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Land-use in the Electric Colombian System: Hidden Impacts and Risks of Large-scale Renewable Projects

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ABSTRACT

In the sustainable development era, massive land-use for electricity production represents a crucial challenge for environmental and social systems. Available information about the use of land in this sector is limited, for that reason in this paper we include the power density methodology to evaluate land-use in Colombia to produce electricity. The power density metric depicts the relation between energy produced and area used in this process, considering extraction-conversion-storage. The analysis between power electricity generation and land-use is made for the Colombian electric system, finding that there is no direct relationship between the area occupied by a generation plant and the electricity produced, since the evidence does not show that at larger areas greater power is obtained. Hydropower plants have large spectrum values of power densities, depending on the dam construction purpose (river-flow control). Fossil-fired power plants require less land for its production even including the fuel extraction area. Photovoltaic and wind-power plants in this comparison have the lowest power density values, accordingly, they require far larger areas and represent a risk for sustainability in this perspective.

Keywords: Power Density, Electricity, Land-use, Sustainability.
JEL Classifications:Q24, Q25, Q40, Q48

1. INTRODUCTION

Interest in the use of large-scale renewable energy has been growing in recent years. However, extensive use of land for electricity production risks replicating some of the negative effects of dirty energy´s past. In addition to well-known ecological damages, environmental justice literature has also called the attention to the social conflicts prompted by the fossil-fuel based energy system, arguing that it has placed disproportionate burdens on poor communities and communities of color (Baker, 2019), some of those burdens are related to land-use changes induced in their territories.

In this paper we focus on the energy impacts and risks related to the use of natural resources as soil, which can alter the functioning of ecosystems, posing serious risks for the habitability of the planet (Stockholm Resilience Centre, 2015), and can trigger social conflicts from land-use changes implemented when the projects require extensive use of land (Fearnside, 2016) (von Sperling, 2012) (Wang et al., 2012).

Conflicts related to demand for new land for electricity generation arise, as a sector in constant expansion. In fact, there is a growing demand for change in land-uses (Zou et al., 2019) (Vitousek et al., 1997) (Ellis and Ramankutty, 2008) creating new negative impacts (Ekins et al., 2003). Although it is known that extensive land-use triggers ecological imbalances (Turner et al., 2007) (Luo et al., 2020) it is not clear how the deteriorated ecosystems will respond to future alterations.

Traditionally, land-demanded for electricity generation responds to fossil-fired power plants exploiting resources placed in underground deposits and large-scale hydropower plants with a dam to store water. However, with the expansion of another electricity source as solar photovoltaic and wind-power, land conflicts around them have emerged (Avila, 2018) (EJ Atlas, 2016). (Maturano, 2017) (Salazar, 2008) (Democracy, 2017) (Neslen, 2017) (Darby, 2017). As a result of those conflicts, there is a growing recognition of the interdependence between energy and land at large-scale (Gong et al., 2012).

In Colombia, there is a growing interest in those large-scale renewable energies which has hidden impacts and risks related to the extensive land-use. Nowadays the national-interconnected grid has an installed capacity of 17.3 GW (UPME, 2019) where hydropower is the highest contributor with 26 plants and the 66.8% of the total installed capacity, it is followed by fossil-fired power plants with 32.5%. In 2020, other renewables as photovoltaic and wind-power have 0.6 and 0.1% each of installed capacity. However, in 2019, in Colombia was held the first auction of non-conventional renewable energy in Colombia, accounting for 1298.8 MW, five wind projects at large-scale, and three solar photovoltaic projects at large-scale (Moreno and Larrahondo, 2021). The expansion of electric power system in Colombia based on high participation of hydropower plants has represented a critical vulnerability, new findings reveal that climate change provokes modifications in the patterns of duration and frequency of El Niño (Restrepo-Trujillo, 2020). Given the intrinsic vulnerability in the Colombian electric system to produce electric energy properly at any time, some regulatory mechanisms has been designed to improve reliability, however, according to the energy commission in Colombia (CREG) persists risks of coverage in the medium term (Moreno et al., 2021).

This paper focuses on the relationship between large-scale electricity generation infrastructure and its implications for sustainability. The effect of the Colombian electricity generation systems on land demand is analyzed through the modified power density metric proposed by Vaclav (2010), this metric quantifies the use of land according to the power capacity generation of each power plant. The methodology employed here included two novelties concerning this metric: a detailed geophysical characterization of the Colombian conditions for oil and gas reservoirs, and a broader concept of land use for hydropower, including the dam hillside.

The first section discusses the methodology for power density estimation and all the considerations made for the Colombian case. Then, the power density for all-electricity sources in Colombia is calculated and analyzed, mainly hydropower and fossil-fired power plants. Finally, it is presented a discussion where the main point is the extensive land-use and transformation that is required for electricity generation from renewables, and the negative non-quantified impacts created thereof, which are not yet fully recognized in the discussion around renewables.

2. CALCULATING POWER DENSITY FOR ELECTRICITY INFRASTRUCTURES

This section proposes a methodology to calculate the power density value for fossil-fired power plants, hydropower, photovoltaic and wind-power plants, according with some specifications by sources. We are using the power density as indicator of land-use for electricity generation.

Indeed, power density concept expresses the energy flow per time per horizontal surface unit to relate the capacity of electricity production with the land used to produce it. The extension of land used varies according to the infrastructure required. Power density is calculated according to Equation 1, the power in watts [W] is the rate of change of energy concerning time. The unit of power in watts corresponds to joule per second. The area involves all land-use required by the infrastructure to produce it (i.e., machinery equipment, routes, camps).

$$\rho = \frac{P}{a}\left[\frac{W}{m^3}\right] \quad (1)$$

For electricity production each source has particularities in the process, roughly Figure 1 presents the big stages for it. Fossil-fired plants require land for extracting the input, stored and finally the electric conversion; while renewables do not require extracting, but hydropower when use dams require land for the water storing.

2.1. Quantifying Power Density to Fossil-fired Power Plants

To quantify the power density of fossil-fired power plants it is proposed to calculate the land used in the extraction of resources and the land used by the infrastructure to convert it into electricity. Therefore, to obtain an approximation of the land used in the extraction it is used some physical properties as specific density, specific energy, extraction recovery rate, and mine thickness. For this paper, we use average values for fuels without compromising the relevance of the results given that the plants in Colombia use similar fuels according to each case.

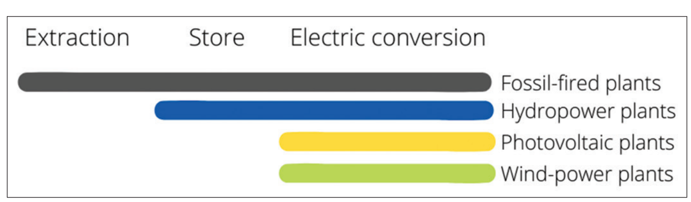
Power density for fossil-fired power plants (ρ_{PC}) is calculated as Eq. 2 present, it depends on the energy amount generated in one year (EY) and the areas to extract and convert it. The areas correspond to the space occupied by the fossil-fired power plants (FPP) and the land used for the extraction process (EP)[1].

$$\rho_{PC} = \frac{EY}{FPP + EP} \quad (2)$$

To determine the power generated in one year (EY) is used Eq.2, where alpha is a time-constant; usually, in the site of fossil-

1 The acronym responded to the first's letters of the variable's name, to short the math expression. For example, the Energy amount generated in one Year, has as acronym *EY*.

Figure 1: Stages of the generation process considered in land use for each source



Source: Own elaboration

fired power plants there are several production units, the total power corresponds to the sum of all generation units, these situations are analyzed as a set given that the power capacity is equal to the sum up of all the units. For it is used alpha as a time correlation.

$$EY = Power\ capacity\ \alpha \quad (3)$$

As well, to know the space occupied by the extraction is required first the available maximum fuel extracted (*MFE*) from the source using Eq.3, that is the maximum extraction rate, resulting from the reservoir depth (*y*), the extraction recovery rate (*RR*), the fuel-specific density (ρ_r) and fuel energy density (ρ_e). This last equation is the one in which more assumptions must be made, it is assumed average densities, as well as a 95% recovery rate, and a homogeneous reservoir depth. It is important to indicate that depth is not precisely the reservoir height, but the fuel height column inside the reservoir. Such clarification is essential considering that in Colombia there are wells 7 km deep, but this does not imply that the oil column is 7 km high.

$$MFE = y \cdot RR \cdot \rho_r \cdot \rho_e \quad (4)$$

For the analysis presented in this research, values shown in Table 1 were used. These values correspond to data from official entities of the Energy and Mine Minister of Colombian government.

Knowing MFE, the space required to extract the fossil-fuel (*EP*) is determined using Eq. 4 and it comes from the ratio between the fuel energy required (*FR*) and the maximum fuel extracted (*MFE*). Fuel energy required is the energy amount generated by a year affected by combustion efficiency.

$$EP = \frac{FR}{MFE} \quad (4)$$

2.2. Quantifying Power Density for Hydropower

Hydropower projects in developing countries such as Colombia are different in geographical, economic, political, and technical aspects (IFC, 2017). To quantify the power density of hydropower infrastructures two considerations should be made related to the reservoir level, and the flooded area (Vaclav, 2015).

Table 1: Variables used in Colombian hydrocarbons.

Unit	Bituminous coal	Gas	Oil (ACPM)
$\rho_r \left[\frac{t}{m^3}\right]$	1.4	0.000743	0.832
$\rho_e \left[\frac{GJ}{t}\right]$	25	5 360	4 310
y [m]	6	15	15
RR	95%	95%	95%

Source: own elaboration. In Colombia is called ACPM, which is the acronym for Combustible Motor Oil. Data obtained from, RR (Insitituto Nacional de Investigaciones Geológicas Mineras - INGEOMINAS, 1999) (UPME, CONSORCIO SILVA CARREÑO and ASOCIADOS S.A., & HUGO MILLÀN, 2004) (Santamaría et al., 2012); ρe (Incombustión, 2016); ρr of ACPM (Ministerio de Minas y energía and Ministerio de ambiente y desarrollo territorial, 2007), and ρr for Gas (CREG, 2008)

Reservoir level changes depending on the seasonal fluctuations of climate variability. This paper purports to use the flooded area instead of the water mirror as Vaclav (2015) proposed. The water mirror is a water-base specular reflection, it is an approximation for the flooded area; while the flooded area represents the land used including the mountain slope. The area's data has been taken from official Environmental reports of the Colombian government (Ministerio de Minas y energía, 2009), (Ministerio de minas y energía, 2016), (Ministerio de Ambiente y Desarrollo Sostenible, 2016).

When a hydropower chain system is considered, if they are not going to be presented as individual projects but one, the generation capacity as well as the flooded area should be added as one single unit for the power density estimation.

2.3. Quantifying Power Density for Wind and Photovoltaic Power Plants

Finally, for wind-power projects, the projected area is composed by each turbine if the park has secondary uses as agriculture or cattle, if not, it is considered the whole area occupied by the park, including roads. Same considerations apply for photovoltaic plants.

3. RESULTS OF POWER DENSITY FOR THE ELECTRIC COLOMBIAN SYSTEM

Table 2 presented the data of installed capacity and area by each source analyzed in the power density index for Colombia.

The power density (PD) is calculated. Results from the 26 hydropower plants analyzed are presented in Table 3.

For photovoltaic and wind-power, results are presented in Table 4. *Enel el Paso*, *Celsia solar Yumbo*, and *Celsia solar Bolivar* are the photovoltaic plants. There is only one wind-power plant named *Jepirachi* in Colombia by 2020.

By each fuel, power density data is presented in Table 5.

We can observe in Figure 2 the graphical representation of power density for the Colombian electric system. In particular, the highest dispersion range is found for hydropower, while the lowest dispersion is for coal-fired power plants.

Table 2: Installed capacity and quantity of the grid

Source	Installed capacity (MW)	Area (km^2)	Quantity
Hydropower	11 041	922,8	26
Photovoltaic	104,1	2,51	3
Wind-power	18,4	0,20	1
Gas-fired power plants	2,401	3,26	9
Coal-fired power plants	1,619	2,8	6
Oil-fired power plants	1,344	0,71	7
Total	16,527,5	932,3	55

Source: own elaboration, data from the real-time systems and wholesale power market management from Colombian system (XM).

Table 3: Hydropower power densities for the electric Colombian system

Hydropower	Installed capacity (MW)	Area (m²)	ρ_P (W/m²)
Playas	207	292,000,000	0,7
Prado	51	42,000,000	1,2
Esmeralda	30	12,600,000	2,4
Cucuana	56	15,596,671	3,6
Urra	338	74,000,000	4,6
El Quimbo	400	82,500,000	4,8
Calima	132	19,340,000	6,8
Escuela de minas	55	7,730,000	7,1
Betania	540	74,000,000	7,3
Guatron hydropower chain	512	64,000,000	8,0
Guatape	560	62,400,000	9,0
Sogamoso	819	69,340,000	11,8
Salvajina	315	20,310,000	15,5
Jaguas	170	10,600,000	16,0
San francisco/Santo Domingo	135	6,953,800	19,4
La tasajera	306	11,000,000	27,8
Miel I	396	13,760,000	28,8
Porce II	405	8,900,000	36,4
Chivor	1,000	12,800,000	78,1
Guavio	1,250	13,440,000	93,0
Porce III	700	4,610,000	151,8
Amoya la esperanza	80	252,688	316,6
San Carlos	1,240	3,400,000	364,7
Carlos Lleras	78	213,131	366,0
Alto y bajo Anchicayá	429	1,040,000	412,5
San Miguel	52	73,440	708,1

Source: Own elaboration

Table 4: Non-conventional renewables power densities for the Colombian electric system

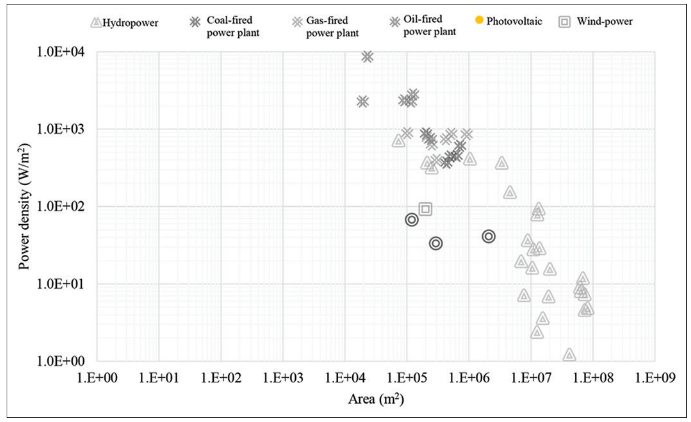
Power plant	Installed capacity (MW)	Area (m²)	ρ_P (W/m²)
Enel El Paso	86,2	2,100,000	41,04
Celsia solar Yumbo	9,8	294,859	33,2
Celsia solar Bolivar	8,03	120,000	67,16
Jepirachi 1-15	18,42	199,491	92,3

Source: Own elaboration

4. ANALYSIS AND DISCUSSION

The power density for hydropower plants has a range of values, the highest power density is *San Miguel* with 708,1 W/m², while the lowest is *Playas* with just 0,7 W/m². Considering the construction year, it is worth noting that the hydropower projects constructed during the last two decades exhibit PD between 4 W/m² and 12 W/m², except for *Porce II* with 151,8 W/m². There is no evidence that technological advances have improved the power density of hydropower plants in the Colombian case, two projects constructed and opened in the same period can have drastically different power density values. *Playas* and *Calima* were inaugurated in 1.966 but *Playas* has a PD of 0,7 W/m² while *Calima* 6,8 W/m²; in contrast, the most recent projects are *El Quimbo* and *Hidrosogamoso* both started its operations between 2015 and 2016, the first one has a PD of 4,8 W/m², and the second of 11,8 W/m².

Figure 2: Power density of the Colombian electric system



Source: Own elaboration

In Colombia by 2020 there are three photovoltaic projects, the power density range is between 33,2 and 67,2 W/m². *Celsia solar Yumbo,* located in Valle del Cauca has a 4,5-5 KWh/m² average radiation, *while El Paso*, located in Cesar, has average radiation of 5-5,5 KWh/m² (IDEAM, 2019). Nevertheless, *Celsia solar Bolivar*, has the highest PD with 67,2 W/m², taking the same average radiation as *Celsia solar Yumbo*.

There are 5364 MW of generation capacity from fossil-fired power plants, distributed as follows: carbon with 30,2%, gas 44,8% and other fuels 25,1%. In other fuels are three plants using ACPM with a total capacity of 255,3 MW; two of them work with oil fuel and have 135 MW of installed capacity; and the system has one oil-fired power plant that use a Gas-Jet A1. By each fuel, the extraction area is significantly larger, if is not included in the total area, the power density value is 30% lower for coal plants, 64% in gas plants and 0.4% in fuel oil plants.

A summary is presented in Table 6. The highest power density comes from oil-fired plants and the lowest from hydropower. Discriminating by plant, *Termovalle 1* has the highest power density, with 8.619 W/m², in contrast, the lowest power density comes from *Playas* with 0,7 W/m²

Fossil-fired plants exhibit similar PD values, and they are more efficient from the perspective of land-use, in comparison to hydropower, photovoltaic and wind-power plants in Colombia, although, oil-fired power plants are the source that has the best relation between land-use and electricity generation. They could generate more electricity in less space for more than 100 times.

According to the findings showed here, it could be argued that fossil-fired plants require less land for electricity production; they are more efficient from a conventional land-use perspective compared to hydropower, photovoltaic, and wind in Colombia. However, this could be apparent given that during fossil-power electricity production it is released significant pollution that cover several tracts of land, which would increase the amount of land impacted that was previously calculated. Indirect land use is affected by pollution in all power plants, not just by fossil-fired ones in the emission. For instance, for photovoltaic power there

Table 5: Fossil-fired power plant

Power plant	Fuel	Installed capacity (MW)	Transformation area (m^2)	Extraction area (m^2)	ρ_P (W/m^2)
Zipaemg 2, 3, 4, 5	Coal	225	419,833	88,978	442,2
Paipa 1,2, 3		178	133,719	70,391	872,1
Paipa 4		160	373,304	63,273	366,5
GUAJIRA 1 y 2		286	522,429	113,101	450,0
Gecelca 3, 32		437	549,887	172,815	604,7
Tasajero 1, 2		333	301,506	15,492	1,050,5
TEBSA 3 y 4	Gas	120	192,022	111,215	395,7
Termocandelaria 1, 2		314	134,472	291,014	738,0
Flores 1		160	105,034	148,287	631,6
Proelectrica 1, 2		90	18,355	83,411	884,4
Merilectrica 1		167	62,602	154,775	768,2
Tebsab		791	192,022	733,095	855,0
Flores 4b		450	105,034	417,058	861,9
Termocentro cc		279	136,654	258,576	705,9
Termoyopal		30	77,137	27,803	285,9
Termoemcali 1	Acpm	213	90,456	328	2,346,2
Termosierrab		353	125,873	545	2,792,3
Termovalle 1		200	22,895	308	8,619,2
Termodorada 1	Jet-A1	44	19,315	67	2,270,0
Termocentro cc	Mezcla Gas - Jet-A1	264	116,259	407	2,262,8
Cartagena 1, 2, 3	Oil fuel	182	244,764	281	742,7
Termonorte		88	94,952	38	926,4

Source: own elaboration. Transformation area represents the space occupied for the fossil-fired power plants in storage and conversion without including the extraction area

Table 6: Power density data summary for the Colombian electric system

Source	Highest	Lowest
Hydropower	412,5	0,7
Photovoltaic	67,2	33,2
Wind-power	92,3	92,3
Coal-fired power plant	1.050,5	366,5
Gas-fired power plant	884,4	285,9
Oil-fired power plant	8.619,2	742,7
Total	8.619,2	0,7

Source: Own elaboration

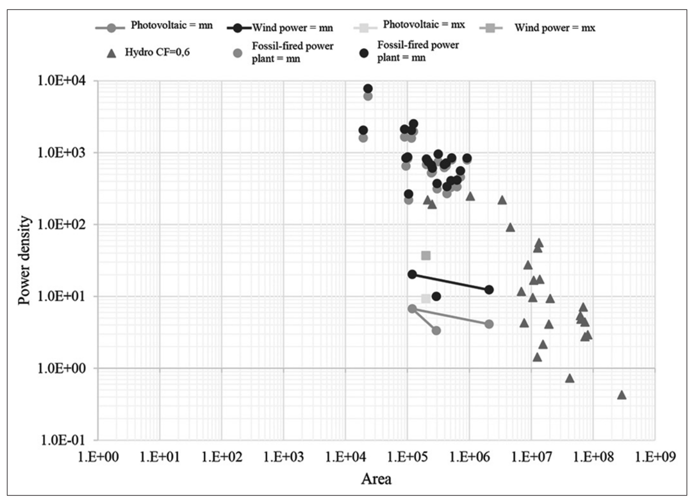
is land required by the mineral's extraction that will be used in the panel manufacture.

To analyze the variations in power density with different capacity factors (CF), we considered a range of values of CF for each electricity source, for wind-power plants between 10% and 40%, for photovoltaic between 10% and 30%, for hydropower 60% and fossil-fired power plants between 70% and 90% (dos Reis and Silveria, 2001). Figure 3 presents the power density considering the capacity factor for the same sources presented before.

However, CF is a value affected not only by technical issues but market and regulatory issues as well. In Colombia, the capacity factor in the same source depends on the electric dispatch rules of the market dynamic.

To reduce the green-house gas emissions from fossils, the Colombian rule is that most of the energy should come from renewables (hydropower, photovoltaic, wind-power) and if that energy produced is not enough, the fossil-fired power plants start its electricity production. In consequence, fossil-fired power plants have reduced CF because of the energy policy in the country but not for technical issues as renewables have. Photovoltaic and wind-power are the sources with higher decrease in power density metric because its capacity factor is the lowest.

Figure 3: Power density considering the capacity factor



Source: Own elaboration

4.1. The Risk of Increasing Demand for Land for New Renewable Energy

There is a close relationship between climate change and land-use (IPCC, 2019), since the land faces the pressure and challenge of continuous expansion of human activities replacing large portions of virgin land for new setups (Thanvisitthpon, 2019) such as energy infrastructure. Energy is a growing industrial sector increasingly demanding land, which makes it an important driver of land-use change.

Even though, land-use has been discussed just in terms of area, from a sustainability perspective this analysis should also integrate the human impacts on ecosystems produced on that land, as well as the social impacts. The Legacy-adjusted Human Footprint Index (LHFI) evaluate the spatiotemporal variation of anthropic impact, it allows an in-depth understanding of the large-scale land-use consequences of human uses such as the generation of electricity. In Colombia LHFI between 1.970 and 2.015 has increased by 50% (Correa et al*.,* 2020), during the same period electricity infrastructure was developed.

Geographically, the highest value of LHFI was found in the Caribbean and Andean regions, places that have been strategic for the electricity supply in the country, 28 out of the 29 hydropower are in the Andean valley, mainly in the western cordillera foothills, the rest is in the Caribbean region. In fact, 98, 98% of land-used by electricity generation comes from hydropower (Table 1) and they are located in the region with the highest LHFI, and have been constructed during that critical period.

Continuing increase of LHFI is alarming, consequences could be devastating for biodiversity not just in Colombia but far beyond, as the country holds 10% of global biodiversity, the Andean region also hosts many ecosystems very important for hydric regulation and water supply, while the Caribbean region is rich in dry tropical forests, currently endangered (Correa et al*.,* 2020). This should trigger alerts in the context of new electricity demands and the expansion of new renewables as photovoltaic and wind that will demand large tracts of land in function of its lowest power densities as presented in Table 7.

Comparing data from Table 7 to other sources, it is founded that power density average for hydropower is near to 1,6 W/m^2 (Vaclav, 2015), however, it is hard to analyze such values is average considering the high volatility of it, and that for power density it is not recommended using the average values. Akosombo is a hydropower in Ghana, has a power density of 0,1 W/m^2 with installed capacity of 912 MW and 8.502 m^2 (ICE, 2017), extremely low compared with the Colombian data; on the opposite side, Arun III an hydropower in Nepal with installed capacity of 900 MW has a power density of 800 W/m^2 (Vaclav, 2015), extremely high also compared with the Colombian data.

Similarly, the hydropower power density-average is going to be far from the Colombian scenario because of the country´s geographical characteristics, the highest rates of PD belong to projects situated in high mountains, whose tall dams impound small but deep reservoirs in contrast with project outside those altitudes with bigger reservoirs.

Table 7: Average power density for the electric Colombian system

Source	Average power density [W/m^2]
Hydropower	79,8
Photovoltaic	9,4
Wind-power	23,1
Coal-fired power plant	523,6
Gas-fired power plant	629,7
Oil-fired power plant	2284,4

Source: Own elaboration

For photovoltaic systems the average power density is 10 W/m^2 (Vaclav, 2015), similar to the values calculated for the two projects in Colombia. For wind-power, the common power density value is 1 – 11 W/m^2 (Vaclav, 2015) but these values correspond to installed capacities greater that 20 MW. Jepirachi wind-power in Colombia has 18 MW put it out of comparison, for similar magnitudes there are no other studies. As well, the limited number of photovoltaic and wind-power systems in the country do not allow for further comparisons.

In contrast, coal-fired power plants generate electricity commonly with PD in excess of 1.000 W/m^2 (Vaclav, 2015) but this is not an average value, PD can vary in order of chemical components because of the geographical formation and the extraction technologies. Gas-fired power plants have an average around 1.200 W/m^2 in contrast with the 629 W/m^2 of Colombian systems, but as the other sources, the average is highly uncertain: Roosevelt Island Bridge on the East River, NY has a PD of 20.000 W/m^2 (Vaclav, 2015). Finally, oil-fired power plants have no data for comparison because liquid fuels became too expensive to be used for electricity generation after, most of the power plants based on oil were shut down or converted to burning either coal or natural gas.

Regarding social conflicts associated with land-use change for energy generation, even though it is beyond the scope of this article, it is important to mention that, as documented by some scholars (Roa-Avendaño, et al., 2017; Roa-García, 2016) the fossil-fuel industry in Latin America has been associated with serious socio-environmental conflicts that have expanded and intensified during the last two decades, affecting the livelihoods and territories of ethnic and marginalized communities, especially in rural areas of the countries. In Colombia, besides the oil and coal industry, large hydropower plants have been a source of conflicts with rural populations, especially because many of them required the dislocation of local communities and have been associated with phenomena of violence.

Despite expectations being high regarding the non-conventional renewables and their capacity to reduce land conflicts, results presented here raise some concerns related to the considerable land requirements for electricity generation from renewables. While Colombia's electricity demand grows year after year, it is important to acknowledge the implications of this growing demand in terms of land-use change and pressures on the territories.

The Colombian government is promoting new generation plants, which means that projects will be required to relocate communities, changing the land-use of these territories, and causing fragmentation of ecosystems. To address social conflicts, land-use analysis represents an essential tool for decision making on land use allocation, considering the stakeholders' interests (Rodríguez and Zinck, 2016). Understanding the power densities for each generation project has the potential to contribute to better estimate land-use impacts from those projects.

5. CONCLUSIONS

After using our adapted PD metric to analyze the current electricity generation sources installed in Colombia, it was found that the ones that require less land are those coming from fossil sources, followed by hydropower, wind, and, finally, photovoltaic. When power density calculation for fossil-fired power plants do not include the fuel extraction area, the value is 30% lower for coal plants, 64% for gas plants and 0.4% for fuel oil plants. Yet, by including the extraction area, the power density obtained is significantly larger than when only the conversion area is considered.

Hydropower demands 98.9% of the land destined for electricity production in the country but 65.4% of the electricity installed capacity comes from them. Instead, all fossil-power plants required 0,7% of land and have the 33,9% of installed capacity. The hydropower plants have large spectrum values depending on the dam construction purpose. A dam with river-flow control for flooding demanded more land than the ones constructed solely for electricity generation.

Other renewables available in Colombia such as photovoltaic and wind-power require more land for electricity production than hydropower. However, there are still few projects using that source in the country, it is possible that future projects will improve their land use because of process optimization and better technologies, but this is unknown so far. Nevertheless, we can certainly expect that those new sources will demand large extensions of land, which is especially problematic in a country where land disputes have been at the core of the social and armed conflict.

REFERENCES

Avila, S. (2018), Environmental justice and the expanding geography of wind power conflicts. Sustainability Science, 13(3), 599-616.

Baker, S.H. (2019), Anti-resilience: A roadmap for transformational justice within the energy system. Harvard Civil Rights-Civil Liberties Law Review, 54, 1-48.

Darby, M. (2017), Giant Tunisian Desert Solar Project Aims to Power EU. Available from: https://www.climatechangenews.com/2017/08/04/giant-solar-project-tests-sahara-eu-power-export-dream [Last accessed on 2019 Nov 19].

Democracy, O. (2017), Another Case of Energy Colonialism: Tunisia's Tunur Solar Project, Open Democracy. Available from: https://www.opendemocracy.net/en/north-africa-west-asia/another-case-of-energy-colonialism-tunisia-s-tunur-solar-pro [Last accessed on 2019 Nov 19].

dos Reis, L., Silveria, S. (2001), Energia Elétrica Para o Desenvolvimento Sustetável. Brazil: Editora da Universidade de Sao Pablo.

EJ Atlas. (2016), Quilombola Communities Affected by Wind Power Projects in Caetité Region. Brazil: EJAtlas. Available from: https://www.ejatlas.org/conflict/quilombola-communities-affected-by-wind-power-projects-in-caetite-region-brazil [Last accessed on 2019 Nov 19].

Ekins, P., Simon, S., Deutsch, L., Folke, C., de Groot, R. (2003), A framework for the practical application of the concepts of critical natural capital and strong sustainability. Ecological Economics, 44(2-3), 165-185.

Ellis, E.C., Ramankutty, N. (2008), Putting people in the map: Anthropogenic biomes of the world. Frontiers in Ecology and the Environment, 6(8), 439-447.

Fearnside, P.M. (2008), Challenges for Sustainable Development in Brazilian Amazonia.

Fearnside, P.M. (2016), Environmental and social impacts of hydroelectric dams in Brazilian Amazonia: Implications for the aluminum industry. World Development, 77, 48-65.

Gong, J., Liu, Y., Chen, W. (2012), Land suitability evaluation for development using a matter-element model: A case study in Zengcheng, Guangzhou, China. Land Use Policy, 29, 464-472.

ICE. (2017), Akosombo Dam, Institution of Civil Engineers (ICE). Available from: https://www.ice.org.uk/what-is-civil-engineering/what-do-civil-engineers-do/akosombo-dam [Last accessed on 2021 Feb 10].

IDEAM. (2019), Atlas Interactivo-Radiación IDEAM. Available from: http://www.atlas.ideam.gov.co/visorAtlasRadiacion.html [Last accessed on 2019 Jul 16].

IFC. (2017), Hydroelectric Power a Guide for Developers and Investors Hydroelectric Power a Guide for Developers and Investors III. Available from: http://www.fichtner.de [Last accessed on 2020 Feb 26].

IPCC. (2019), Climate Change and Land. Available from: https://www.ipcc.ch/report/srccl/[Last accessed on 2019s Nov 19].

Luo, C., Li, Z., Liu, H., Li, H., Wan, R., Pan, J., Chen, X. (2020), Differences in the responses of flow and nutrient load to isolated and coupled future climate and land use changes. Journal of Environmental Management, 256, 109918.

Maturano, I.R. (2017), Yucatán ante un nuevo horizonte: Urgencia de conocimiento científico en el proceso local de la transición energética. Herbario CICY, 9(1), 118-125.

Ministerio de Ambiente y Desarrollo Sostenible. (2016), Auto No. 150 Del 27 De Abril de 2016. Available from: http://www.minambiente.gov.co/images/normativa/app/autos/5d-auto 150.pdf [Last accessed on 2020 Apr 07].

Ministerio de Minas y Energía. (2009), Resolución número 221 de 21 julio 2009. Available from: https://www.minenergia.gov.co/documents/10180/23517/36909-Resolucion-221-21Jul2009.pdf [Last accessed on 2020 Apr 07].

Ministerio de Minas y Energía. (2016), Resolución 288 Del 21 de Octubre de 2016. Available from: https://www.minenergia.gov.co/documents/10180/23517/resolución-288-+21oct2016.pdf/9ac2a454-9b08-455c-b732-7c849a8385de [Last accessed on 2020 Apr 07].

Moreno, R., Cantillo, S., Carrillo-Rodriguez, L.A. (2021), Risk analysis of firm energy coverage in colombia in the medium term. International Journal of Energy Economics and Policy, 11(2), 220-226.

Moreno, R., Larrahondo, D. (2021), The first auction of non-conventional renewable energy in Colombia: Results and perspectives. International Journal of Energy Economics and Policy, 11(1), 528-535.

Neslen, A. (2017), Huge Tunisian Solar Park Hopes to Provide Saharan Power to Europe, Environment, The Guardian. Available from: https://www.theguardian.com/environment/2017/sep/06/huge-tunisian-solar-park-hopes-to-provide-saharan-power-to-europe [Last accessed on 2019 Nov 19].

Restrepo-Trujillo, J., Moreno-Chuquen, R., Jiménez-García, F. (2020), Strategies of expansion for electric power systems based on hydroelectric plants in the context of climate change: Case of analysis of Colombia. International Journal of Energy Economics and Policy, 10(6), 66-74.

Roa-Avendaño, T., Roa-García, M.C., Toloza-Chaparro, J., Navas-Camacho, L.M. (2017), Como el Agua y el Aceite. Conflictos Socioambientales Por la Extracción Petrolera. Bogotá, Colombia:

Centro Nacional Salud, Ambiente y Trabajo, CENSAT Agua Viva.

Roa-García, M.C. (2016), Agua, Democratización Ambiental y Fronteras Extractivas en Colombia, GIGA Working Paper, No. 291.

Salazar, R.L. (2008), Una historia regional en tres tiempos: Campeche siglos XVIII-XX. Península, 3(2), 45-56.

Stockholm Resilience Centre. (2015), Planetary Boundaries. Available from: https://www.stockholmresilience.org/research/planetary-boundaries.html [Last accessed on 2019 Nove 19].

Thanvisitthpon, N. (2019), Impact of land use transformation and anti-flood infrastructure on flooding in world heritage site and peri-urban area: A case study of Thailand's Ayutthaya province. Journal of Environmental Management, 247, 518-524.

Turner, B.L., Lambin, E. F., Reenberg, A. (2007), The emergence of land change science for global environmental change and sustainability. Proceedings of the National Academy of Sciences, 104(52), 20666-20671.

UPME. (2019), Indicadores Oferta. Available from: http://www.upme.gov.co/reports/default.aspx?reportpath=/siel+upme/indicadores/indicadores+oferta&viewmode=detail [Last accessed on 2020 Feb 26].

Vaclav, S. (2010), Power Density Primer: Understanding the Spatial Dimension of the Unfolding Transition to Renewable Electricity Generation (Part I-Definitions). Available from: http://www.masterresource.org/2010/05/smil-density-definitions-i [Last accessed on 2019 Nov 19].

Vaclav, S. (2015), Power Density. Massachuse, London: The MIT Press Cambridge.

Vitousek, P., Mooney, H.A., Lubchenco, J., Melillo, J.M. (1997), Human domination of earth's ecosystems. Science, 277, 494-499.

von Sperling, E. (2012), Hydropower in Brazil: Overview of positive and negative environmental aspects. Energy Procedia, 18, 110-118.

Wang, Q.G., Du, Y.H., Su, Y., Chen, K.Q. (2012), Environmental impact post-assessment of dam and reservoir projects: A review. Procedia Environmental Sciences, 13, 1439-1443.

Zou, L., Liu, Y., Wang, J., Yang, Y., Wang, Y. (2019), Land use conflict identification and sustainable development scenario simulation on China's Southeast Coast. Journal of Cleaner Production, 238, 117899.