consequently, a smaller reduction. Additionally, income tax is affected by the number of deductible costs presented by the project. Therefore, this incentive does not generate a significant decrease in *LCOE* calculation.

Finally, the results obtained for the Feed-in Tariff - *FIT* for each national project are presented in Figure 6. This incentive provides the greatest reduction in the financial exercise as it is a non-taxable income. It impacts both the fixed tariff agreed upon by the government entity and the duration period, ranging from 2, 4, 6, 8, and up to 10 years of the project's useful life. The most optimistic scenario achieves reductions of up to 3 USD¢/kWh of generated energy.

6. CONCLUSIONS

The validity of the proposed methodology is based on Evaluation Type 1, which achieves the same levelized cost of electricity value as international reference models. The added value of the proposed *LCOE* lies in adopting the cash flow matrix as a starting point to represent the project's income and expenses throughout its lifespan.

The accuracy of the *LCOE* is reflected in significant variations in evaluation types that include externalities, which directly affect gross income and introduce a higher degree of uncertainty into the matrix when accounting for accounting standards for project evaluation.

Calculating the *LCOE* without considering externalities and the project's operational conditions can lead to significant inaccuracies, as evidenced in the cash flows. Under these circumstances, the *LCOE* serves merely as an indicator for comparing technologies evaluated under the same scenario. It cannot be used as a criterion for decision-making or in price negotiations for selling renewable energy to the grid or establishing sales revenues in non-interconnected settlements.

Among the evaluated incentives, the Feed-in Tariff has the most significant impact on the *LCOE*, reducing it by up to *3 USD¢/kWh*. The scope of the *FIT's* impact stems from its characterization as a non-taxable income, inversely affecting the *LCOE*. It can provide benefits both in terms of the agreed-upon value and the duration of participation within the project's lifespan.

Fiscal incentives such as investment tax credits or income deductions require high percentages and/or periods of time to have a considerable influence on the cash flow. In other words, incentives of such characteristics do not contribute significantly to promoting the use of renewable energy due to their low level of contribution.

It is observed that the *LCOE* obtained from the proposed methodology and the value calculated by UPME present variations, with some cases being more significant than others. This is due to differences in financial exercises, such as degradation value, discount rate, income tax, and some unspecified costs. Additionally, the proposed methodology works with constant values.

To evaluate the national photovoltaic project more accurately, the costs presented in the supporting documentation for the development of the GeoLCOE application were considered. However, it was observed that the values do not align with the international average for this type of technology, resulting in a higher *LCOE* that falls outside the international *LCOE* ranges. It is recommended to review these costs and investigate the possible causes of the increases.

Overall, the proposed methodology provides a valuable framework for evaluating renewable energy projects, emphasizing the need for comprehensive and accurate evaluation methodologies. However, further research and refinement are necessary to address specific regional or sector-specific factors that impact project economics. These findings underscore the importance of understanding the true costs and benefits of renewable energy projects, enabling informed decision-making and fostering the widespread adoption of sustainable energy sources.

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