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LARGE-SCALE SOLAR PV LCOE COMPREHENSIVE BREAKDOWN METHODOLOGY

METODOLOGÍA PARA LA DESAGREGACIÓN DETALLADA DEL LCOE DE PLANTAS FOTOVOLTAICAS A GRAN ESCALA

METODOLOGIA PARA A DESAGREGAÇÃO DETALHADA DO LCOE DE PLANTAS FOTOVOLTAICAS À GRANDE ESCALA

Alejandro Castillo-Ramírez[1], Diego Mejía-Giraldo[1] and Nicolás Muñoz-Galeano[1]*

[1]Grupo de Investigación en el Manejo Eficiente de la Energía GIMEL,
Universidad de Antioquia, Medellín, Antioquia, Colombia

e-mail: nicolas.munoz@udea.edu.co

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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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**To whom correspondence should be addressed*

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 eletricidade (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 desagrega 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 20MW 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, Mejía & Giraldo, 2015). In fact, the cost breakdown methodology presented in this paper is the underlying approach on which Geo*LCOE* 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. THEORICAL 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:

$$LCOE = LCOE_I + LCOE_f \tag{1}$$

Where $LCOE_I$ and $LCOE_f$ represent *LCOE* components due to investment and fixed O&Mcost respectively.

Levelized Investment Cost

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

$$LCOE_I = IRF \cdot \left[\frac{IC}{8760 \cdot CF \cdot \sum_{t=1}^{T} x_t \cdot \gamma^t} \right] \tag{2}$$

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

$$IRF = \frac{1-\alpha \sum_{t=1}^{5} i_t \cdot \gamma^t - \alpha \cdot \sum_{t=1}^{T_0} d_t \cdot \gamma^t}{1-\alpha} \tag{3}$$

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

$$IRF = CW + ME + EE + ICFC + OWN \tag{4}$$

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:

$$LCOE_f = \frac{OC + \sum_{t=1}^{T} TFA_t \cdot \gamma^t}{8760 \cdot \mathrm{CF} \cdot \sum_{t=1}^{T} x_t \cdot \gamma^t} \tag{5}$$

Where *OC* are split into two elements as:

$$OC = (DMS \cdot \gamma^{\mathrm{T}} + \mathrm{OR} \cdot \gamma^{\mathrm{T}/2}) \cdot IC \tag{6}$$

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:

$$TFA_t = EQM_t + S_t + LSM_t + RM_t + CC_t + OEM_t + OI_t + OLC_t \tag{7}$$

The complete breakdown of fixed O&M is shown in Section denomined 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*

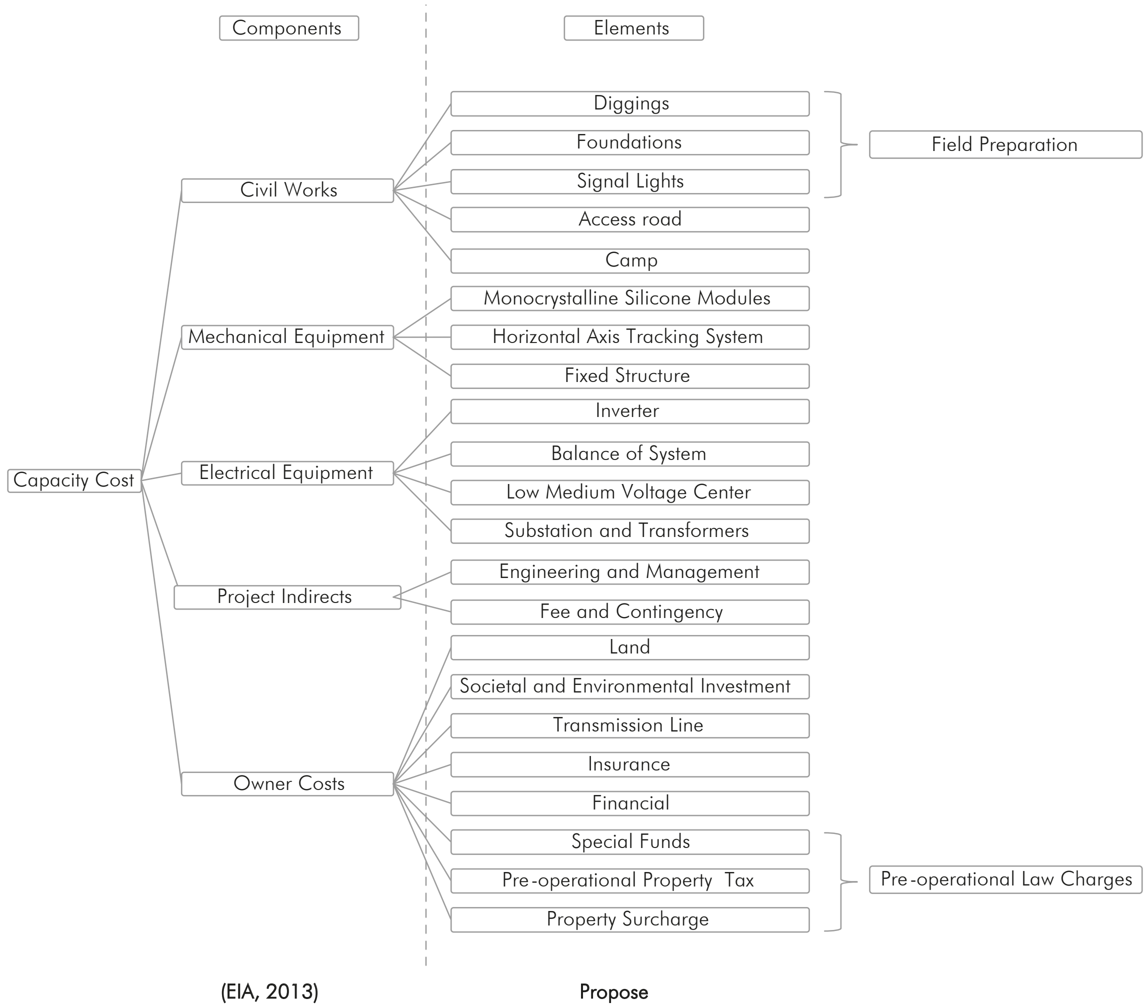

Figure 1. Proposed IC breakdown

(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 raking 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.

<u>Indirect Cost, Fee and Contingency Cost Component (ICFC)</u>

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.

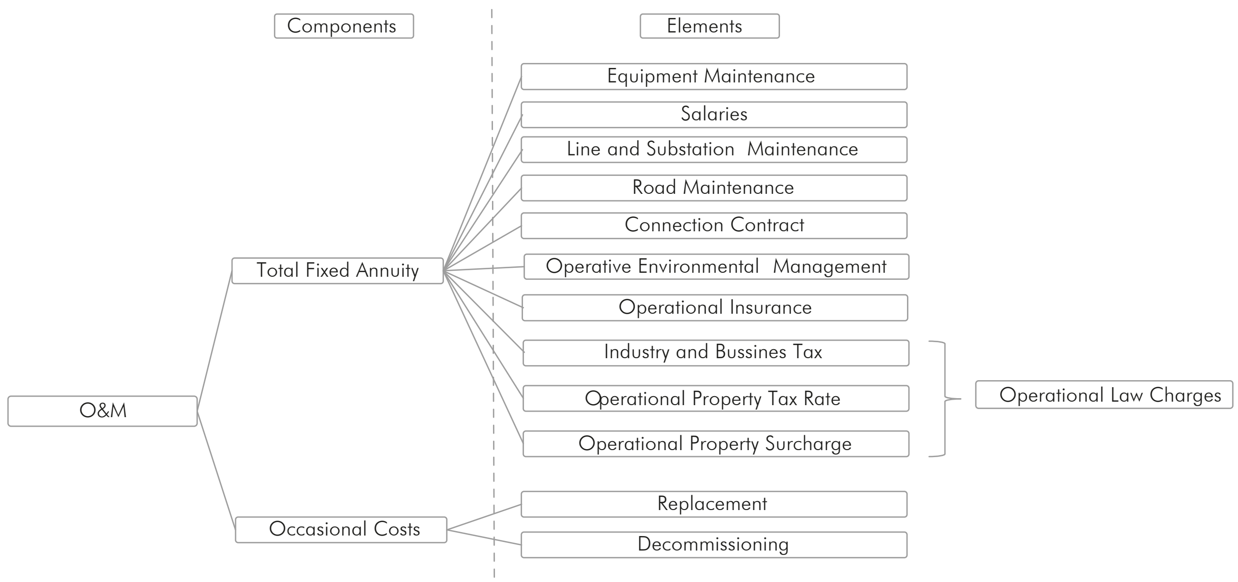

Figure 2. Proposed fixed O&M costs breakdown

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 Uribia, 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 α 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$/KW); however specialized literature usually reports these values as rates (%) of *IC* (*EMR, FCR, INR* and *FINR* respectively). The sum of *EMR, FCR, INR* and *FINR* is defined in this paper as a *SDE* (Sum of Dependent Elements). The rest of *IC* elements are considered as independent since they do not depend on *IC*. In fact, these can be directly obtained from the specialized literature in US$/KW. Their sum is referenced to as *SDI* (Sum of Independent Elements) in this paper. *SDE* and *SDI* are input parameters for Equations 14, 15, 18 and 19 in Table 1.

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

Element	Input parameter	Cost		Formula	Reference
		CAP=20 MW	CAP=150 MW		
D	-	37.80	37.80	D	(Martínez, 2010)
F	-	151.20	151.20	F	
SL	-	63.41	63.41	SL	
AR	RC	305 962.39	305 962.39	$AR = \frac{RC \cdot LR}{1000 \cdot CAP}$ (8)	(UPME & Integral, 2005)
	LR	4	4		
C	CA	200	2 000	$C = \frac{CA \cdot CAC}{1000 \cdot CAP}$ (9)	
	CAC	400	320		
MSM	FM	650	650	$MSM = FM \cdot \left(1 + \frac{PDM}{1000}\right)$ (10)	(ENF, 2016; NREL 2015; Sahoo, 2014)
	PDM	12.79	12.79		
HATS	FT	220	220	$HATS = FM \cdot \left(1 + \frac{PDT}{1000}\right)$ (11)	(NREL, 2015)
	PDT	9.15	9.15		
FS	FFS	160	160	$T = FFS \cdot \left(1 + \frac{PDFS}{1000}\right)$ (12)	
	PDFS	9.30	9.30		

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

Element	Input parameter	Cost		Formula	Reference
		CAP=20 MW	CAP=150 MW		
INV	FI	110	110	$INV = FI \cdot \left(1 + \frac{PDI}{100}\right)$ (13)	(AE, 2014a; AE, 2014b; NREL, 2015)
	PDI	3.56	3.56		
BOS	-	160	160	*BOS*	(NREL, 2012, 2015)
LMVC	-	76.13	0	*LMVC*	(CREG, 2008)
ST	-	114.53	38.79	*ST*	
EM	EMR	10	10	$EM = \frac{EMR}{100 - SDE} \cdot SIE$ (14)	(EIA, 2013)
FC	FCR	9.5	9.5	$FC = \frac{FCR}{100 - SDE} \cdot SIE$ (15)	
L	LA	3.50	3.5	$L = \frac{LA \cdot LC}{1000} \cdot SIE$ (16)	(NREL, 2013)
	LC	6 544	6 544		
SEI	-	3.58	3.58	*SEI*	(CONELEC, 2012)
TL	LIC	124 492.40	177 882.80	$TL = \frac{LIC \cdot LL}{CAP}$ (17)	(CREG, 2008)
	LL	35	35		
IN	INR	1.50	1.50	$IN = \frac{INR}{100 - SDE} \cdot SIE$ (18)	(NREL, 2010)
FIN	FINR	3.05	3.05	$FIN = \frac{FINR}{100 - SDE} \cdot SIE$ (19)	(UPME & Integral, 2005)
SF	SFR	40	40	$SF = \frac{SFR}{100} \cdot L$ (20)	(CRC, 1981)
PPT	PTR	150	150	$PPT = \frac{PTR}{100} \cdot \frac{TR}{1000} \cdot \frac{MC}{12} \cdot L$ (21)	
	TR	16	16		(CMU, 2012)
	MC	12	12		(Solarpack, 2012)
PPS	PSR	25.90	25.90	$PPS = \frac{PSR}{100} \cdot PPT$ (22)	(CRC, 1993)

Table 2. *IC* results

Investment Cost (*IC*)	(US$/kW) (2015)	
	PV 20 MW	PV 150 MW
Civil Structural Material and Installation (*CW*)	317.60	264.83
Mechanical Equipment Supply and Installation (*ME*)	973.27	973.27
Electrical / I&C Supply and Installation (*EE*)	464.58	312.71
Indirect Costs, Fee and Contingency (*ICFC*)	515.87	418.05
Owner Costs (*OWN - including project finance and transmission line*)	368.68	170.54
Project Cost (*IC- including finance and transmission line*)	2 640.00	2 139.40

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

Element	Input parameter	Cost		Formula		Reference
		CAP=20 MW	CAP=150 MW			
EQM	-	26.45	23.91	EQM		(EIA, 2013)
S	AS	2 106 272	2 106 272	$S = \frac{AS \cdot JM}{RMER}$	(23)	(Unicórdoba, 2013)
	JM	0.1	0.06			
LSM	-	0.69	0.69	LSM		(UPME & Integral, 2005)
RM	RMR	3	3	$RM = AR \cdot \frac{RMR}{100}$	(24)	
CC	-	12.85	12.85	CC		(ACCEFYN & GTZ, 2002)
OEM	-	3.59	3.59	OEM		(CONELEC, 2012)
OI	OIR	0.50	0.50	$OI = OIR \cdot IC$	(25)	(NREL, 2010)
ICT	ICTR	5	5	$ICT = \frac{ICTR \cdot IC}{RMER}$	(26)	(CRC, 1981)
	CI	97.97	97.97			(BRC, 2016)
OPT	PTR	150	150	$OPT = \frac{PTR}{100} \cdot \frac{TR}{1000}$	(27)	(CRC, 1981)
	TR	16	16			(CMU, 2012)
OPS	PSR	25.90	25.90	$OPS = \frac{PSR}{100} \cdot OPT$	(28)	(CRC, 1993)
OR	INV	17.90	11.59	$OR = INV$	(29)	-
DMS	DMSR	5	5	$DMS = \frac{DMSR}{100} \cdot IC$	(30)	(IEA, 2010)

Table 4. Total fixed annuity costs results

Total Fixed Annuity (TFA_t)	(US$/kW-Yr) (2015)	
	PV 20 MW	PV 150 MW
Equipment Maintenance (*EQM*)	26.45	23.91
Salaries (*S*)	1.30	0.78
Lines and Substation Management (*LSM*)	0.69	0.69
Road Maintenance (*RM*)	1.83	0.24
Connection Costs (*CC*)	12.85	12.85
Operative Environmental Management (*OEM*)	3.59	3.59
Operational Insurance (*OI*)	13.20	10.70
Operational Law Charges (*OLC*)	0.92	0.92
Total Fixed Annuity (*TFA*)	60.83	53.68

Table 5. Occasional costs results

Occasional Costs (OC)(Expressed in present value terms)	(US$/kW) (2015)	
	PV 20 MW	PV 150 MW
Occasional Replacement (*OR*)	113.91	113.91
Decommissioning (*DMS*)	12.84	10.40
Occasional Costs (*OC*)	126.75	124.31

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.

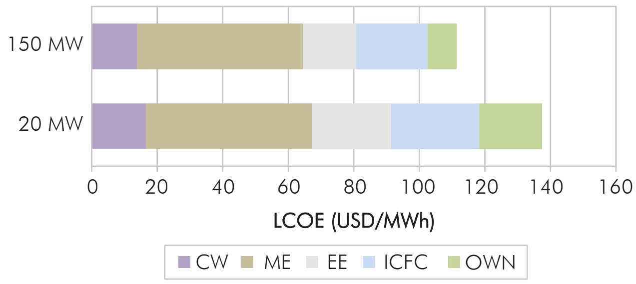

Figure 3. Levelized *IC* per component

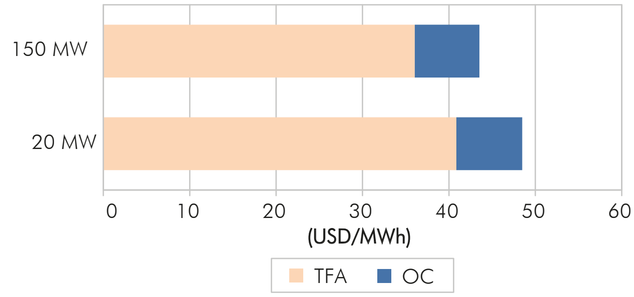

Figure 4. Levelized O&M cost per component

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.

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.

Table 6. Levelized *IC* cost contribution by element

IC	PV 20 MW		PV 150 MW	
	(US$/kW) (2015)	Percentage	(US$/kW) (2015)	Percentage
D	1.9679	1.4318%	1.9679	1.7669%
F	7.8717	5.7273%	7.8717	7.0674%
SL	3.3010	2.4017%	3.3010	2.9637%
AR	3.1858	2.3179%	0.4248	0.3814%
C	0.2082	0.1515%	0.2221	0.1994%
MSM	38.1682	27.7703%	38.1682	34.2682%
HATS	12.5020	9.0962%	12.5020	11.2246%
FS	0.0000	0.0000%	0.0000	0.0000%
INV	5.9306	4.3150%	5.9306	5.3247%
BOS	8.3299	6.0606%	8.3299	7.4787%

Table 6. Levelized *IC* cost contribution by element (Continuation)

IC	PV 20 MW		PV 150 MW	
	(US$/kW) (2015)	Percentage	(US$/kW) (2015)	Percentage
LMVC	3.9633	2.8836%	0.0000	0.0000%
ST	5.9629	4.3384%	2.0196	1.8132%
EM	13.7728	10.0207%	11.1612	10.0207%
FC	13.0841	9.5197%	10.6031	9.5197%
L	1.1924	0.8676%	1.1924	1.0706%
SEI	0.1739	0.1265%	0.1739	0.1561%
TL	11.3423	8.2523%	2.1609	1.9401%
IN	1.7810	1.2958%	1.4433	1.2958%
FIN	4.2007	3.0563%	3.4042	3.0563%
SF	0.4770	0.3470%	0.4770	0.4282%
PPT	0.0215	0.0156%	0.0215	0.0193%
PPS	0.0056	0.0040%	0.0056	0.0050%
Total	**137.4427**	**100.0000%**	**111.3809**	**100.0000%**

Table 7. Levelized O&M cost contribution by element

IC	PV 20 MW		PV 150 MW	
	(US$/kW) (2015)	Percentage	(US$/kW) (2015)	Percentage
EQM	17.7678	36.6529%	16.0608	36.9005%
S	0.8706	1.7959%	0.5223	1.2001%
LSM	0.4605	0.9499%	0.4605	1.0580%
RM	1.2330	2.5435%	0.1644	0.3777%
CC	8.6338	17.8105%	8.6338	19.8366%
OEM	2.4096	4.9706%	2.4096	5.5361%
OI	8.8658	18.2891%	7.1847	16.5072%
ICT	0.1524	0.3145%	0.1524	0.3503%
OPT	0.3692	0.7616%	0.3692	0.8483%
OPS	0.0956	0.1973%	0.0956	0.2197%
OR	6.8460	14.1225%	6.8460	15.7290%
DMS	0.7716	1.5917%	0.6253	1.4366%
Total	**48.4759**	**100.0000%**	**43.5246**	**100.0000%**

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

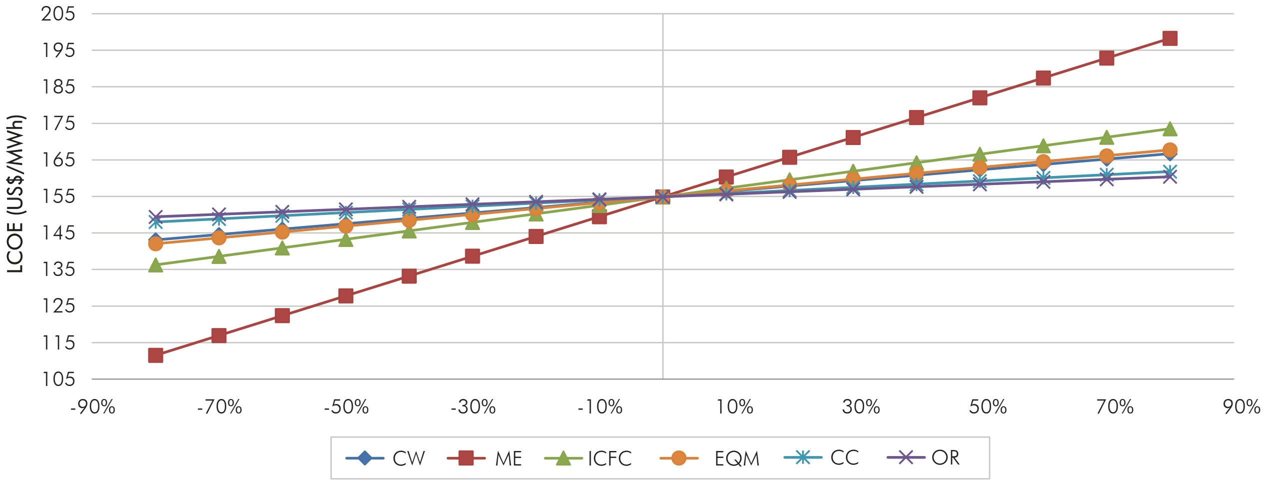

Figure 5. LCOE Sensitivity Analysis (150 MW Solar PV)

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 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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AUTHORS

Alejandro Castillo Ramírez
Affiliation: *Grupo de Investigación en el Manejo Eficiente de la Energía GIMEL, Universidad de Antioquia, Medellín, Antioquia, Colombia.*
e-mail: alejandro.castillor@udea.edu.co

Diego Mejía Giraldo
Affiliation: *Grupo de Investigación en el Manejo Eficiente de la Energía GIMEL, Universidad de Antioquia, Medellín, Antioquia, Colombia.*
e-mail: diego.mejia@udea.edu.co

Nicolás Muñoz Galeano
Affiliation: *Grupo de Investigación en el Manejo Eficiente de la Energía GIMEL, Universidad de Antioquia, Medellín, Antioquia, Colombia.*
e-mail: nicolas.munoz@udea.edu.co

NOMENCLATURE

AR	Access Road, US$/kW
AS	Average Salaries, COP/Month
BOS	Balance of System, US$/kW
C	Camp, US$/kW
CA	Camp Area, m^2
CAC	Camp Cost, US$/$m^2$
CAP	Capacity, MW
CB	Customs Brokerage, %
CC	Connection Contract, US$/kW-Yr
CF	Capacity factor, %
CI	Cumulative Inflation
CIF	Cost, Insurance and Freight, US$/kW
CPI	Consumer Price Index, %
CW	Civil Works, US$/kW
D	Diggings, US$/kW
DMS	Decommissioning, US$/kW
DMSR	Decommissioning Rate, %
ECM	Equipment and Complementary Maintenance, US$/kW-Yr
EE	Electrical Equipment, US$/kW
EM	Engineering and Management, US$/kW
EMR	Engineering and Management Rate, %
EQM	Equipment Maintenance, US$/kW-Yr
f,	Total Fixed Costs, US$/kW-Yr
F	Foundations, US$/kW
FC	Fee and Contingency, US$/kW
FCR	Fee and Contingency Rate, %
FFS	FOB Fixed Structure, US$/Kw
FIN	Financial, US$/kW
FINR	Financial Rate, %
FM	FOB Modules, US$/Kw
FOB	Free on Board, US$/kW
FP	Field Preparation, US$/kW
FS	Fixed Structure, US$/kW
FT	FOB Trackers, US$/Kw

HATS	Horizontal-axis Tracking System, US$/kW
i_t	Special Tax Deduction, Yearly %
IC	Investment Costs, US$/MW
ICFC	Indirect Costs, Fee and Contingency, US$/kW
ICO	Installation Cost, %
ICT	Industry and Commerce Tax, COP/kW
ICTR	Industry and Commerce Tax Rate, COP
IN	Insurance, US$/kW
INR	Insurance Rate, %
INV	Inverter, US$/kW
JM	Jobs per MW, Jobs/MW
L	Land, US$/kW
LA	Land Area, Ha/MW
LC	Land Cost, US$/Ha
LCOE	Levelized Cost of Electricity, US$/MWh
LL	Line Length, km
LMVC	Low to Medium Voltage Center, US$/kW
LO	Logistic Operator, %
LR	Length of the Road, km
LSM	Line and Substation Maintenance, US$/kW-Yr
MC	Months Construction, Months
ME	Mechanical Equipment, US$/kW
MSM	Monocrystalline Silicone Modules, US$/kW
NTI	National Transport and Insurance, %
OC	Occasional Costs, US$/KW
OEM	Operative Environmental Management, US$/kW-Yr
OI	Operational Insurance, US$/kW-Yr
OIR	Operational Insurance Rate, %
OLC	Operational Law Charges, US$/kW-Yr
OR	Occasional Replacement, US$/kW
OWN	Owner Cost, US$/kW
O&M	Operation and Maintenance, US$/kW-Yr and US$/kW
PDFS	Physical Distribution Fixed Structure, %
PDM	Physical Distribution of the Modules, %
PDT	Physical Distribution of the Trackers, %
PLC	Pre-operational Law Charges, US$/kW

PPS	Pre-operational Property Surcharge, US$/kW
PPT	Pre-operational Property Tax, US$/kW
PS	Property Surcharge, %
PTR	Property Tax Rate, %
RC	Road Cost, US$/km
RM	Road Maintenance, US$/kW-Yr
RMER	Representative Market Exchange Rate, COP/US$
RMR	Road Maintenance Rate, %
S	Salaries, US$/kW-Yr
SDE	Sum of Dependent Elements, %
SEI	Societal Environmental Investment, US$/kW
SF	Special Funds, US$/kW
SFR	Special Funds Rate, %
SIC	Shipping and Insurance Cost, %
SIE	Sum of Independent Elements, US$/kW
SL	Signal Lights, US$/kW
ST	Substation and Transformer, US$/kW
t	Year of assessment, Year
T	Lifetime of the Project, Years
TA	Tariff, %
TFA	Total Fixed Annuity, US$/kW-Yr
TI	Total Investment, US$
TL	Transmission Line, US$/kW
TR	Thousand Rate, ‰
TVA	Total Variable Annuity, US$/MWh
VMC	Variable Maintenance Cost
VAT	Value Added Tax, %
WACC	Discount Rate (Nominal), %
α	Income Tax Rate, %
d_t	Depreciation, %
γ	Discount Factor, dimensionless
$LCOE_I$	Levelized Cost of Electricity due to Investment, US$/MWh
$LCOE_f$	Levelized Cost of Electricity due to Fixed Costs, US$/MWh
x_t	Degradation factor of year t,
T_0	Depreciation Period, Years