LARGE-SCALE SOLAR PV LCOE COMPREHENSIVE BREAKDOWN METHODOLOGY

ABSTRACT

This paper presents a breakdown cost methodology to evaluate Levelized Costs of Electricity for large-scale Photovoltaic (PV) plants. The breakdown is based on a comprehensive taxonomy to evaluate Investment Costs (IC) and Operation and Maintenance (O&M) expenditures. We added an IC disaggregation level, called elements, on top of the five-component breakdown of the Energy Information Administration (EIA). In addition, a novel structure for disaggregating O&M costs is also proposed. The methodology is evaluated over a 20-MW and a 150-MW PV power plant hypothetically placed in the municipality of Uribia (Guajira Colombia). Also deterministic sensitivity analysis based on discount rate (WACC, Weighted Average Capital Cost), energy generated, O&M costs and IC is performed to aid investors in their decisions.

Keywords: LCOE breakdown, Large-Scale Photovoltaic, Investment Costs, Operational and Maintenance Costs, Incentives, WACC.


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Este artículo presenta una metodología para evaluar los costos nivelados de la electricidad (Levelized Cost of Electricity-LCOE), en plantas fotovoltaicas (Photovoltaic - PV) a gran escala. Para ello se propone una desagregación detallada de los LCOE a partir de una taxonomía rigurosa que evalúa los Costos de Inversión (Investment Cost - IC) y los Gastos de Operación (Operation and Maintenance – O&M). Partiendo de la estructura de la Administración de Información Energética (Energy Information Administration – EIA) que desglosa los IC en cinco componentes, hemos añadido un nivel adicional de desagregación denominado elementos. Asimismo, una nueva estructura para desagregar los costos de O&M es presentada. La metodología es evaluada en plantas PV de 20 MW y 150 MW PV hipotéticamente ubicadas en el municipio de Uribia (Guajira Colombia). También se desarrolla un análisis de sensibilidad determinístico usando factores como el Costo Promedio Ponderado de Capital (WACC – Weighted Average Capital Cost), la energía producida, los gastos de O&M y los IC con el ánimo de facilitar las decisiones de los inversionistas.

Palabras clave: Desagregación del LCOE, Fotovoltaica a Gran Escala, Costos de Inversión, Costos de Operación y Mantenimiento, Incentivos, WACC.

RESUMEN

Este artículo presenta una metodología para evaluar los costos nivelados de la electricidad (Levelized Cost of Electricity-LCOE), en plantas fotovoltaicas (Photovoltaic - PV) a gran escala. Para ello se propone una desagregación detallada de los LCOE a partir de una taxonomía rigurosa que evalúa los Costos de Inversión (Investment Cost - IC) y los Gastos de Operación (Operation and Maintenance – O&M). Partiendo de la estructura de la Administración de Información Energética (Energy Information Administration – EIA) que desglosa los IC en cinco componentes, hemos añadido un nivel adicional de desagregación denominado elementos. Asimismo, una nueva estructura para desagregar los costos de O&M es presentada. La metodología es evaluada en plantas PV de 20 MW y 150 MW PV hipotéticamente ubicadas en el municipio de Uribia (Guajira Colombia). También se desarrolla un análisis de sensibilidad determinístico usando factores como el Costo Promedio Ponderado de Capital (WACC – Weighted Average Capital Cost), la energía producida, los gastos de O&M y los IC con el ánimo de facilitar las decisiones de los inversionistas.

Palabras clave: Desagregación del LCOE, Fotovoltaica a Gran Escala, Costos de Inversión, Costos de Operación y Mantenimiento, Incentivos, WACC.

RESUMO

Este artigo apresenta uma metodologia para avaliar os custos nivelados da electricidade (Levelized Cost of Electricity-LCOE), em plantas fotovoltaicas (Photovoltaic - PV) em grande escala. Para esse propósito se propõe uma desagregação detalhada dos LCOE a partir de uma rigorosa taxonomia que avalia os Custos de Investimento (IC, por suas siglas em inglês) e as Despesas de Operação (Operations and Maintenance – O&M). Partindo da estrutura da Administração da Informação Energética (Energy Information Administration – EIA) que desglosa os IC em cinco componentes, adicionamos outro nível de desagregação chamado de “elementos”. Também é apresentada uma nova estrutura para desagregar os custos de O&M. A metodologia é avaliada em plantas PV de 20 MW e 150 MW PV hipoteticamente localizadas no município de Uribia (Guajira, Colômbia). Da mesma forma, desenvolve-se uma análise de sensibilidade determinística empregando fatores como o Custo Médio ponderado de Capital (Weighted Average Capital Cost - WACC), a energia produzida, as despesas de O&M e os IC para viabilizar as decisões dos investidores.

Palavras-chave: Desagregação do LCOE, Fotovoltaica em Grande Escala, Custos de Investimento, Custos de Operação e Manutenção, Incentivos, WACC.
1. INTRODUCTION

Diversification of power generation technologies is one of the necessary drivers needed to achieve a reliable energy supply meeting electricity demand expectations in the long run (Ross, 2014). The continuous search for cost-efficient Renewable Energy Technologies (REts) is gradually increasing the level of diversification in different energy markets and countries. In Latin America, the renewable energy potential, given the abundance of natural resources, also represents an appealing opportunity for diversifying the energy mix (Herreras et al., 2015). In fact, one of the most promising RETs in Latin America is solar PV, in spite of the fact that current technology implementation is at its early stage (GTM, 2015).

Assessing the cost competitiveness of RETs is of great importance nowadays. The financial viability of a solar PV power plant is usually measured in terms of the Levelized Cost of Electricity (LCOE). This determines the equivalent per-unit cost of energy (typically expressed in US$/MWh) that represents total investment and operational cost of a power plant over its lifetime. Originally, the LCOE method was proposed by the International Atomic Energy Agency IAEA (1984) comparing costs between generating units. In this paper, we interpret LCOE as the project’s lifetime constant price at which electricity can be sold such that IC, debt with interests, rent and taxes, O&M costs, equipment replacements and a return to investors can be covered (Reichelstein & Yorston, 2013). Other LCOE definitions are described in Poulsen and Hasager (2016).

The LCOE of solar PV has been also compared with electricity price in order to determine its competitiveness. For instance, Branker, Pathak and Pearce (2011) mention that the LCOE of large-scale PV systems is already competitive in some locations in the United States and Canada. Similarly, Pérez et al. (2015) compares LCOE and electricity prices in Mexico, Honduras, and Chile. Indeed, according to Breyer and Gerlach (2013), solar PV systems could be competitive in most of the Latin American countries by 2020.

Several online platforms that facilitate computing LCOE of solar PV systems are publicly available. Some platforms like NREL (2016) and Appropedia (2013) employ an aggregate model of investment, fixed and variable O&M costs. Reference OpenEI (2016) shows the LCOE of the US based on historical data. Other platforms like NREL (2014a) consider a more detailed cost breakdown. At the Colombian level, the platform called GeoLCOE computes a geographically based LCOE of new hypothetical generation projects located across the country (Castillo, Mejia & Giraldo, 2015). In fact, the cost breakdown methodology presented in this paper is the underlying approach on which GeoLCOE relies upon (UDEA & UPME, 2015). Computing LCOE of solar PV based on a comprehensive breakdown structure allows more effectively managing portions of data that needs to be updated on a regular basis. Indeed, reference NREL (2014b) mentions that if the cost breakdown is based on specific component specification, it will provide a standardized approach to characterize total lifetime expenditures.

In this paper, a comprehensive LCOE breakdown methodology, based on the disaggregation of both IC and O&M costs, is described. Our proposed IC breakdown is built on top of the structure of Energy Information Administration (EIA) as shown in EIA (2013), which has defined one IC level of five components. In fact, one of our contributions relies on the addition of another IC breakdown level—for each of the EIA IC components—called elements. That is, each of the five components is split into several elements whose costs are carefully described. Also, a mathematical formulation for each of them is proposed. Likewise, our second contribution consists of an O&M cost structure split into two components, which in turn are disaggregated into several elements. Also, the mathematical modeling of the particular Colombian tariffs, such as taxes and fees on electrical and mechanical equipment imports, is our final contribution. The proposed cost breakdown allows investors, policy- and decision-makers to effectively tracking financial viability of solar PV in Colombia. Finally, the LCOE of hypothetical solar PV projects of 20 MW and 150 MW, located in Uribia, Guajira, are computed using this methodology. In addition, to better understanding marginal effects of data, a sensitivity analysis with respect to WACC, capacity factor, O&M costs, and IC is also shown.

2. THEORETICAL FRAMEWORK

Adapted LCOE Model

There are several rigorous mathematical LCOE approaches that involve recent financial, fiscal, and
incentive aspects. See references (Reichelstein & Yorston, 2013; Comello & Reichelstein, 2016; Castillo, Mejía & Molina, 2017). In this work, we adapt the approach of Castillo et al. (2017) since it already incorporates fiscal incentives impact on RETs in Colombia. Also, this approach allows us to implement the cost breakdown methodology proposed in this paper. In general, the LCOE can be computed as:

$$LCOE = LCOE_I + LCOE_f$$

Where \( LCOE_I \) and \( LCOE_f \) represent LCOE components due to investment and fixed O&M cost respectively.

**Levelized Investment Cost**

The contribution of IC to total LCOE, we employ the result of Castillo et al. (2017) as follows:

$$LCOE_I = IRF \cdot \frac{IC}{8760 \cdot CF \cdot \sum_{t=1}^{T} x_t \cdot \gamma^t}$$

Where, \( CF \) is the annual capacity factor. \( T \) is the lifetime of the project, \( x_t \) is the annual degradation factor. \( \gamma \) is the discount factor and \( IRF \) is the incentive-based reduction factor which can be defined as follows:

$$IRF = \frac{1 - \alpha \sum_{i=1}^{I} i \cdot \gamma^i - \alpha \sum_{t=1}^{T} d_t \cdot \gamma^t}{1 - \alpha}$$

The \( IRF \) component of \( LCOE_I \) combines the effect of the rent tax \( \alpha \), depreciation \( d_t \), and the STD –expressed as a yearly percentage \( i \) of IC, which is typically employed by regulators for reducing taxable income (CRC, 2014). According to EIA (2013), IC can be disaggregated as follows:

$$IRF = CW + ME + EE + ICFC + OWN$$

Our cost breakdown methodology shows that \( CW, ME, EE, ICFC \) and \( OWN \) can also be disaggregated in elements. The reader can refer to the notation section at the end of the paper for additional details. This element breakdown is shown in section investment cost structure.

**Levelized O&M Cost**

Although operational costs have traditionally been split into both fixed and variable O&M, variable O&M costs are considered zero for solar PV plants (EIA, 2013). Our proposed formulation of LCOE due to fixed O&M is computed as follows:

$$LCOE_f = \frac{OC + \sum_{t=1}^{T} TFA_t \cdot \gamma^t}{8760 \cdot CF \cdot \sum_{t=1}^{T} x_t \cdot \gamma^t}$$

Where \( OC \) are split into two elements as:

$$OC = (DMS \cdot \gamma^T + OR \cdot \gamma^T) \cdot IC$$

Replacement cost (OR) and decommissioning cost (DMS) are modeled at the middle and at the end of the project’s lifetime respectively. \( TFA_t \) is the total year \( t \) fixed O&M cost in US$/kW-year. Our approach considers that \( TFA_t \) is split into eight elements as:

$$TFA_t = EQM_t + S_t + LSM_t + RM_t + CC_t + OEM_t + OI_t + OLC_t$$

The complete breakdown of fixed O&M is shown in Section denominated Operating costs structure.

### 3. METHODOLOGY

**Proposed LCOE Comprehensive Breakdown Structure**

Although several authors have exposed significant contributions to the LCOE formulation (see references: Reichelstein & Sahoo, 2015; Ueckerdt, Hirth, Luderer & Edenhofer, 2013; Hernández & Martínez, 2013) they present consolidated investment, fixed and variable O&M costs. However, EIA’s IC approach is based on a five-component breakdown, which we split in elements for better cost certainty. Thus, we have proposed a two-level structure for disaggregating IC components in elements as depicted in Figure 1. Additionally, a novel structure, shown in Figure 2, for comprehensively considering O&M costs is also proposed.

**Investment cost structure**

The component cost is adapted from EIA (2013). The subsequent level is based on a 22-element structure as depicted in Figure 1. Next, we describe components with their corresponding elements.

**Civil Works Cost Component \( CW \)**

The \( CW \) cost component approach is based on a five-element breakdown: Diggings (D) refers to excavation of ditches allowing the placement of drivers and connections to different equipment installation, it also includes the subsequent compacting. Foundations
(F) consist of concrete footings for upper structures like racking or tracking systems and solar panels. Signal Lights (SL) involve points of light for night signage, perimeter fencing and gates. Those three elements are known as Field Preparation (FP). Access Road (AR) comprises the construction of a secondary unpaved road, which includes drainage and protection works. Camp (C) refers to infrastructure for staff accommodation during construction and plant operation, water services, electricity, telephone, and air conditioning.

**Mechanical Equipment Cost Component (ME)**

The ME cost component approach is based on a three-element breakdown: Monocrystalline Silicone Modules (MSM) also known as solar panels; these are devices that convert solar radiation into electrical energy through the photoelectric effect. Horizontal-Axis Tracking System (HATS) allows the modules to follow the course of the sun. Fixed Structure (FS) also known as racking or mounting hardware; it is a fixed structure used to tilt the modules in the optimal position to capture radiation at a specific latitude. The tracking system and the fixed structure are elements mutually exclusive.

**Electrical Equipment Cost Component (EE)**

The EE cost component approach is based on a four-element breakdown: Inverters (INV) transform the Direct Current (DC) produced by modules into Alternating Current (AC). Balance of System (BOS) includes electrical wiring, meter, protections, junction boxes, cabinets, copper conductors for grounds, switchgear, combiners, fuses, breakers, and all other ancillary equipment. Low Medium Voltage Center (LMVC) is...
a transformer station that raises the voltage from low to medium voltage. *Substation and Transformer (ST)* is another transformer station that takes into account the bay line, sectioning bay, transformer bay, bus bar module, differential protection, control system, home control, and main group of transformers raising the voltage from medium to high.

**Indirect Cost, Fee and Contingency Cost Component (ICFC)**

The ICFC cost component approach is based on a two-element breakdown: *Engineering and Management (EM)* comprises the cost of preliminary feasibility and engineering studies, and construction management and start up. On the other hand, *Fee and Contingency (FC)* constitute contractor overhead costs, fees and profit; also, contractor and owner contingencies are considered.

**Owner Cost Component (OWN)**

The OWN cost component approach is based on an eight-element breakdown: *Land (L)* use refers to the area where the project is installed. *Societal Environmental Investment (SEI)* consists of costs related to the reduction of negative environmental impacts such as public health, construction safety, loss and degradation of natural resources, and sociocultural impacts on the community. *Transmission Line (TL)* refers to the electrical connection of the PV plant to the nearest transmission system sub-station. *Insurance (IN)* offers the management of general liability, assets and environmental risks. *Financial (FIN)* Costs comprises the gradual increments in the costs of elements and loan interests. *Special Funds (SF)* refers to municipal funding for social services. *Pre-operational Property Tax (PPT)* is an annual amount paid by the property’s owner during construction phase. The property tax depends on the area of the project, the property tax rate and the sector rate that each individual municipality promotes. *Pre-operational Property Surcharge (PPS)* is a percentage that municipalities apply annually to the total property tax during the construction phase. These last three elements are known as *Pre-operational Law Charges (PLC)*.

**Operating costs structure**

The components and elements of a photovoltaic O&M costs are classified into two main categories as shown in Figure 2: 1) **Total Fixed Annuity (TFA)**, which comprises both, the equipment maintenance and complementarity costs (operational insurance and environmental management); and 2) **Occasional Costs (OC)**, such as replacement and decommissioning costs, which are expenses that must be counted in a particular period. Variable O&M costs are not considered in this study since they are negligible.

![Figure 2. Proposed fixed O&M costs breakdown](image-url)
Equipment Maintenance (EQM) includes routine preventive and predictive maintenance for general equipment. Salaries (S) include remuneration of the plant operator, staffing and monthly fees. Line and Substation Maintenance (LSM) refers to the annual maintenance cost. Road Maintenance (RM) includes annually inspection and cleaning of the access road. Connection Contract (CC) refers to the annual cost associated with the access to the transmission system. Operative Environmental Management (OEM) is the set of practices that help the investors to reduce their environmental impacts. Operational Insurance (OI) refers to the payment of hedging mechanism against the risks associated with civil liability, property and environmental catastrophes. Industry and Commerce Tax (ICT) is a local tax established upon the revenue generated from industrial, commercial or service activities. Operational Property Tax (OPT) and Operational Property Surcharge (OPS) are the same expenditures that PPT and PPS respectively, but those have to be paid during the operation phase. These last three elements are known as Operational Law Charges (OLC). Variable Maintenance Costs (VMC) are expenditures that change with energy production. However, variable maintenance costs were not considered in this paper. Occasional Replacement (OR) refers to the cost of purchasing additional inverters. And decommissioning (DMS) makes reference to the retirement of the assets at the end of the project’s lifetime.

**Physical Distribution Model**

If the electromechanical equipment necessary for constructing a solar PV power plant must be imported, it is necessary to consider the cost of International and National Physical Distribution (INPD) guaranteeing the arrival of the equipment in good condition. This cost is broken down in eight categories:

- **Free On Board (FOB):** indicates the equipment cost at a specific loading port.

- **Shipping and Insurance Cost (SIC):** refers to the shipping cost from the port of loading to the port of destination. SIC is computed as a percentage of the FOB cost of the equipment.

- **Customs Brokerage (CB):** percentage of the Cost, Insurance and Freight (CIF) of the equipment, which is the sum of FOB and SIC.

- **Tariff (TA):** is a national tax charged on imported equipment. This tax rate is obtained from the corresponding commodity code. This tariff is estimated over the CIF value.

- **Value Added Tax (VAT):** percentage of the sum of CIF and TA.

- **Logistic Operator (LO):** considers the cost of provision of services such as arrival of the goods at port, inventory management, brokerage and customs inspection and nationalization, unloading of cargo, usage of facilities at port, warehousing and a letter of credit.

- **National Transport and Insurance (NTI):** includes shipping costs within the country, i.e., transportation cost from the sea port to the plant’s location.

- **Installation Cost (ICO):** includes the labor required to install the equipment.

### 4. RESULTS

The LCOE breakdown of a solar PV project of 20 MW and another of 150 MW (placed in the municipality of Uriába, Guajira, Colombia) is described in this section. In particular, LCOE evaluation for 150-MW PV power plant considers the low medium voltage converter (LMVC) into the inverters. Also, the analysis in both projects considers a transmission line whose length is 35 km (UPME, 2015). This research considers a nominal after-tax WACC of 8%. Inflation is considered to be zero. The project is allocated with a 30-year lifetime (typical for this kind of projects) (IRENA, 2016). A five-year depreciation period is used according to the fiscal incentives promoted by Law 1715 (CRC, 2014). Income tax rate \( \alpha \) is considered at 34%. And special tax deduction is 50% in year one. A capacity factor \( CF \) of 18.77% was taken from reference UDEA & UPME (2015).
IC Breakdown Data

This section is structured by a compilation of updated data allowing quantifying the IC and O&M costs comprehensively. Investment data was collected from information disclosed in several references as shown in Table 1. It displays each element with its corresponding numerical value. Also, a formula allowing to calculate the cost of each element is given (Equations 8-22).

The extra-cost caused by the INPD of imported elements is 12.79%, 9.15%, 9.30% and 3.56% for the solar modules (PDM), the tracking structure (PDT) or the fixed structure (PDFS) and the inverters (PDI), respectively.

The elements composing the IC can also be classified into dependent and independent elements according to the IC dependency. In that sense, the dependent elements are EM, FC, IN and FIN (US$/KW); however specialized literature usually reports these values as rates (IC), (EMR, FCR, INR and FINR respectively). The sum of EMR, FCR, INR and FINR is defined in this paper as SDE (Sum of Independent Elements). The rest of IC elements are considered as independent since they do not depend on IC. In fact, these can be directly obtained from the specialized literature in US$/KW. Their sum is referenced to as SDI (Sum of Independent Elements).

IC Results

Table 2 shows the results of each one of the investment cost components as described in the last section Levelized Investment Cost. The mechanical equipment is the most expensive component given the high cost of both, the solar modules and the tracking structure. Total numbers indicate that the IC is within the range (1 500 US$/kW – 3 000 US$/kW) as shown in reference IEA (2014) for the year 2015.

O&M Breakdown Data

Table 3 shows the computation (Equations 23-30) of O&M element costs based on an input parameter data. In this study only staff salaries are considered. Also, Representative Market Exchange Rate (RMER) is assumed as 1 950 COP/US$.

O&M Costs Results

Tables 4 and 5 show the results of the O&M costs and OC. They reveal that equipment cost maintenance is the most expensive component due to inverter maintenance and module washing. Also, the operational insurance is another component with a significant share of total O&M costs. It should be noted that EQM cost element is usually referred to as Fixed O&M cost in different reports (EIA, 2013; IEA & NEA, 2015).

Table 1. IC Elements and input parameters data
<table>
<thead>
<tr>
<th>Element</th>
<th>Input parameter</th>
<th>Cost</th>
<th>Formula</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>INV</td>
<td>FI</td>
<td>110</td>
<td>$INV = FI \cdot \left(1 + \frac{PDI}{100}\right)$</td>
<td>(AE, 2014a; AE, 2014b; NREL, 2015)</td>
</tr>
<tr>
<td></td>
<td>PDI</td>
<td>3.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LMVC</td>
<td></td>
<td>76.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ST</td>
<td></td>
<td>114.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EM</td>
<td>EMR</td>
<td>10</td>
<td>$EM = \frac{EMR}{100 - SDE} \cdot SIE$</td>
<td>(EIA, 2013)</td>
</tr>
<tr>
<td>FC</td>
<td>FCR</td>
<td>9.5</td>
<td>$FC = \frac{FCR}{100 - SDE} \cdot SIE$</td>
<td>(NREL, 2013)</td>
</tr>
<tr>
<td>L</td>
<td>LA</td>
<td>3.50</td>
<td>$L = \frac{LA \cdot LC}{1000} \cdot SIE$</td>
<td>(NREL, 2013)</td>
</tr>
<tr>
<td></td>
<td>LC</td>
<td>6 544</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEI</td>
<td></td>
<td>3.58</td>
<td>$SEI$</td>
<td>(CONELEC, 2012)</td>
</tr>
<tr>
<td>TL</td>
<td>LIC</td>
<td>124 492.40</td>
<td></td>
<td>$TL = \frac{LIC \cdot LL}{CAP}$</td>
</tr>
<tr>
<td></td>
<td>LL</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IN</td>
<td>INR</td>
<td>1.50</td>
<td>$IN = \frac{INR}{100 - SDE} \cdot SIE$</td>
<td>(NREL, 2010)</td>
</tr>
<tr>
<td>FIN</td>
<td>FINR</td>
<td>3.05</td>
<td>$FIN = \frac{FINR}{100 - SDE} \cdot SIE$</td>
<td>(UPME &amp; Integral, 2005)</td>
</tr>
<tr>
<td>SF</td>
<td>SFR</td>
<td>40</td>
<td>$SF = \frac{SFR}{100} \cdot L$</td>
<td>(CRC, 1981)</td>
</tr>
<tr>
<td></td>
<td>PTR</td>
<td>150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPT</td>
<td>TR</td>
<td>16</td>
<td>$PPT = \frac{PTR \cdot TR}{100} \cdot \frac{MC}{12} \cdot L$</td>
<td>(CMU, 2012)</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PSR</td>
<td>25.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PPT</td>
<td>25.90</td>
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</table>

**Table 1. IC Elements and input parameters data (Continuation)**

**Table 2. IC results**

<table>
<thead>
<tr>
<th>Investment Cost (IC)</th>
<th>(US$/kW) (2015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Civil Structural Material and Installation (CW)</td>
<td>317.60</td>
</tr>
<tr>
<td>Mechanical Equipment Supply and Installation (ME)</td>
<td>973.27</td>
</tr>
<tr>
<td>Electrical / I&amp;C Supply and Installation (EE)</td>
<td>464.58</td>
</tr>
<tr>
<td>Indirect Costs, Fee and Contingency (ICFC)</td>
<td>515.87</td>
</tr>
<tr>
<td>Owner Costs (OWN - including project finance and transmission line)</td>
<td>368.68</td>
</tr>
<tr>
<td>Project Cost (IC- including finance and transmission line)</td>
<td>2.640.00</td>
</tr>
</tbody>
</table>

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Table 3. O&M cost elements and input parameters data

<table>
<thead>
<tr>
<th>Element</th>
<th>Input parameter</th>
<th>Cost CAP=20 MW</th>
<th>Cost CAP=150 MW</th>
<th>Formula</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment Maintenance (EQM)</td>
<td>-</td>
<td>26.45</td>
<td>23.91</td>
<td>EQM</td>
<td>(EIA, 2013)</td>
</tr>
<tr>
<td>Salaries (S)</td>
<td>AS</td>
<td>2 106 272</td>
<td>2 106 272</td>
<td>S = AS·JM</td>
<td>(Unicórdoba, 2013)</td>
</tr>
<tr>
<td>Lines and Substation Management (LSM)</td>
<td>-</td>
<td>0.69</td>
<td>0.69</td>
<td>LSM</td>
<td>(UPME &amp; Integral, 2005)</td>
</tr>
<tr>
<td>Road Maintenance (RM)</td>
<td>RMR</td>
<td>3</td>
<td>3</td>
<td>RM = AR·RMR / 100 (24)</td>
<td></td>
</tr>
<tr>
<td>Connection Costs (CC)</td>
<td>-</td>
<td>12.85</td>
<td>12.85</td>
<td>CC</td>
<td>(ACCEFYN &amp; GTZ, 2002)</td>
</tr>
<tr>
<td>Operative Environmental Management (OEM)</td>
<td>-</td>
<td>3.59</td>
<td>3.59</td>
<td>OEM</td>
<td>(CONELEC, 2010)</td>
</tr>
<tr>
<td>Operational Insurance (OI)</td>
<td>OIR</td>
<td>0.50</td>
<td>0.50</td>
<td>OI = OIR·IC (25)</td>
<td></td>
</tr>
<tr>
<td>Operative Law Charges (OLC)</td>
<td>-</td>
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<td>OLC</td>
<td>(BRC, 2016)</td>
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<tr>
<td>Total Fixed Annuity (TFA)</td>
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<td></td>
<td>(2015)</td>
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Table 4. Total fixed annuity costs results

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<tr>
<th>Equipment Maintenance (EQM)</th>
<th>Salaries (S)</th>
<th>Lines and Substation Management (LSM)</th>
<th>Road Maintenance (RM)</th>
<th>Connection Costs (CC)</th>
<th>Operative Environmental Management (OEM)</th>
<th>Operational Insurance (OI)</th>
<th>Operational Law Charges (OLC)</th>
<th>Total Fixed Annuity (TFA)</th>
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<tr>
<td>26.45</td>
<td>1.30</td>
<td>0.69</td>
<td>1.83</td>
<td>12.85</td>
<td>3.59</td>
<td>13.20</td>
<td>0.92</td>
<td>60.83</td>
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Table 5. Occasional costs results

<table>
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<tr>
<th>Occasional Costs (OC)</th>
<th>(Expressed in present value terms)</th>
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<tr>
<td></td>
<td>(US$/kW) (2015)</td>
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<tr>
<td></td>
<td>PV 20 MW</td>
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<tr>
<td>Occasional Replacement (OR)</td>
<td>113.91</td>
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<tr>
<td>Decommissioning (DMS)</td>
<td>12.84</td>
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<tr>
<td>Occasional Costs (OC)</td>
<td>126.75</td>
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</table>
LCOE Results and Discussion

This section describes the LCOE results using data presented in Tables 2 and 3. Figures 3 and 4 illustrate the breakdown of nominal levelized investment and O&M costs for both projects respectively. Total nominal levelized investment of the 20 MW and 150 MW projects are 137.44 US$/MWh and 111.38 US$/MWh respectively. Also, the levelized O&M cost of the 20 MW project is 48.48 US$/MWh, and the levelized O&M cost of the 150 MW project is 43.53 US$/MWh. Additionally, the economic scale between the investment costs for both projects is observed due to the fact that the unitary costs of some elements (like AR and TL) decrease if the plant capacity increases.

As shown in Figure 3, ME and ICFC are the most expensive components of the total nominal levelized investment costs. It is important to clarify that ME are noticeably high due to the tracker system cost. Indeed, the reference IEA (2014) suggests that investment costs would reduce from 2 000 US$/MW in 2015 to 700 US$/kW in 2050, which would cause LCOE fall from 177 US$/MWh in 2015 to 56 US$/MWh in 2050.

Table 6 and 7 show results disaggregated in elements. Table 6 shows the contribution of each element to the levelized investment cost, which in turn represents more than 70% of total LCOE for both projects. In fact, MSM, EM, FC, HATS, TL, BOS, ST, F, and INV represent around 87% of IC for both projects.

Table 7 shows the contribution of each element to the levelized O&M cost, which represents less than 30% of the total LCOE for both projects. In fact, EQM, OI, OR, and CC; represent around 88% of IC for both projects.

Figure 4 indicates that the TFA is the most expensive component of the total nominal levelized O&M cost. The high cost of TFA could be explained by the equipment maintenance cost, i.e., inverter maintenance cost, occasional module washing cost.

Tables 6 and 7 show results disaggregated in elements. Table 6 shows the contribution of each element to the levelized investment cost, which in turn represents more than 70% of total LCOE for both projects. In fact, MSM, EM, FC, HATS, TL, BOS, ST, F, and INV represent around 87% of IC for both projects.
The total LCOE adds up to 185.92 US$/MWh for the 20 MW power plant and 154.91 US$/MWh for the 150 MW power plant. Certainly, IEA and NEA (2015) state that uncertainty in conventional LCOE calculations ranged from 80 US$/MWh (in United States) to 239 US$/MWh (in Japan) with a median around 135 US$/MWh in 2015. Imports cost, connection cost, operational insurance cost and lack of experience in equipment installation are some of the reasons why LCOE of both solar PV projects is still high.

**Sensitivity analysis**

In order to capture the change in LCOE caused by relative percentage change in input parameters, we have constructed a sensitivity diagram as illustrated in Figure 5. This diagram captures the impact on LCOE caused by
IC elements $CW$, $ME$, and $ICFC$; and O&M elements $EQM$, $CC$, and $OR$. According to Figure 5, both $ME$ and $ICFC$ are the elements that impact $LCOE$ the most; however, the percentage change of $ME$ with respect to 973.27 US$/kW, which represents 45.50% of the total IC, is more significant than the percentage change of ICFC with respect to 418.05 US$/kW. This shows the importance in reducing costs of both solar and tracking modules for achieving lower $LCOE$. On the other hand, although $EQM$ and $CW$ are not comparable since they are of different nature, it was observed that their impact over $LCOE$ is similar. This is due to the fact that net present value of $EQM$ is approximately the same as $CW$. A similar situation is observed between $CC$ and $OR$.

5. CONCLUSIONS

This paper proposes a methodology to evaluate $LCOE$ of PV plants considering multiple cost components as well as other important aspects of the geographical location of the project. To do so, a comprehensive breakdown of the investment and O&M costs is proposed. For instance, physical distribution of equipment, connection costs, insurances, societal and environmental aspects, and taxes and incentives according to local and current regulations are considered. The cost breakdown is based on specific component specification. By using this methodology it is possible to standardize the mechanism to characterize total lifetime expenditures of solar PV projects. The methodology was applied to evaluate two solar PV projects (20 MW and 150 MW) located in Uribia (Guajira, Colombia). The achieved $LCOE$ results are within the 2015 international $LCOE$ ranges, indicating that the proposed methodology is consistent. A sensitivity analysis was also performed to identify the most influential $LCOE$ elements. The proposed methodology for evaluating $LCOE$ of solar PV projects can be a useful tool for supporting the decision-making process of potential investors.

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REFERENCES


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**NOMENCLATURE**

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<td>BOS</td>
<td>Balance of System, US$/kW</td>
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<tr>
<td>C</td>
<td>Camp, US$/kW</td>
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</tr>
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<td>Camp Cost, US$/m²</td>
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