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Solar photovoltaic potential to complement hydropower in Ecuador: A GIS-based framework of analysis

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ABSTRACT

In Ecuador, more than 85% of electricity production relies on hydropower and consequently the supply of electricity relies on water availability. During the dry season (October-March) hydropower capacity could diminish up to one-third of its installed capacity or more under a severe drought causing a substantial augmentation of thermoelectric power output to offset the lack of hydropower to cover electricity demand, and consequently increasing the overall operational cost and emission of CO2 of the power system. Compensating hydropower seasonality with non-hydro renewable energy is thus necessary to safeguard and maintain in the long-term the supply of clean and affordable electric service. This thesis studies the potential of non-hydro renewable energy such as PV to compensate the seasonality of hydropower and assess its impact on the long-term expansion of the Ecuadorian power system. To do so, a GIS-based and participatory multi-criteria analysis is applied to find the best suitable areas to deploy PV power that is complementary to hydropower from a technical, economic and environmental viewpoint. Then, using the Stochastic Dual Dynamic Programming software a long-term simulation (2019-2030) of the power system's operation under a baseline and alternative expansion scenario without and with PV respectively is performed in order to assess the economic and environmental impact of integrating complementary PV in the expansion of the Ecuadorian power system. Results indicate that the installation capacity potential of complementary PV is 35,7 GWp which is equivalent to 4.3 times the actual capacity of the Ecuadorian power system, and it is distributed in suitable land areas mainly in the South of Ecuador with a total area of 805 km^2 that is equivalent to 0.3% of the area of the country. Comparing simulation results of power system expansion scenarios shows that the alternative scenario that considers a high penetration of PV in the power system (3.9 GWp) reduce by half the annual operational cost of the power system and more than one quarter (33%) of the lifecycle GHG emission by 2030. Thus, integrating PV rather than thermoelectric power in the long-term expansion of the power system is the best option from an economic and environmental viewpoint. This study set the basis to encourage planners and decision makers to consider these findings for future expansion plans in order to set up a sustainable power system for Ecuador at low cost and environmental impact.

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LIST OF ABBREVIATIONS

AHP	The Analytical Hierarchy Process
CSP	Concentrated Solar Power (CSP)
ENSO	El Niño Southern Oscillation
IPCC	Intergovernmental Panel on Climate Change
MEER	Ministry of Electricity and Renewable Energy
MPE	Master Plan of Electricity (MPE)
PV	Solar photovoltaic
SDDP	Stochastic Dual Dynamic Programming

1 INTRODUCTION

1.1 The Ecuadorian power system

A significant progress on expanding the generation and distribution of electricity has been achieved since the origins of the Ecuadorian power system in the 60's. Electricity grids reach 97% of the inhabited national territory (MEER, 2016). The installed capacity of generation has increased from 1075MW in 1961 to 8226 MW in 2016 due to the massive construction of hydropower plants (MEER, 2016; Peláez-Samaniego, et. al., 2007). In 2017 most of the electricity demand (23.3 TWh/year) was covered with hydropower (72.3%) complemented with thermoelectric power (25.9%) that used fossil fuels such as diesel, fuel-oil and natural gas, and non-hydro renewable energy (1.8 %), such as biomass, photovoltaic, and wind. With this new configuration of the power system, electricity importations from Colombia and Peru were eliminated; which in previous years was between 10-15% of the total electricity demand (ARCONEL, 2018).

The massive construction of hydropower power plants that started in 2008 and still some projects are under construction. Once these projects are finalized by 2019 an increased capacity of 956MW will be added; and consequently, the total installed capacity of the power system will be 9182 MW. The high share of hydropower displaced thermoelectric power, and as a result the consumption of imported fossil fuels. Figure 1.1 is shown a typical day of the dry season in 2014 were half of the electricity demand was covered by thermoelectric power, while in 2017 it was roughly 15%. As a consequence of less thermoelectric power, the overall operational cost and greenhouse gas (GHG) emissions of the power system reduced significantly. For instance, in 2016 3,599,835 tCO_2/year were avoided due to the construction of the hydropower plants (MEER, 2016). The new configuration of the power system will secure in the short-term a clean supply of electricity in Ecuador including the ability to export electricity to Colombia and Peru (MEER, 2016). However, the challenge today is to maintain this high share of renewable energy (85%) in the electricity matrix in order to safeguard a clean, affordable and reliable electricity supply in the long-term.

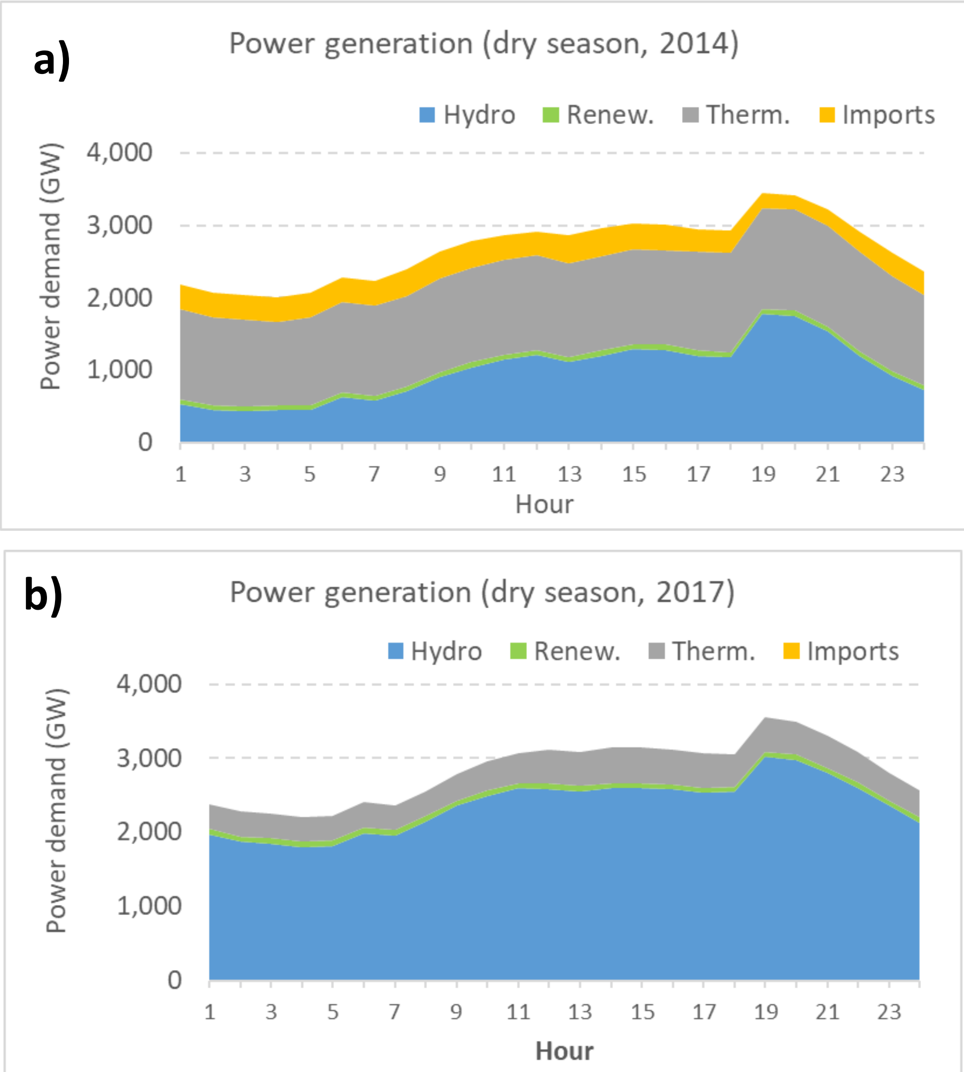


Figure 1.1 Power generation during a typical day in the dry season: a) December 2014, b) December 2017

1.1.1 The expansion problem of hydro-thermal power system

Literature suggests that power systems with a high share of hydropower are vulnerable due to the variability of hydrological resources (Batlle, 2014; Paredes & Ram, 2017). In South America most of the countries rely on hydropower (IRENA, 2016b) which has a strong seasonality and inter-annual variation due to the El Niño Southern Oscillation (ENSO) that could result in a severe reduction of power generation and consequently in an increment of expensive and polluting thermoelectric power to offset the lack of hydropower (Schmidt, et. al., 2014, 2016b).

In Ecuador, the situation is critical since most of the hydropower plants do not have reservoirs, so there is no capacity to store water and secure the supply of clean electricity during the dry season. In fact, the Master Plan of Electricity (MPE) (MEER, 2016) suggest that during dry season (October-March) hydropower generation could diminish up to one-third of its installed capacity causing a periodic and progressive increment of thermoelectric power capacity in the long-term to cover the electricity demand growth, especially during dry seasons (Figure 1.2).

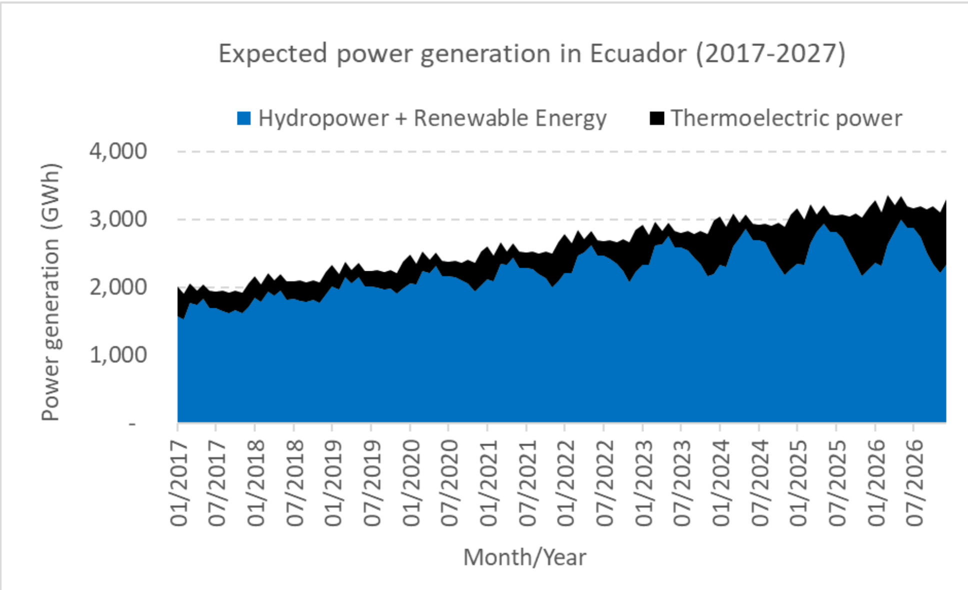


Figure 1.2 Expected power generation by technology in Ecuador, 2017-2016 (MEER, 2016)

Hydropower is still seen as a political priority in Ecuador for the expansion of the power system (MEER, 2016). However, developing the remaining hydropower potential; which is 6785MW and concentrated mainly in the Amazon region (Figure 3.1), will have on the one side, severe socio-ecological impacts since inhabited areas and sensitive rainforest ecosystems will be flooded (de Faria & Jaramillo, 2017; Soito & Freitas, 2011). On the other side, more hydropower will produce a significant surplus of generated electricity in the wet season (March-September) resulting in a substantial water spillage and a waste of energy worsening the power imbalance. An alternative to solve this power imbalance is to develop the remaining hydropower potential located in the Pacific water basin (Figure 3.1) which has a semi-complementary hydrological cycle with the Amazon region since its maximum availability of hydrological resources for electricity production occurs between January-March (Figure 1.3). However, the untapped potential of the Pacific Ocean water basin is only 20% of the Amazon region and in both water basins the hydrological resources are reduced drastically during the last quarter of the year. Thus, developing the remaining hydropower potential will not solve the power imbalance in the future.

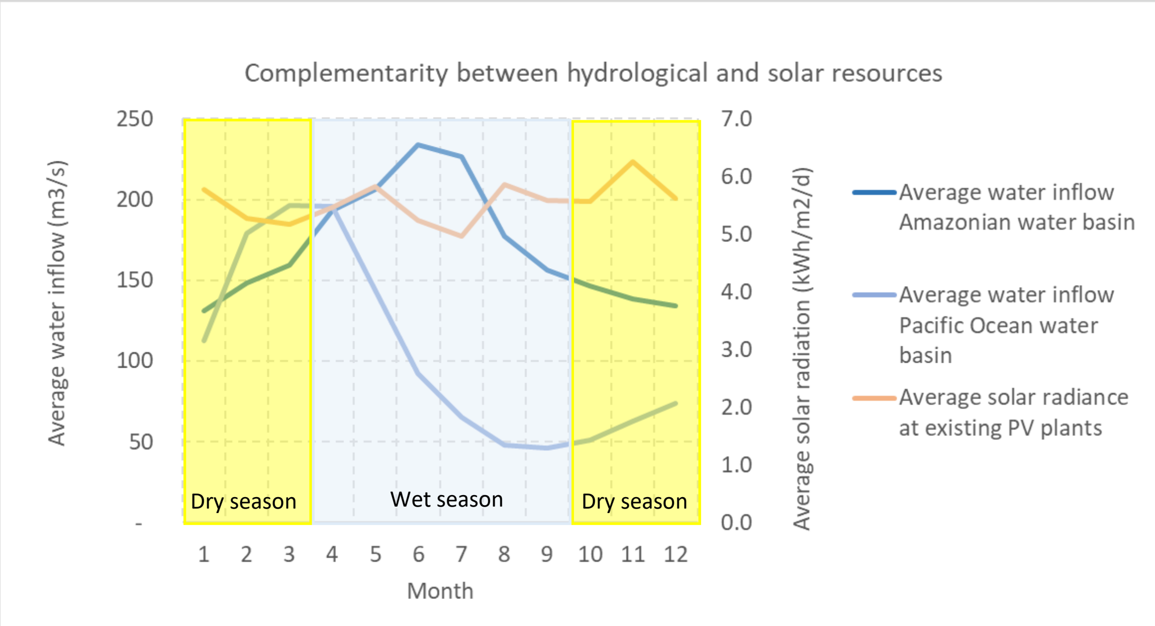


Figure 1.3 Complementarity between hydrological and solar resources in Ecuador, (MEER, 2016)

1.1.2 Tackling hydropower seasonality

Literature suggests that an increase of non-hydro renewable energy such as wind, solar or biomass can compensate the seasonality and inter-annual variation of hydropower by producing the maximum amount of electricity during the dry season; and thus, reducing the need of thermoelectric power (Malagueta et al. 2014; Chade & Sauer 2013; Schmidt et al. 2016; Urzua et al. 2016). However, the potential of non-hydro renewable power plants to complement hydropower generation has not been studied in Ecuador.

Among, non-hydro renewable energy resources available in Ecuador such as solar, wind, and biomass (ARCONEL, 2008; ESIN, 2014; MEER, 2013), solar photovoltaic (PV) seems to have a promising potential to solve the problem of variability of hydropower generation in Ecuador. The operation of existing 23 PV power plants located along the country shows that electricity production is high during the dry season (Figure 1.3); and thus, PV has the potential to compensate the reduction of hydropower. Also, PV has an advantage over other forms of non-hydro renewable energy as solar irradiance is available at many locations (ARCONEL, 2008), and PV has the lowest inter-annual variability of electricity generation compared with wind power (Schmidt, et. al., 2016a).

Identifying and evaluating Ecuador's PV potential to compensate the hydropower variability and seasonality in the long term is relevant to enhance decision-making on planning the sustainable power system expansion. PV potential relies not only on the availability of solar resources but also on land availability as it has been extensively studied in the literature (section 2.2) through the development of spatially explicit models using Geographic Information Systems (GIS). However, these spatially explicit models have failed to integrate into their analysis the temporal dimension of the problem by assessing the complementarity between PV and hydropower and the long-term effects on power system expansions from an energy system analysis viewpoint (section 2.1).

Thus, grounded on two bodies of literature the hypothesis that this research sets out can now be defined as follows: An integrated, spatially and temporal explicit approach is capable to identify and evaluate the potential of complementary PV that could tackle the inter-annual variability of hydropower in Ecuador.

1.2 Research Gaps

The literature reviewed demonstrated that increasing the share of complementary non-hydro renewable energy sources (e.g. PV) reduce the vulnerability of power systems with a high share of hydropower that is caused by climate alterations and hydrological seasonality. More research is needed in Ecuador to enhance our understanding of the potential of complementary renewable energy like PV that can tackle hydropower seasonality, and evaluate its impact on the expansion of the power system, which has received little attention in official expansion plans (ARCONEL, 2013).

GIS-based suitability analysis has proved to be a powerful method to identify the best locations for PV; however, little is known about its ability to identify suitable locations for PV in countries like Ecuador, where the criteria of complementary between renewable energy and hydropower are needed for the sustainable expansion of power systems. Thus, this thesis seeks to contribute to filling this knowledge gap through the development of an integrated, spatially and temporal explicit approach (i.e. GIS-based MCA and energy system analysis tools) to identify suitable and best location for PV that compensate the seasonality of hydropower, and assess PV impact in the long-term operation of the power systems in order to support decision-making of future expansion plans in Ecuador.

1.3 Research objective and questions

The objective of this thesis is to build a spatially and temporal explicit approach that can be potentially useful for exploring and evaluating the potential of PV that can compensate an inter-annual variability of hydropower in Ecuador; and assessing the economic and environmental impact of integrating PV in the long-term operation of the Ecuadorian power system. Thereby, providing decision-makers with support for making better-informed decisions about power system expansion in the long-term.

To achieve the thesis goal the specific research questions are:

1. How much and where are located suitable land areas for PV in Ecuador considering land restrictions from local expert's viewpoint?
2. How much and where are located the best suitable land areas for PV that can compensate seasonality of hydropower in Ecuador considering land suitability criteria from local expert´s viewpoint?
3. What are the installation capacity potential and expected energy production of complementary PV in Ecuador?
4. What are the economic and environmental impacts of complementary PV in the long-term operation of Ecuador´s power system?

1.4 Thesis structure

This thesis is organized into six chapters. Chapter 1 gives a general introduction and provides a background of the Ecuadorian power system problem. An overview of the research objectives and questions is also given. Chapter 2 presents a definition of concepts and a literature review of complementarity principles in power systems with a high share of hydropower, and GIS-based land suitability analysis for PV deployment. Chapter 3 presents the methodological framework of this thesis, including an overview of data collection and analytical methods used during the research process. Chapter 4 and 5 present the results and discussions of the thesis respectively. Finally, chapter 6 summarizes the main findings and conclusions of this study. It also presents study limitations, suggestions for future research and sketches policy recommendations.

2 LITERATURE REVIEW

2.1 Power system and complementary renewable energy

2.1.1 Hydropower vulnerability in South America

South America is a region highly dependent on hydropower; for instance, in 2013 more than half of the total electricity in the region was produced by hydropower, e.g. Paraguay 100% and Argentina 23% (IRENA, 2016b). The region still has an untapped hydropower potential and remains a policy priority for future expansion of power systems (IRENA, 2016b). Nevertheless, the availability and reliability of hydropower generation rely on climate conditions making electricity supply in several Latin American countries vulnerable to climate alteration (IRENA, 2016b; Paredes & Ram, 2017). Among climate conditions that influence hydropower, the first is the ENSO which is a semi-periodic phenomenon responsible for changes in rainfall patterns that could result in severe droughts and consequently in low hydropower generation (IRENA, 2016b). For instance, in Brazil, a stark drought in 2014 reduced drastically hydropower generation to 90% of the average generation between 2011-2013 forcing to dispatch more than double of the planned thermoelectric power generation resulting in high energy cost and GHG emissions (Schmidt, et. al., 2016).

A second climate condition is related to climate change which in fact is exacerbating the ENSO and worsening the vulnerability of hydropower (Beard et al., 2010; de Lucena et al., 2009). According to The Intergovernmental Panel on Climate Change (IPCC) in next century there will be rising temperatures around the planet influencing annual water streamflow, shifts of seasonal flows, an increase of streamflow variability (including floods and droughts); as well as, increased evaporation from reservoirs and changes in sediments fluxes (Jimenez et al., 2014). Variations on rainfall patterns due to climate change effects have the highest potential to impacts hydropower (IRENA, 2016b; Kundzewicz et al., 2007). For instance, in Brazil, recent studies show that hydropower generation could fell up to 30% due to climate change impacts (de Queiroz, et. al., 2016). From Kumar et al., (2014) it is expected an increment (20-30%) on water availability in the Ecuadorian Amazon where most of the hydropower capacity is located (MEER, 2016). Therefore, an increment on electricity production is probable in Ecuador due to climate change. However, these projections are at global and regional scale, and as

Hamududu and Killingtveit (2012) suggested climate change impacts on hydropower can vary locally.

Power system especially those with a high share of hydropower plants without reservoirs as in Ecuador are more vulnerable to alterations on rainfall patterns since water cannot be stored to use during the dry season (de Lucena et al., 2009; de Queiroz et al., 2016; Soito & Freitas, 2011). Thus, the optimal expansion and operation of power systems is a challenge faced by many countries in South America that need to be solved in the short and mid-term to ensure reliable, affordable and clean electricity (Paredes et al., 2017). In this regards, recent studies (Marinho, 2011; Schmidt et al., 2014; Silva, et.al, 2016) suggest that an optimal mix of complementary non-hydro renewable energy (i.e. wind, solar, biomass, geothermal) in power system with a high share of hydropower increases power supply reliability and optimize the exploitation of hydropower resources.

2.1.2 Complementarity mechanisms for power system operation and expansion

Complementarity between renewable energy sources in a power system can be defined as the extent that their energy output is not positively correlated over time (Kougias et al. 2016). Such complementarity helps to tackle the problem of intermittency of renewable energy such as solar and hydropower since their min/max energy output occurs at different periods of time. For instance, for the case of power systems with a high share of hydropower at a yearly scale, it means that non-hydro renewable energy (e.g. wind, solar) should have the maximum production during the dry season or the period of minimum hydropower production; and thus, limiting the operation of thermoelectric plants. During the wet season or the period of maximum hydropower production non-hydro renewable energy should have the minimum production avoiding significant surplus electricity generation and consequently water spillage or a waste of energy in hydropower plants.

In Table 2.1 two categories of complementary mechanism applied for different stages of power system management are presented and discussed for the Ecuadorian case (IRENA 2016a): i) System expansion mechanisms which involve decisions to increase new power capacity for an optimal coverage of future electricity demand, and ii) System operation mechanisms which comprises the ideal management of existing power capacity to cover optimally the present electricity demand. From reviewed complementarity mechanisms, PV seems to be a promising complementary strategy for the expansion and operation of power systems due to its strong climate synergy with hydrological resources, short construction time, low-trend prices, and growth projections in South America (IRENA, 2016a).

Table 2.1 Complementarity mechanisms for system expansion and operation in Ecuador (IRENA, 2016b)

Stage	Mechanism	Description	Ecuador's situation
Complementary system expansion mechanisms	1.1 Climate synergies: climate variability and adequacy of supply	When hydropower generation is low due to climate variability (e.g. ENSO), the generation of other (non-hydropower) renewable energy is not reduced or even increases	During the dry season (October-March) of hydropower solar radiation and biomass resources (e.g. sugar cane) increase considerably (ARCONEL, 2008; ESIN, 2014). Thus, a strong climate synergy exists between them.
	1.2 Climate synergies: climate change vulnerability and strategic expansion	Diversifying the electricity mix provides resilience to climate change, which can cause a reduction in hydropower generation	Ecuador relies mainly (85%) on hydropower. The participation of other sources like wind, solar, biomass is small (≈2,5%)
	1.3 Implementation of generation infrastructure	Delays in the construction of large power plants (e.g. hydropower) can lead to imbalances in electricity supply/demand which can be lessened with the implementation of modular non-hydropower renewable energy technologies with short constructions times.	Construction times of hydropower in Ecuador ranges between 5-8 years and most of the project has suffered delays. However, PV has relatively short construction times of 1-2 years to tackle potential power imbalances.

Stage	Mechanism	Description	Ecuador's situation
	1.4 Ownership diversification	Allow diversification of project ownership and the entry of new players in the power market by implementing smaller-scaled non-hydropower renewable energy technologies (e.g. solar roofs).	The participation of new players and private generators are limited by law (Ecuador, 2015b).
Complementary system operation mechanism	2.1 Hydropower flexibility used to counteract the short-term variability of other renewable energy technologies	Hydropower with reservoirs can counteract the intermittency of non-hydropower renewable energy (e.g. wind, solar) at lower prices than other technologies (e.g. natural gas)	There is a high hydropower capacity, thus, there is a strong capacity to counteract the intermittency of non-hydro renewable energy.
	2.2 Seasonal complementarity	Hydropower generation during drier seasons is low but for some non-hydro renewable energy technologies the production increases.	See 1.1.
	2.3 Portfolio diversification	A diversified portfolio of non-dispatchable renewable energy plants (e.g. wind, solar) is less volatile in the short term than that of each individual plant.	See 1.2

Different authors have studied the above-mentioned mechanisms to integrate complementary non-hydro renewable energy sources in power system expansion in South America. Chade & Sauer (2013) studied wind power as a substitute for a thermoelectric power in Brazil. They found the possibility to meet the future electricity demand by 2040 using only hydro and wind power. The expansion plan using wind energy is 57% the cost of the plan based on expanding thermoelectric plants (natural gas, coal, and nuclear energy). Schmidt et al. (2016a) and Silva et al. (2016) found similar results and highlight the role of wind energy in reducing significantly the risk of load shedding due to droughts in Brazil.

Malagueta et al. (2014) studied the potential of different Concentrated Solar Power (CSP) technologies for the expansion of the Brazilian power system by 2040 with and without thermal storage and hybridization with natural gas and biomass. Results suggest that implementing auctions and incentives to integrate CSP will replace thermoelectric generation and from 2030 onwards hydropower is not needed anymore because solar capacity increase and thermal storage reduced variable generation during the day. Also, it contributed to a higher integration of wind energy. Moreover, this expansion plan is about 144 billion dollars dearer than an expansion plan based on hydropower, and thermoelectric power plants fueled by natural gas and sugarcane bagasse. Fichter et al. (2017) found that the hybridization of CSP with biomass makes CSP a technology economically feasible, and contributes to regularize the energy imbalance resulting from large-scale wind power and solar photovoltaic expansion, becoming an attractive alternative as base power for power systems.

(Schmidt, et. al., 2016a) studied an optimal mix of wind, PV, and hydropower for the expansion of the Brazilian power system by 2050. Authors found that in an expansion plan based only on hydropower and thermoelectric power plants there is 10 times more risk of load shedding than an expansion plan based on PV, wind, hydropower and thermoelectric power plants. Wind and PV power plants limit the participation of thermoelectric power plants to only 4% even if the future electricity demand double by 2040. Hydropower does not need to be expanded from current levels and it will cover 50% of the total electricity demand. Their reservoirs will allow integrating a higher share of PV (37%) than wind (9%). Suggesting that PV has an advantage over wind power in decreasing electricity supply risk in power systems (Schmidt, et. al., 2016b). Urzua et al. (2016) simulated the economic consequences of different scenarios of integrating PV and wind energy (10%, 15%, 20% and 30% of total generation) in the Chilean power system (2017–2027). Results show that an increased penetration of intermittent renewable energy increases the generation and transmission investment cost, which are not counterweighted with the reduction of the generation cost. Thus, authors recommend diversifying the portfolio of renewable energy by incorporating more predictable renewable energy generation (i.e. biomass, geothermal and small-scale hydroelectric power plants).

Above studies demonstrated that complementary renewable energy sources are a feasible strategy to optimize the operation and expansion of power systems. However, in Ecuador, the study of non-hydro and complementary renewable energy (wind, solar photovoltaic, geothermal, biomass) has received little attention in official expansion plans (MEER, 2016). A knowledge gap that this research seeks to fill in order to support decision-making.

2.2 GIS-based land suitability analysis to deploy solar photovoltaic

In order to assess the land suitability to deploy PV at a wider national scale, a combination of Geographic Information System (GIS) and Multi-Criteria Analysis (MCA) have been commonly applied (Table 2.2) in order to integrate multiple and spatially explicit criteria, and expert`s judgments. Most of these studies focused on Europe, North-America, Africa, and Asia; but, none in South America.

Table 2.2 Reviewed GIS-based land suitability analysis to deploy solar photovoltaic

ID	Source	Suitability method	Scale	Location
1	Domínguez Bravo et al. (2007)	BOR[1]	National	Spain
2	Dahle et al. (2008)	BOR	National	USA
3	Wang and Koch (2010)	BOR	Multiple countries	Germany, France, Austria, Italy, Switzerland
4	Omitaomu et al. (2012)	BOR	National	USA
5	Stoms et al. (2013)	BOR	Sub-national	USA
6	Sun et al. (2013)	BOR	Sub-national	China
7	Mahtta et al. (2014)	BOR	National	India
8	Polo et al. (2015)	BOR	National	Vietnam

ID	Source	Suitability method	Scale	Location
9	Anwarzai and Nagasaka (2016)	BOR	National	Afghanistan
10	Jahangiri et al. (2016)	BOR	Multiple countries	Bahrain, Cyprus, Egypt, Iran, Iraq, Israel, Jordan, Kuwait
11	Merrouni et al. (2016)	BOR	Sub-national	Morocco
12	Arán Carrión et al. (2008)	AHP[3]	District	Spain
13	Uyan (2013)	AHP	Sub-national	Turkey
14	Watson and Hudson (2015)	AHP	Sub-national	UK
15	Charabi and Gastli (2011)	AHP-OWA[3]	National	Oman
16	Sánchez-Lozano et al. (2013)	AHP-TOPSIS[4]	Sub-national	Spain
17	Janke (2010)	WLO[5]	Sub-national	USA
18	Mondino et al. (2014)	WLO	Sub-national	Italy
19	Brewer et al. (2015)	WLO	Sub-national	USA
20	Sánchez-Lozano et al. (2014)	ELECTRE-TRI[6]	Sub-national	Spain

[1]BOR= Boolean overlay
[2]AHP=Analytic Hierarchy Process
[3]OWA=Ordered weighted averaging
[4]TOPSIS=Technique for Order Preference by Similarity to Ideal Solutions,
[5]WLO=Weighted linear overlay,
[6]ELECTRE-TRI=Elimination and Choice Translation Reality
Note: These methods are explained below

Above reviewed studies relied essentially on two approaches: compensatory and non-compensatory (Arán Carrión et al., 2008). Non-compensatory approaches aim to find the best locations for PV applying a simple Boolean overlay (i.e. BOR) of multiple criteria maps. On the contrary, compensatory approaches assign weights to criteria before a weighted overlay of criteria in order to find the best location for PV. The premise of compensatory approach is that by weighting criteria trade-offs are harmonized and the better decision can be taken. For instance, the high weight of a given criteria (e.g. solar radiation) can be compensated by a low weight of another criterion (e.g. distance to roads) to evaluate the land suitability for PV. Compensatory approaches used different methods to assign criteria’s weights. Studies that applied a Weighted Linear Overlay (WLO) used authors´ judgment (Janke, 2010), artificial neural network modeling

(Mondino et al., 2014) or statistics (Brewer et al., 2015) to define criteria’s weights. Conversely, studies that applied the Analytic Hierarchy Process (AHP) used experts’ judgment to evaluate criteria’s relative importance and assigns their weights, and to ensure reliable results, probable contradictions of expert’s choices were assessed through a consistency test. Watson & Hudson (2015) applied the AHP in a public consultation with local experts to validate criteria weights from actual practitioners on siting PV.

In most compensatory approaches once criteria`s weights were defined, a weighted sum of the criteria maps were applied to obtain a map of the degree of land suitability for PV. However, other authors have combined AHP with different methods to integrate the criteria and calculate the degree of land suitability for PV. Charabi & Gastli, (2011) applied an Ordered Weighted Averaging (OWA) to produce a number of scenarios of land suitability for PV by incorporating criteria weights obtained from AHP, and order weights specified by means of fuzzy (linguistic) quantifiers. Sánchez-Lozano et al. (2013) used the Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS) to ranks the best location for PV at cadastral level by calculating the distances from the positive and negative ideal solutions according to the evaluation criteria and their corresponding weights defined by AHP. On the contrary, Sánchez-Lozano et al., (2014) differentiate from other authors by applying The Elimination and Choice Translation Reality (ELECTRE-TRI) method; which, do not find the best location for PV through a relative evaluation of competing criteria; but, perform a classification of candidate PV locations based on absolute merits and downsides. Moreover, authors highlight that ELECTRE-TRI does not require to define precise numerical values for criteria weights; which can be a challenging task for a local expert. However, the ELECTRE-TRI method has not been frequently applied.

Non-compensatory and compensatory approaches are applied in almost the same number of reviewed studies. The former is included in most of the reviewed studies (11 of 20) perhaps for its simplicity of use. However, compensatory approaches offer other advantages: i) allow to trade-off among criteria and reach better decisions, ii) permit qualitative and fuzzy evaluations facilitating the analysis of complex real-world problems, iii) facilitate communication among stakeholders encouraging participation and to reach consensus, iv) accounts for inconsistencies on the choices of experts or decision-makers (Arán Carrión et al., 2008). For all of these advantages, compensatory approaches are the most preferable method applied in energy studies (Pohekar & Ramachandran, 2004). Moreover, none of the reviewed studied has incorporated in their analysis criteria to quantify the complementarity between power sources (e.g. hydropower and PV); which is a specific problem for the study area.

3 MATERIALS AND METHODS

3.1 Study location

This research was conducted in Ecuador (Figure 3.1), one of the smallest countries in South America with an area of 256 370 km^2 including Galapagos Islands (INEC, 2017). Ecuador is located on the equatorial line and borders with Colombia in the North, with Peru in the South and East, and with the Pacific Ocean in the west. Ecuador has four geographical regions: 1) Coast: occupies approximately a quarter of the national territory, 2) Sierra: extends along the Andean mountains and where the capital, Quito is located, 3) Amazon region: occupies approximately half of the territory, and from where the main country`s source of income is obtained (oil), and 4) The Galapagos Islands: a National Park located at approximately 1000km from the coast.

Figure 3.1 Study area and the Ecuadorian power system (ARCONEL, 2015)

3.2 Methodological framework

The overall methodology applied in this thesis is shown in Figure 3.2; which, included two research phases: i) GIS-based suitability analysis, and ii) Energy system analysis, which are explained in detail in following sections.

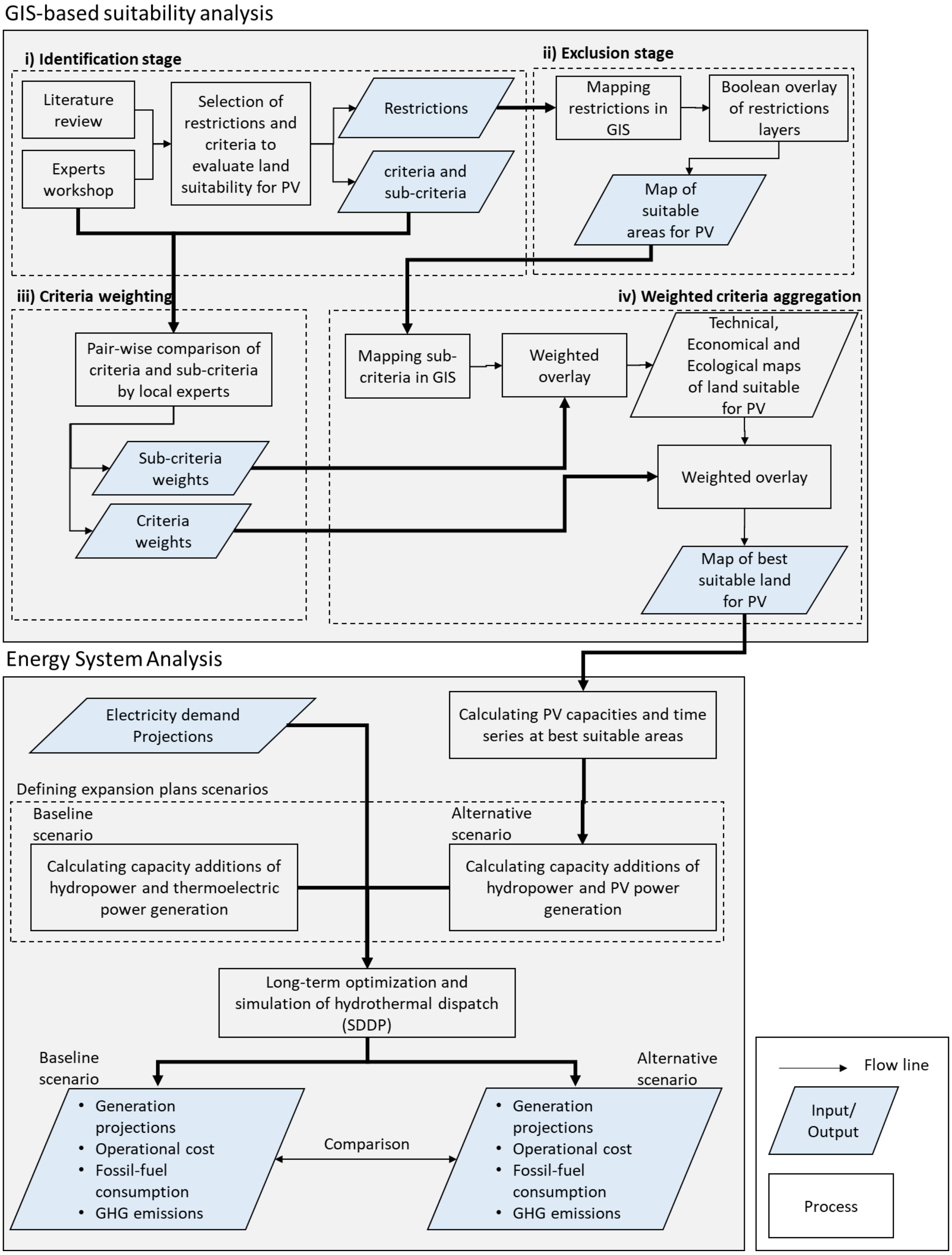


Figure 3.2 Research methodology adapted from van Haaren and Fthenakis (2011); Anwarzai and Nagasaka (2016); Urzua et al. (2016)

3.2.1 GIS-based suitability analysis

A GIS-based participatory and compensatory multi-criteria analysis was applied in the first research phase to identify and evaluate suitable areas to deploy complementary PV power plants in Ecuador. The Analytical Hierarchy Process (AHP) (Saaty, 1989) was selected because it is one of the leading approach applied in reviewed studies that evaluate land suitability for PV (Table 2.2) but also in other energy studies (Pohekar & Ramachandran, 2004). Moreover, the AHP has proved to be a flexible approach to check inconsistencies and allows the participation of local experts, the latter providing an opportunity to understand the research problem from local experts' viewpoint (Charabi & Gastli, 2011; Watson & Hudson, 2015).

The AHP is a structured method for organizing and supporting group decision making. Based on experts' knowledge and their understanding of the problem, the AHP allows to evaluate and select the best alternatives to attain a decision goal. The AHP starts by decomposing the decision goal into a hierarchy of criteria maps related to different aspects (e.g. economic, technical and ecological) of the decision goal. Then, local experts through pairwise comparisons derive a numerical weight for each criteria map in relation to their influence on the decision goal. Finally, criteria maps and weights are aggregated through a Boolean overlay in order to evaluate the best location that suits the decision goal (Arán Carrión et al., 2008; Charabi & Gastli, 2011; Sánchez-Lozano et al., 2013; Uyan, 2013; Watson & Hudson, 2015).

The adopted AHP method included four steps (Figure 3.2.a): i) restrictions and criteria identification, ii) exclusion of non-suitable land for PV, iii) criteria pairwise comparison and weighting by local experts, and iv) evaluation of land suitability for PV through weighted criteria aggregation. These steps are explained in the following sections.

i) Restriction and criteria identification

A set of restrictions to identify non-suitable land for PV and a set of criteria and sub-criteria to evaluate the level of land suitability for PV were identified from an extensive literature review (Appendix 1) together with a local experts' workshops. Local experts included: two engineers responsible for planning the electricity generation expansion, one environmental manager, and one researcher with experience in renewable energy. Once the restrictions and criteria were defined all geographic data to map them were collected from government institutions (Table 3.1).

Table 3.1 Datasets and sources used to map selected criteria and restrictions

Dataset	Data type	Reference	Source of the dataset
Volcanic hazard areas	Vector	(SGT, 2011)	Risk Management Secretariat (SGR)
Flood risk areas	Vector	(MAGAP, 2015)	Ministry of Agriculture and Livestock (MAGAP)
Main rivers of Ecuador	Vector	(IGM, 2013a)	Geographic Military Institute (IGM)
Urban areas of Ecuador	Vector	(IGM, 2013c)	
Rural villages	Vector	(IGM, 2013b)	
Administrative boundaries of Ecuador provinces	Vector	(INEC, 2007)	National Institute of Statistics and Census (INEC)
National roads network	Vector	(MTOP, 2015)	Ministry of Transport and Public Works (MTOP)
Protected areas	Vector	(MAE, 2015c)	Ministry of the Environment (MAE)
Biosphere reserves	Vector	(MAE, 2015a)	
Protected forest and vegetation	Vector	(MAE, 2015d)	
Communally protected forest “Socio Bosque”	Vector	(MAE, 2015b)	
Land uses of Ecuador	Vector	(MAE, 2017)	
Terrain slope of Ecuador	Raster (resolution 200m)	(MEER, 2013)	Ministry of Electricity and Renewable Energy (MEER)
Monthly average solar irradiation	Raster (resolution 1000m)	(ARCONEL, 2008)	Agency for Regulation and Control of

Dataset	Data type	Reference	Source of the dataset
Electric Transmission Network of Ecuador	Vector	(ARCONEL, 2017)	Electricity (ARCONEL)

Table 3.2 shows the selected restrictions and their rationale to be used in order to eliminate from the analysis all non-suitable areas for PV. These include the most frequent ones from reviewed literature (Appendix 1) prioritized by local experts for Ecuador conditions.

Table 3.2 Restrictions for PV installation in Ecuador

Restriction	Rationale obtained from local experts`workshop
Flood risk areas	Dataset MAGAP, (2015) consisted of four ratings of flood risk; rates high and middle were classified as non-suitable land for PV, and, rates low and no-risk were classified as suitable land for PV.
Rivers	Dataset IGM, (2013a) contains the main rivers of Ecuador; Installing PV on the river are not allowed. Thus, these areas were classified as non-suitable land for PV.
Volcanic risk	Dataset SGT, (2011) consisted of six ratings of volcanic eruption risk (highest, high, middle, low, very low, lowest). All rates were classified as non-suitable land for PV.
Inhabited areas	Datasets IGM, (2013b) and IGM (2013c) include rural and urban areas of Ecuador. A buffer area of 500m was applied to these areas. As PV plants could have a visual impact. The inhabited areas (urban and rural) and its respective buffer areas were classified as non-suitable land for PV.
Protected and natural areas	Datasets MAE, (2015c, 2015a, 2015d, 2015b) includes national parks, biosphere reserves, protected forests and vegetation, and communally protected forest “Socio Bosque program”. A buffer area of 1000m was applied to these areas. As a PV development could damage natural and protected areas, these areas including their respective buffer areas were classified as non-suitable land for PV
Slope	Datasets MEER, (2013) contain terrain slope used to elaborate the wind atlas of Ecuador. To minimize the investment of infrastructure and to maximize electricity production from PV,

Restriction	Rationale obtained from local experts`workshop
	locations with slope values bigger than 15% were classified as non-suitable for PV
Roads	Dataset MTOP, (2015) contains the main roads of Ecuador. Installing PV on roads are not allowed. Thus, these areas were classified as non-suitable for PV
Complementary areas	Datasets ARCONEL, (2008) contain twelve raster maps depicting the monthly average global solar radiation in Ecuador. In order to focus this study in areas where PV production is maximum during the dry season of hydropower (October-March), all locations that have their maximum solar radiation between April-September were classified as non-suitable land for PV.
Amazon provinces	Dataset INEC, (2007) contains the administrative boundaries of Ecuador provinces. The six provinces of the Ecuadorian Amazon region (i.e. Orellana, Napo, Pastaza, Morona Santiago, Zamora Chinchipe and Sucumbíos) were classified as non-suitable land for PV. Installing PV in these provinces will require more transmission infrastructure increasing investment cost and electricity loss. Moreover, PV could cause deforestation in the Amazonian rainforest, and create land conflicts with indigenous people.

Table 3.3 shows the hierarchy of criteria and sub-criteria used to evaluate the degree of land suitability for PV in Ecuador. The knowledge, experience, and discussions of workshop participants as practitioners validated the choices from an extensive literature review (Appendix 1). Three criteria were considered relevant for the suitability analysis, i.e. technical, economical and environmental. For each criteria a set of sub-criteria was defined. The rationale for these choices is given below.

Table 3.3 Criteria used to evaluate land suitability for PV obtained from workshop

Criteria	Sub-Criteria	Rationale from local expert`s workshop
Technical	Solar Radiation	From the monthly average solar radiation dataset (ARCONEL, 2008) the average annual global solar radiation was calculated. The higher the solar radiation the higher the PV production; thus all suitable land with the highest solar radiation were classified with the highest level of suitability for PV, and vice-versa.

Criteria	Sub-Criteria	Rationale from local expert`s workshop
Economic	Slope	The lower the terrain slope (MEER, 2013) the higher the PV electricity production. Thus, all suitable land with the lowest terrain slope were classified with the highest level of suitability for PV, and vice versa.
	Distance to roads	From the dataset national roads network (MTOP, 2015) the Euclidean distance to main roads was calculated. The closer a PV plant is to the main roads the lower the installation and operation cost. Thus, all suitable lands with the closest distance to main roads were classified with the highest level of suitability for PV, and vice versa.
	Distance to electric network	From the dataset electric transmission network (ARCONEL, 2017) the Euclidean distance to electric networks was calculated. The closer a PV plant is to the electric network the lower the installation cost and operation cost. Thus, all suitable lands with the closest distance to the electric network were classified with the highest level of suitability for PV, and vice versa.
Ecological	Land Use	From the official land uses dataset (MAE, 2017) a classification of land suitability for PV was defined as follows: i) Agriculture and productive land are the worst suitable (1), ii) native forest, forest plantation, and paramo are moderate suitable (2), iii) shrub and herbaceous vegetation are high suitable (3), and iv) barren land is the best suitable (4).
	Distance to inhabited areas	From the dataset urban areas (IGM, 2013c) and rural villages (IGM, 2013b) the Euclidean distance to inhabited areas was calculated. The further away a PV is from inhabited areas the lower the visual impact. Thus, all suitable lands that have the highest distance of inhabited areas were classified with the highest level of suitability for PV, and vice versa.

ii) Exclusion stage

All restrictions datasets (Table 3.2) were converted to raster layers using a 200 m resolution so as to be consistent with the other raster datasets. Then, these raster layers were reclassified using a Boolean logic scale as follows: Zero (0) to represent no-suitable land for PV and one (1) to denote suitable land for PV. All reclassified restrictions layers were multiplied together (raster calculator) resulting on a land suitable raster map for development of complementary PV in Ecuador; also, the resulting raster layer was converted into a vector layer (polygons). A final exclusion of land areas was applied. To avoid small-scale PV power plants, a minimum PV capacity was set at 20MW which occupies in Ecuador approximately $0.46km^2$ (Figure 3.7). Thus, all resulting polygons with an area less than $0.46km^2$ (12 raster cells) were eliminated. Moreover, to avoid too isolated and scattered PV power plants all polygons that were more than 15km further away from main roads were also eliminated.

iii) Criteria weighting

The four local experts during the workshop applied a pair-wise comparison among sub-criteria (n) under the same criteria (e.g. solar radiation, terrain slope). The value of pairwise comparison (a_{ij}) between sub-criteria a_i and a_j were displayed using a reciprocal matrix (n x n) as follows (Sánchez-Lozano et al., 2013):

$$A = \begin{Bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,n} \\ 1/a_{1,2} & a_{2,1} & \cdots & a_{2,n} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1,n} & 1/a_{2,n} & \cdots & a_{n,n} \end{Bmatrix}$$

The values of pairwise comparison were assigned according to the Saaty scale (Table 3.4). The reciprocal values were applied (1/aij) when the relative importance of criteria a_j was more important than a_i (see Table 8.6, 8.7 and 8.8 in Appendix 4).

Table 3.4 Numerical ratings for weighting (Saaty, 1989)

Verbal judgments of preferences between criteria i and j	Numerical ratings of judgments
a_i is equally important to a_j	1
ai is slightly more important than aj	3
ai is strongly more important than aj	5
ai is very strongly more important than aj	7
ai is extremely important than aj	9
Intermediate value	2, 4, 6, 8

Then, a normalized pairwise comparison matrix was calculated where each normalized matrix element (N_{ij}) resulted by dividing each value judgment from the comparison matrix A_{ij} to the sum of the corresponding column (Uyan, 2013). The sub-criteria weight was calculated by averaging the normalized values of the corresponding row in the normalized matrix (N_{ij}) (see Table 8.6, 8.7 and 8.8 in Appendix 4)

The pairwise comparison was verified for their Consistency Ratio (CR) using Eq.1, where CI is the Consistency Index calculated with Eq.2, λmax is the maximum Eigenvalue of the pair-wise comparison matrix A_{ij}. RI is the random consistency value determined by the number of criteria (n) according to Table 3.5. If the resulting CR≤0.10 the group judgment is consistent; otherwise, the pairwise comparisons are reviewed to avoid inconsistencies (Saaty, 1989).

$$CR = \frac{CI}{RI} \qquad \text{Eq.1}$$

$$CI = \frac{\lambda_{max} - n}{n} \qquad \text{Eq.2}$$

Table 3.5 Random Consistency Indexes (Arán Carrión et al., 2008)

Number of criteria	3	4	5	6	7	8	9	10
RI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Once the weights for each sub-criteria were found to be consistent, the same process was carried out for the three criteria, i.e. technical, economic, environment (see Table 8.9 in Appendix 4).

The resulting weights for each sub-criteria and criteria to evaluate land suitability for PV are shown in Table 3.6. The consistency ratio (CR) calculated to check consistency on the pairwise comparison of criteria and sub-criteria were 3% and 0% respectively; which are within the 10% threshold. Thus, the pairwise comparisons completed by local experts were valid and calculated weights will produce valid results.

Table 3.6 Weights and consistency ratio of selected criteria and category

Criteria	Weight	CR	Sub-criteria	Weight	CR
Technical	0.633	0.03	Solar Radiation	0.900	0
			Slope	0.100	
Economical	0.260		Distance to roads	0.857	0
			Distance to the electric network	0.143	
Ecological	0.106		Land Use	0.889	0
			Distance to inhabited areas	0.111	

iv) Weighted criteria aggregation

All sub-criteria datasets (Table 3.3) were converted to raster layers using a 200 m resolution so as to be consistent with the other raster datasets. Then all sub-criteria were normalized to a linear scale within the range 0-1; where 1 represents the best suitable location, and 0 the worst suitable location. The sub-criteria distance to roads, distance to electric networks and slope have to be minimized (e.g. the closest a PV location to the main road the more suitable) consequently the Eq.3 was applied (Malczewski & Rinner, 2015). For the other criteria which have to be maximized the Eq.4 was applied.

$$n(c_{ik}) = \left(\frac{c_{ik} - max_i\{c_{ik}\}}{min_i\{c_{ik}\} - max_i\{c_{ik}\}}\right) \quad \text{Eq.3}$$

$$n(c_{ik}) = \left(\frac{max_i\{c_{ik}\} - c_{ik}}{max_i\{c_{ik}\} - min_i\{c_{ik}\}}\right) \quad \text{Eq.4}$$

where, $n(c_{ik})$ is its normalized value of the k-th criteria (k=1,2,…,n) for the location i-th (i=1,2,…,n). $max_i\{c_{ik}\}$ and $max_i\{c_{ik}\}$ are the maximum and minimum values respectively of the criteria k-th for the whole study area.

Then, the land suitability score to deploy PV was calculated through a weighted overlay of criteria using Eq.5, 6, 7 and 8

$$SS_i = TS_i * W_{TS} + ES_i * W_{ES} + VS_i * W_{VS} \quad \text{Eq.5}$$

$$TS_i = SR_i * W_{SR} + SL_i * W_{SL} \quad \text{Eq.6}$$

$$ES_i = DR_i * W_{DR} + DL_i * W_{DL} \quad \text{Eq.7}$$

$$VS_i = DI_i * W_{DI} + LU_i * W_{LU} \quad \text{Eq.8}$$

where SS_i is the land suitability score for the location i-th. TS_i is the technical suitability criteria, ESi the economic suitability criteria and VSi the ecological suitability criteria for the location i-th. WTS, WES, and WVS are the weights for the technical, economic and ecological criteria respectively calculated in 3.3.3. SR_i and SL_i are the sub-criteria solar radiation and slope, and W_{SR} and W_{SL} are their corresponding weights. DR_i and DL_i are the sub-criteria distance to roads and distance to an electric network respectively, and W_{DR} and W_{DL} are their corresponding weights. DI_i and LU_i are the sub-criteria distance to inhabited areas and land use respectively, and W_{DI} and W_{LU} are their corresponding weights.

The resulting SS map was categorized in six intervals using a standard deviation classification: i) worst, ii) low, iii) moderate, iv) good, v) high and vi) best suitable land for PV. The higher the SS the better the location for PV. Then, to focus the future effort on developing complementary PV, only the “best suitable” land were considered for the next research phase, explained in the following section.

3.2.2 Energy system analysis.

An energy system analysis was applied in order to study the impact of complementary PV integration in the expansion of the Ecuadorian power system to cover projected electricity demand in Ecuador until 2030. The commercial dispatch model *Stochastic Dual Dynamic Programming* (SDDP) was selected (PSR, 2017a) to model and compare the long-term operation of the power system considering an expansion plan with a high share of PV against a traditional expansion plan based mainly on thermoelectric and hydropower (MEER, 2016). Based on the comparison of simulated results of performance indicators (i.e. operation cost, average marginal cost, fossil fuel consumption, and greenhouse gas emission) the impacts of PV integration in the expansion of the Ecuadorian power system was evaluated. Following are presented the different steps to build and modeling the scenarios in SDDP.

i) Electricity demand projections

Electricity demand is the constraints that SDDP relies in order to optimize power system operation and expansion. Capacity additions of hydropower, thermoelectric or PV power plants in expansion plans must ensure a complete coverage of electricity demand. Figure 3.3 shows the current and projected electricity demand (2018-2030). This is the official electricity demand projection that must be covered in expansion plans with the lowest cost and environmental impact.

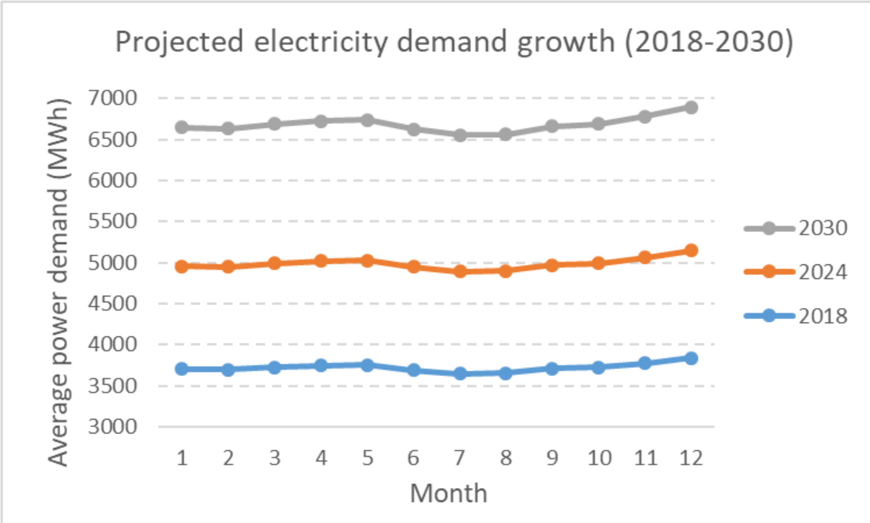


Figure 3.3 Present and projected average monthly electricity demand

To input the electricity demand in SDDP, it has to be characterized by electricity demand blocks (Figure 3.4) as follows: i) High electricity demand block: occurs between 18h00-22h00 mainly associated with residential consumers, ii) Low electricity demand block: occurs between 24h00-07h00, iii) Medium electricity demand block: occurs the rest of the day, associated with commercial and industrial consumers (MEER, 2016).

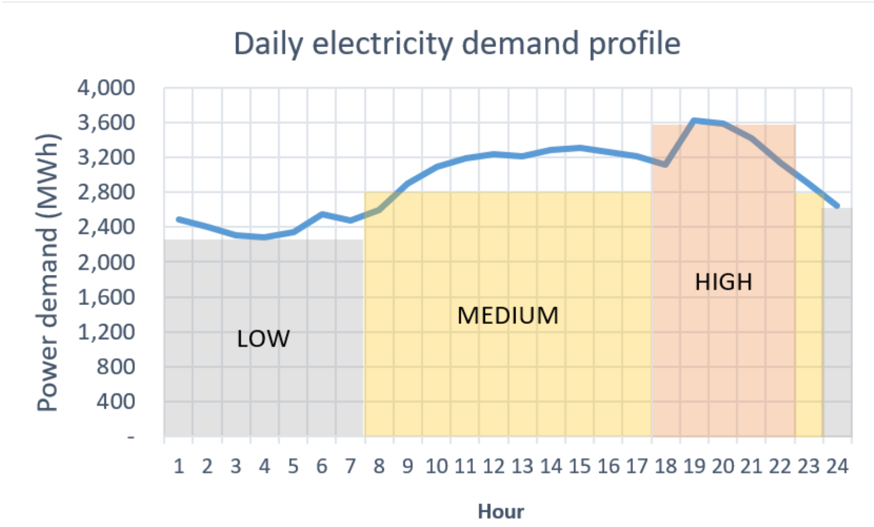


Figure 3.4 Blocks of electricity demand input in SDDP

ii) Expansion plan scenarios of the power system

Two scenarios of the power system expansion were developed to cover the above-mentioned electricity demand growth considering the following principles:

i. *Baseline scenario:* It comprises capacity additions of hydropower and thermoelectric power plants to cover electricity demand growth between 2018-

2030. Hydropower capacity additions are determined by the projects under construction (956MW) and expected to be finished by 2023 (MEER, 2016). The remaining capacity additions are completed with thermoelectric power plants.

ii. *Alternative scenario:* It comprises capacity additions of hydropower and PV power plants to cover electricity demand growth between 2018-2030. It considers the same capacity additions of hydropower of the baseline scenario. However, the remaining expansion of generation is completed only with PV capacity additions. In this scenario, the expansion of thermoelectric is restricted. PV capacity additions were reduced or increased accordingly until the simulations for both the baseline and alternative scenario reached the same levels of electricity demand coverage.

iii) Power system modeling

The SDDP was used for power system modeling since it has been used extensively to find the optimal and low-cost expansion plan of power system with high share of hydropower in Ecuador and other countries in Latin America (de Faria & Jaramillo, 2017; De Queiroz, 2016; Gorenstein, et. al., 1991). In a power system with a high share of hydropower, the generation scheduling is more complex than a power system based mainly on thermoelectric power plants (de Faria & Jaramillo, 2017). For the latter, the decision to some extent is easy because the thermoelectric plant with the lowest fuel cost must be dispatched first to cover future electricity demand. However, for a power system with a high share of hydropower this decision is complex since it depends on water inflows which are a natural random process difficult to forecast but determinant for the operational cost of the power system (De Queiroz, 2016; Gorenstein et al., 1991). The operator must decide under a certain level of uncertainty to save or use water for electricity production in order to keep the overall operating system cost low. If the high use of hydropower is decided and future inflows are high the minimum operational cost of the system is reached. However, if there is a future drought, expensive thermoelectricity must be scheduling increasing the operational cost of the system or even rationing electricity. Similarly, if the operator decides to be excessively conservative by dispatching more thermoelectric plants in order to keep reservoirs at the highest level, and high inflow occurs, the reservoirs will spill resulting on a waste of energy. Likewise, if a low inflow occurs, the reservoirs will avoid the operation of expensive thermoelectric plants, reaching the minimum operational cost of the system. In real life, this stochastic dispatch problem comprises several hydropower plants and multiple years resulting in an exponential increase of scheduling decisions to be solved and the stochastic optimization problem quickly becomes computationally unachievable (Pereira & Pinto, 1991). In this regards, SDDP has proved to be a reliable model to overcome the above mentioned stochastic optimization and determine the optimal dispatch of a large number of hydropower plants for long-term planning horizons (de Faria & Jaramillo, 2017; Gorenstein et al., 1991; Pereira & Pinto, 1991). In fact, SDDP had become the official model to study generation expansion plans in Ecuador (MEER, 2016) and other countries of Latin-American (Batlle, 2014).

The SDDP facilitates to model expansion plans of power system taking into account the hydropower programming problem by computing the least-cost stochastic operating schedule of power generation considering load variation, operational details of hydropower plants (water inflows, storage limits, spillage), thermoelectric plants (generation and fuel constraints, efficiency curves) and transmission networks (power flow limit, security constraints, exports/imports limits), stochastic inflow models to address hydrological uncertainty (seasonality, spatial-temporal dependence, climate phenomena, ENSO) and the variability of non-hydro renewable resources like PV (PSR, 2017b). The basic idea behind SDDP algorithm is to minimize the immediate cost (ICF) and the future cost (FCF) of the power system operation subject to the operating constraints through the study horizon (Figure 3.5). If more hydroelectricity is used today (stage t) the ICF decreases but also FCF increases because more water is used by turbines and less water is stored in reservoirs to supply the future demand, leading to the use of more expensive thermoelectric power generation in the future. The FCF reveals the expected thermoelectric power generation cost from stage t+1 to the end of the study horizon (de Faria & Jaramillo, 2017). More information on the SDDP algorithm is given in PSR (2017a)

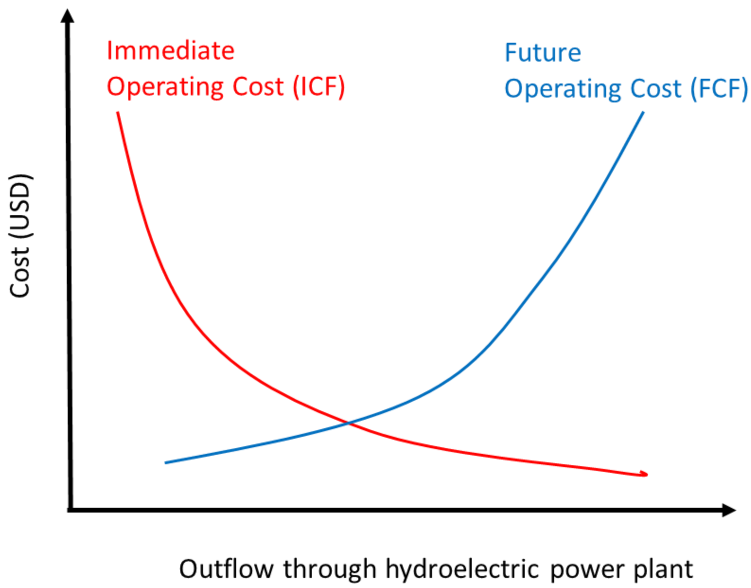


Figure 3.5 Immediate and future cost functions versus outflow through hydroelectric power plants used in SDDP (de Faria & Jaramillo, 2017; PSR, 2017c)

The SDDP model was populated with the database from MEER (2016) to model the baseline scenario of the power system expansion, which included current and future electricity demand until 2030, historical water flow rates of hydropower plants, installed capacity and operational cost of existing and future hydropower and thermoelectric power plants (Appendix 2). For the alternative scenario, the database of the baseline scenario was modified to include PV power plants characteristics (i.e. installed capacity, and time series of electricity productions) derived from this study and explained in next sections.

iv) Calculating PV capacities and generation profiles

To simulate the alternative scenario of the power system expansion in SDDP the installed capacity and time series of hourly electricity production of one year for candidates PV power plants are needed therefore synthetic time series of PV production were calculated. Calculating synthetic time series of hourly electricity production for each PV location (millions of cell raster) in all suitable land area is impractical and demand huge computational efforts in SDDP and GIS. Thus, the adopted approach was to define a time series of hourly electricity production at a PV site that is representative of all suitable land within a zone of influence. The logic behind this is that if two PV systems are located close each other their electricity production will have an almost perfect positive correlation or almost the same generation profiles than if two PV systems are located far away (Perez & Hoff, 2013). Mills and Wiser (2010) suggest that there is a positive correlation of PV electricity production with time-scales of 1 hour if the distance between PV plants is closer than about 75km; however Hoff and Perez (2012) suggest that a moderate correlation (0.5) is observed in a distance < 25km. Under this principle, the study area was divided into zones of influence demarcated by Thiessen polygons created from a set of 17 selected sites of existing and hypothetical PV power plants (Figure 3.6). These zones of influence clustered all suitable areas defined in 3.2.1 ensuring they are closer than 25km of a PV site from which the time series of electricity production is known. In this way, each zone of influence defined a candidate PV power plant for SDDP simulations, whose installation capacity was a function of the available suitable land area within the zone, and its generation profile resembles the time series of electricity production of the known PV site within the zone.

The synthetic time series of hourly electricity production for one year for each PV power plant or zone of influence were derived as follows: i) for zones of influence defined by existing PV power plants (Figure 3.6, red triangle), time series were calculated by averaging the historical hourly electricity production between 01.2015 to 12.2017 (MEER, 2016), and ii) for zones of influence with a hypothetical PV power plants (Figure 3.6, black square) because of the lack of real production data, synthetic time series were calculated using the algorithm proposed by Graham and Hollands (1990) implemented in the free software HOMER Legacy (HOMER, 2017). The inputs to run this algorithm were the PV site latitude and the 12 values of monthly average of solar radiation obtained from ARCONEL (2008). Once time series were defined, they were normalized (hourly electricity production/nominal PV power capacity) in order to bring all production values to a common scale [0-1] and obtain a typical generation profiles for each PV site or zone of influence.

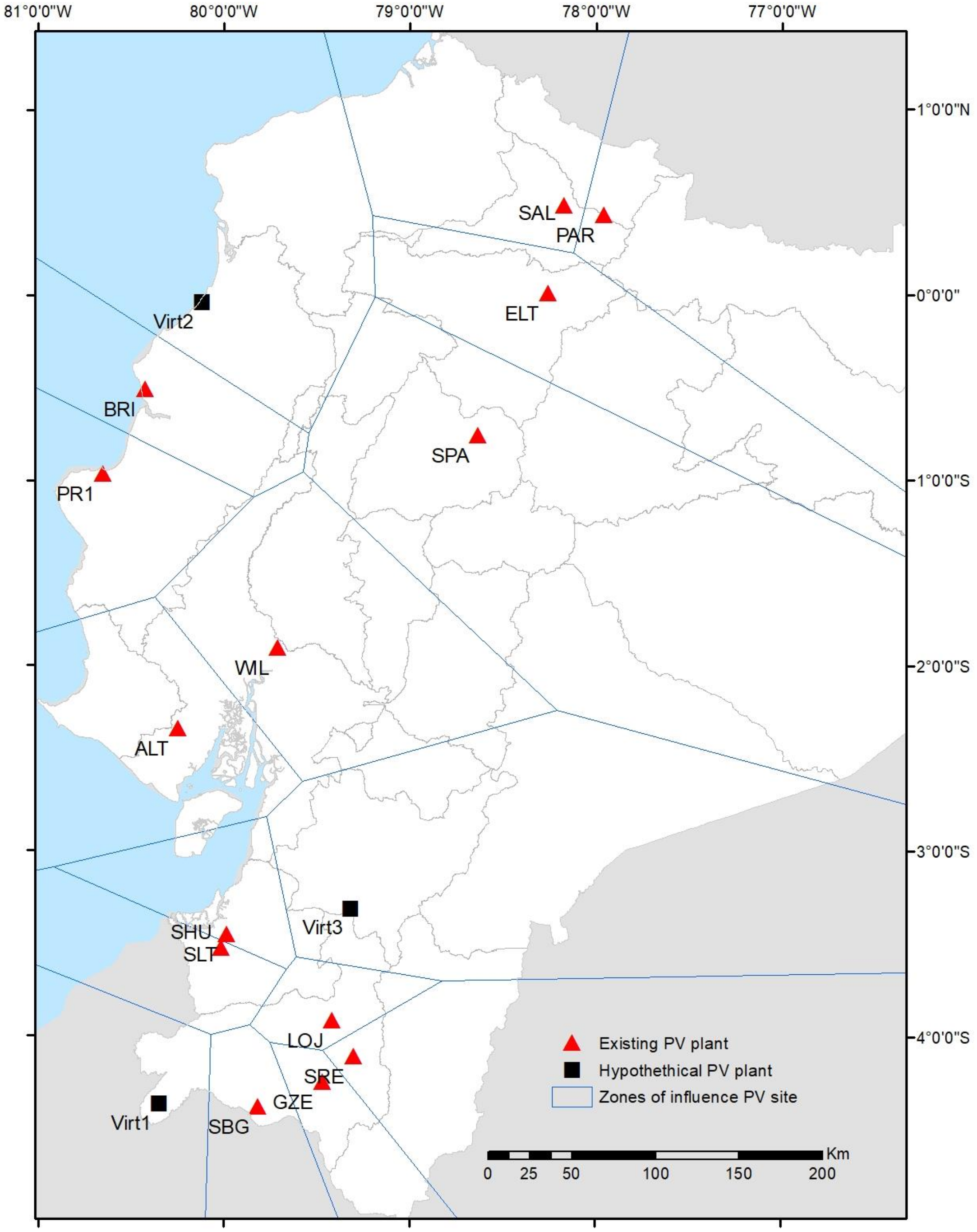


Figure 3.6 Zones of influence of selected PV sites to calculated installed capacity and time series of hourly electricity production

To input in SDDP the time series, they need to be converted into electricity power (MWh). Thus, each normalized time series was multiplied by the installed capacity of each zone of influence (IC_{PVi}) calculated with Eq.8 (Anwarzai & Nagasaka, 2016)

$$IC_{PVi} = SA_i * AF_i * AL_i \quad \text{Eq.8}$$

where SA_i is the available suitable land area (km^2), AF_i is a reduction factor (70%) that accounts for constraints (roads, substation, lack slope, and aspect) that limits to cover all suitable land area with PV. AL_i is the average size of PV plants in Ecuador (i.e. 0.64 MW/km^2 within a terrain slope < 30%) estimated from the size of 23 existing PV plants (Figure 3.7).

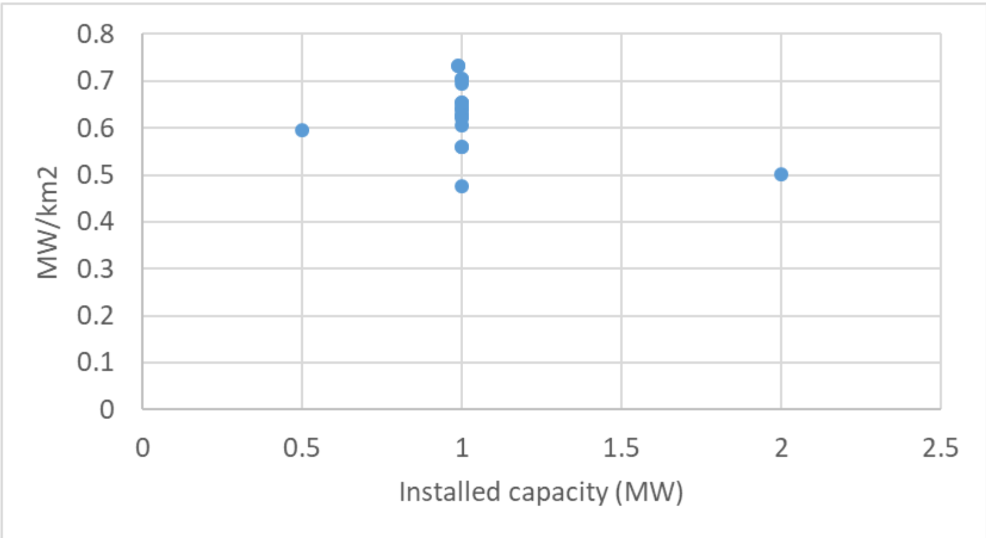


Figure 3.7 Average size of PV plants in Ecuador (MEER, 2016)

v) Performance indicators

The SDDP simulations of the baseline and the alternative expansion scenarios were compared to assess from an economic and environmental viewpoint the impact of integrating a high share of PV in the power system of Ecuador using the following performance indicators: operational cost, average marginal cost, fossil fuel consumption, and GHG emissions.

Operational costs and marginal cost are SDDP outputs at power system level and rely on the input of operational costs of individual power plants defined in the database (Appendix 2). Operational cost for thermoelectric power plants varies from 41.5 to 428 USD/MWh, while for hydropower and PV power was constant at a value of 2 USD/MWh as they do not rely on commodity fuels. On the other hand, the marginal cost in SDDP is the calculated as the variation of the operational cost of the power system with respect to an infinitesimal increase in the electricity demand (PSR, 2017b).

Fossil fuel consumption for each thermoelectric power plant is an output of SDDP calculated from the specific fuel consumption (Liters/kWh) defined in the database (Appendix 2). GHG emissions are a relevant metric to observe Ecuador's commitment to tackling climate change at international agendas. For each technology lifecycle GHG emissions were calculated multiplying the energy produced by the median lifecycle GHG emission reported by the IPCC (Edenhofer, et. al, 2012): thermoelectric (diesel/fuel-oil) 840 gCO_2/kWh, hydropower 4 gCO_2/kWh, PV 46 gCO_2/kWh, wind 12 gCO_2/kWh and bioenergy 18 gCO_2/kWh

4 RESULTS

4.1 Complementary PV potential in Ecuador

4.1.1 Suitable land area for PV.

The total suitable land area for PV in Ecuador was 23819.76 km2, equivalent to 9.3% of the national territory (Figure 4.1). Appendix 3 shows the maps of each selected land restrictions for PV that were chosen and combined in order to calculate the suitable land area for PV. Results showed that most of the suitable land for PV was located on the western side of the country towards the coastline. There were also suitable land areas for PV in the central part of the country along the Andean mountains and towards the borders with Colombia and Peru. Though, this results provide a first insight on where the most suitable land for PV is located, a prioritization of these land areas is required to identify the best location for PV that can compensate the seasonality of hydropower.

4.1.2 Land suitability levels and best locations for PV

Figure 4.2 shows the map that depicts the land suitability level to deploy complementary PV in Ecuador; which was obtained from the aggregation of the resulting technical, economic and ecological land suitability maps (Appendix 5, Figures 8.6, 8.8 and 8.10) and their corresponding sub-criteria maps (Appendix 5, Figures 8.5, 8.7 and 8.9). The resulting map shows a minimum and maximum land suitability values for PV of 0.11 and 0.97 respectively, and an average land suitability value of 0.47. To aid in the selection of the topmost locations to deploy PV, the resulting map was categorized into 6 classes applying a standard deviation classification. The "best suitable" land for PV covered 3.4% (805km2) of the total suitable area in 11 provinces, 6 in the Andean region (Imbabura, Pichincha, Cotopaxi, Chimborazo, Loja) and 5 in the Coastal region (Manabí, Guayas, Santa Elena, Los Rios, and El Oro). Only the best suitable areas were considered to evaluate the installed capacity potential of complementary PV in Ecuador.

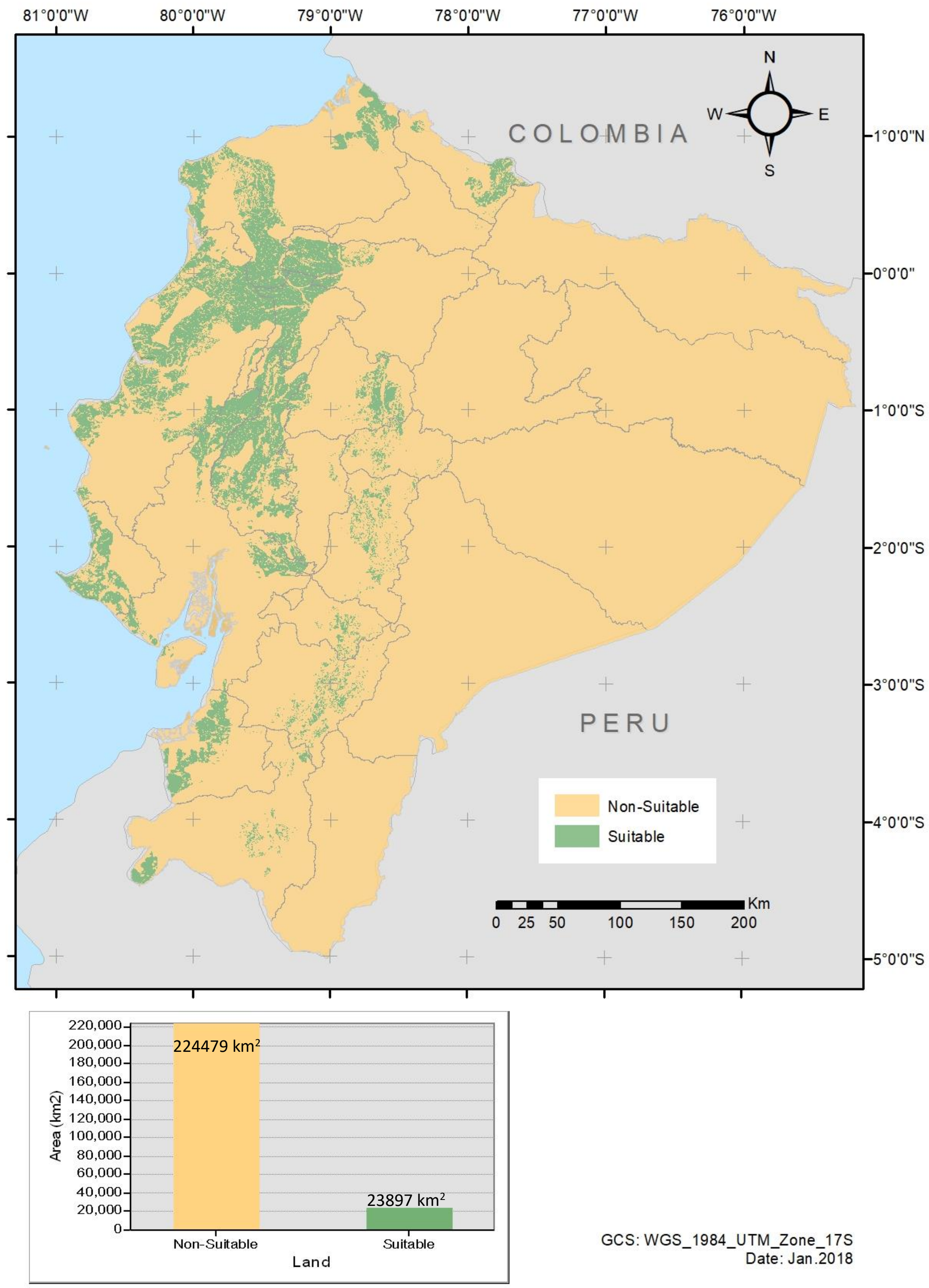


Figure 4.1 Suitable land areas for PV deployment in Ecuador

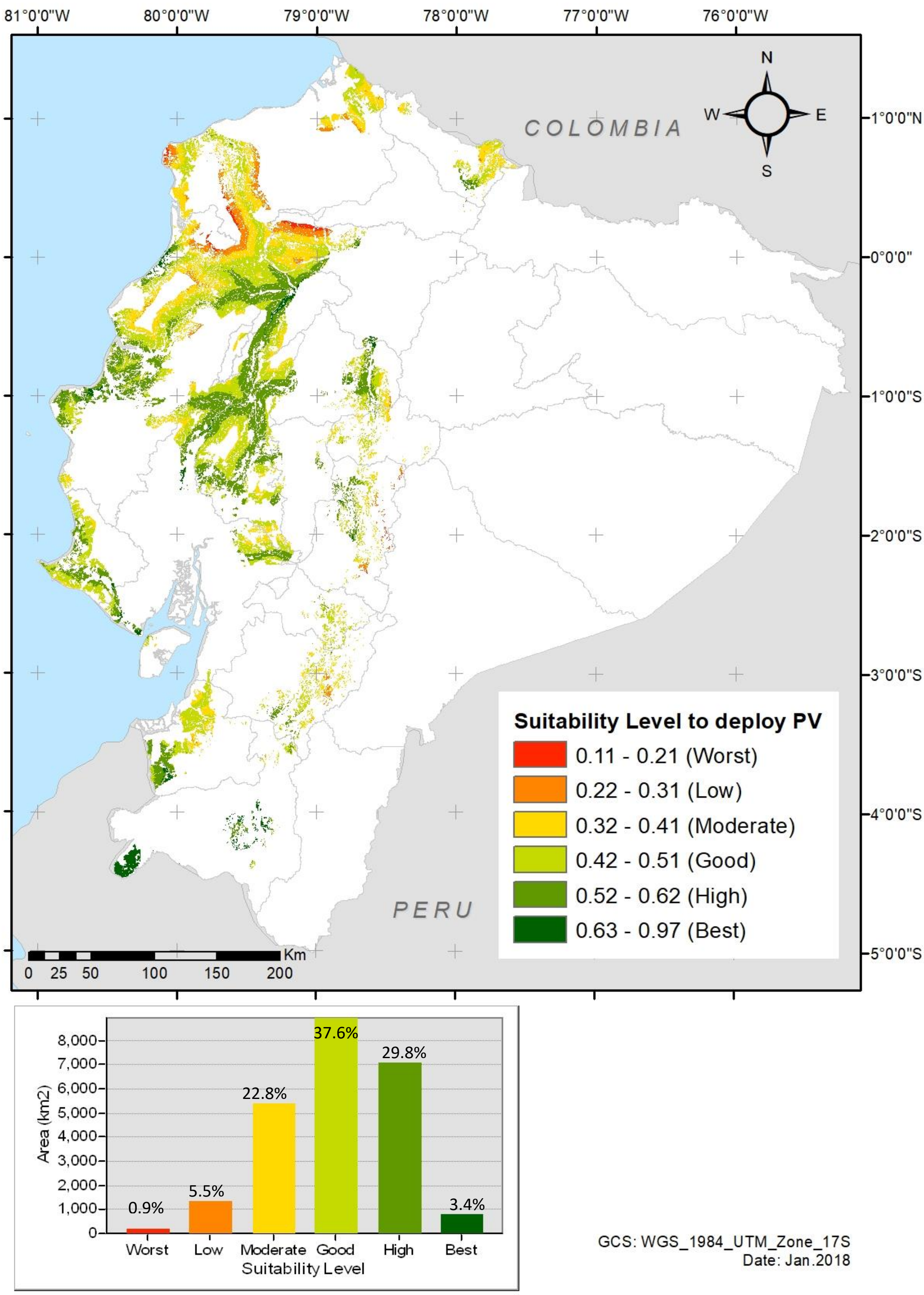


Figure 4.2 Land suitability level to deploy PV in Ecuador.

4.1.3 PV installation capacity and energy potential

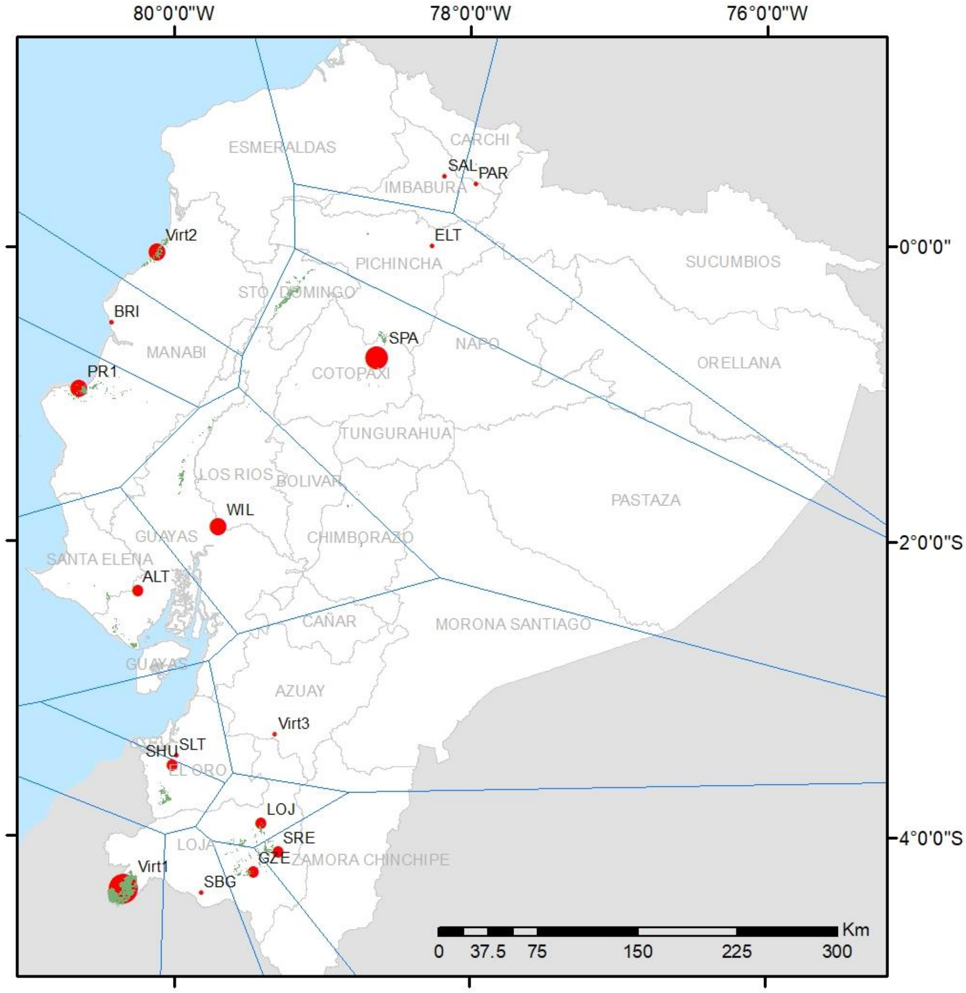
Figure 4.3 shows the installation capacity of complementary PV in the best suitable areas distributed in 17 zones of influence. If the entire extent of the best suitable land areas is covered with PV power plants, the installation capacity reached 35.7 GWp which is 4.3 times the Ecuadorian power system capacity (8.2 GW). The expected annual electricity production of this potential (64,862 GWh/year) was 2.6 times the total present electricity demand (23,500 GWh/year). The PV expected energy production for each zone was calculated summing up the product of the installation capacity by the corresponding synthetic time series of electricity production shown in Appendix 2 (Figure 8.3). Almost half of the complementary PV potential (48.2%) was located in one province, i.e. Loja.

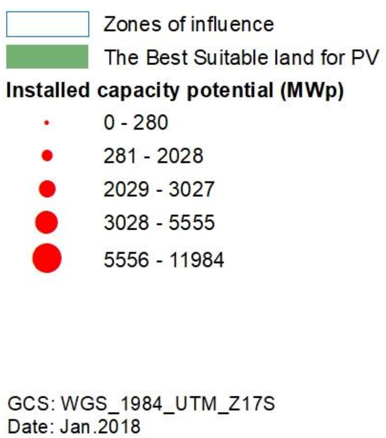
4.2 Impacts of photovoltaic in the expansion of the Ecuadorian power system

4.2.1 Electricity generation scheduling and projections

Table 4.1 shows the present installed capacity, annual capacity additions, and final installed capacity by technology for the proposed baseline and the alternative expansion scenarios of the Ecuadorian power system to ensure the coverage of the projected electricity demand until 2030.

In the baseline scenario, a capacity addition of 1800MW of thermoelectric needs to be added. In the alternative scenario, a capacity addition of 3900 MWp of PV needs to be added (i.e. 10.93% of the total PV installed capacity potential). In both scenarios, a capacity addition of 956MW of hydropower needs to be added, which correspond to hydropower plants under construction nowdays.





Zone of Influence	Best suitable land area (km2)	Installed capacity potential (MW)	Expected electricity production (GWh/year)	% Potential
ALT	39.78	1785	1857	5.0%
BRI	0.95	43	27	0.1%
ELT	3.01	135	212	0.4%
GZE	45.20	2028	3321	5.7%
LOJ	35.82	1607	3281	4.5%
PAR	6.24	280	408	0.8%
PR1	67.47	3027	3929	8.5%
SAL	-	-	-	-
SBG	0.19	9	13	0.0%
SHU	45.20	2028	2434	5.7%
SLT	-	-	-	-
SPA	123.81	5555	8280	15.6%
SRE	35.27	1583	2315	4.4%
Virtual 1	267.09	11984	28372	33.6%
Virtual 2	63.12	2832	6706	7.9%
Virtual 3	2.96	133	315	0.4%
WIL	59.01	2648	3392	7.4%
Total	**795.13**	**35,678**	**64,862**	**100%**

Figure 4.3 Installed capacity potential of complementary PV in best suitable areas of Ecuador.

Table 4.1 Proposed generation expansion plans to cover projected demand

	Capacity additions baseline scenario (MW)			Capacity additions alternative scenario (MW)			
	Hydro	Thermal	Existing Non-hydro Renewable	Hydro	Thermal	Existing Non-hydro renewable energy	PV
Total capacity 2017	4061	1940	179	4061	1940	179	-
Annual additions							
2018	574	0	0	574	0	0	0
2019	253	0	0	253	0	0	0
2020	0	0	0	0	0	0	0
2021	0	0	0	0	0	0	0
2022	0	0	0	0	0	0	0
2023	129	0	0	129	0	0	0
2024	0	300	0	0	0	0	900
2025	0	0	0	0	0	0	0
2026	0	400	0	0	0	0	1200
2027	0	0	0	0	0	0	0
2028	0	1100	0	0	0	0	1200
2029	0	0	0	0	0	0	600
2030	0	0	0	0	0	0	0
Total capacity 2030	5017	3740	179	5017	1940	179	3900

Figure 4.4 depicts the optimal dispatch of electricity generation by technology for the initial (2018) and final (2030) conditions of the baseline and alternative expansion scenario of the power system presented above. These are the least-cost stochastic operating schedule and expansion of the Ecuadorian power system that resulted from simulations of the whole operational period (2018-2030) using SDDP. Results show that the initial condition was the same in both scenarios since it represents the power system operation before any generation additions.

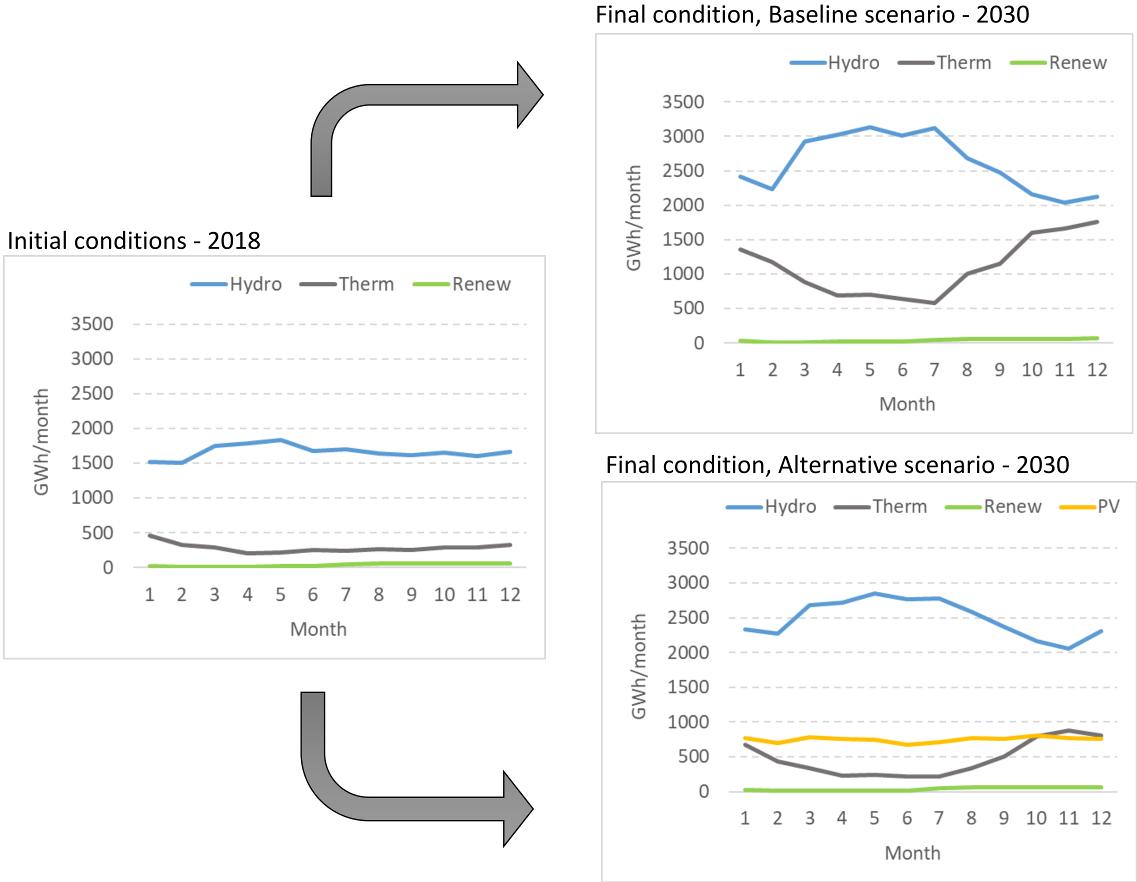


Figure 4.4 Optimal generation scheduling and expansion of the Ecuadorian power system for the baseline and alternative scenario.

Note: Hydro=hydropower generation, Therm=Thermoelectric power generation, Renew=existing renewable energy power generation (i.e. wind, biomass, PV), PV=Photovoltaic power generation

In the initial condition of the power system in both scenarios, hydropower was the main source of electricity generation (84%) complemented with a minor share (14%) of thermoelectric power, and a small share (2%) of non-hydro existing renewable energy (i.e. wind, PV, biomass). In the final condition (2030) of the power system expansion in both scenarios, an increment of hydropower generation was observed during the wet season (March-October) due to the abundance of rainfall in the Amazon region. Thus, as soon as the electricity demand growths, the share of hydropower generation will increase reducing the existing waste of generation (water spillage) during the wet season representing economic losses at present days.

In the final condition (2030) of the baseline scenario, the average share of hydropower (70%) had a small reduction compared with the initial condition (84%). However, thermoelectric power share (29%) increased approximately two times the share of the initial conditions (14%). Also, it was observed that thermoelectric power in the driest month, i.e. December, was 5.3 times the share of the initial conditions. Thus, a massive installed capacity of thermoelectric power (3.8GW) is needed to cover electricity demand during the dry season (October-March) while during the wet season (March-October) this capacity will be in standby mode due to the high availability of hydropower generation.

On the other hand, in the final condition of the power system in the alternative scenario, again the average share of hydropower (66%) had a slight reduction compared with the share in the initial condition (84%); however, this reduction was greater than the baseline scenario. It was also observed a considerable reduction of the share of thermoelectric power (13%) compared with the baseline scenario (29%) due to the high penetration of PV. All in all, in the alternative scenario a high share (87%) of renewable energy (i.e. hydropower, photovoltaic, wind, and biomass) was achieved. Thus, it is possible to cover electricity demand growth until 2030 with a high share of renewable energy by developing a small percentage (10.9%) of the identified PV installation capacity potential; which, will represent approximately 35% of the total installed capacity of the power system by 2030.

From simulation results of both scenarios the performance indicators described in 3.2.2 were calculated and compared to evaluate the impact of adding a large share of complementary PV in the long-term operation and expansion of the power system of Ecuador. These results are presented in the next sections.

4.2.2 Average marginal and operational cost

Figure 4.5 depicts the average marginal cost for the baseline and alternative scenario for the whole simulation period (2018-2030). The average marginal cost in both scenarios had a growth trend. However, in the alternative scenario, the marginal cost was on average 20% cheaper than the baseline scenario. Thus, an infinitesimal increase in the electricity demand in the alternative scenario will result in a small variation of the operational cost compared with the baseline scenario.

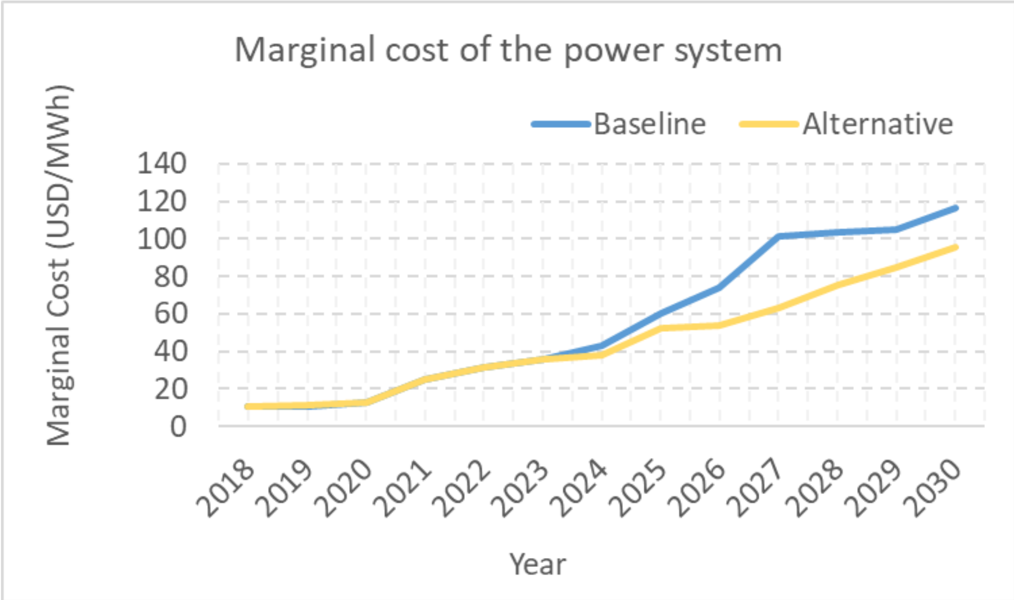


Figure 4.5 Marginal cost of the baseline and alternative scenario

Figure 4.6 depicts the resulting annual operational cost of the power system from the initial (2018) to the final (2030) conditions for both the baseline and alternative scenario. The annual operational cost at the final period was 1,407 and 703 USD millions for the baseline and alternative scenario respectively. Therefore, a high reduction (50%) of the annual operational cost of the long-term operation of the power system can be achieved with the integration of PV. Additionally, the average operational cost of thermoelectric power is approximately 8 times the operational cost of any other renewable energy (hydro, PV). Thus, any new addition of thermoelectric power will have a considerable impact on the long-term operational cost of the power system.

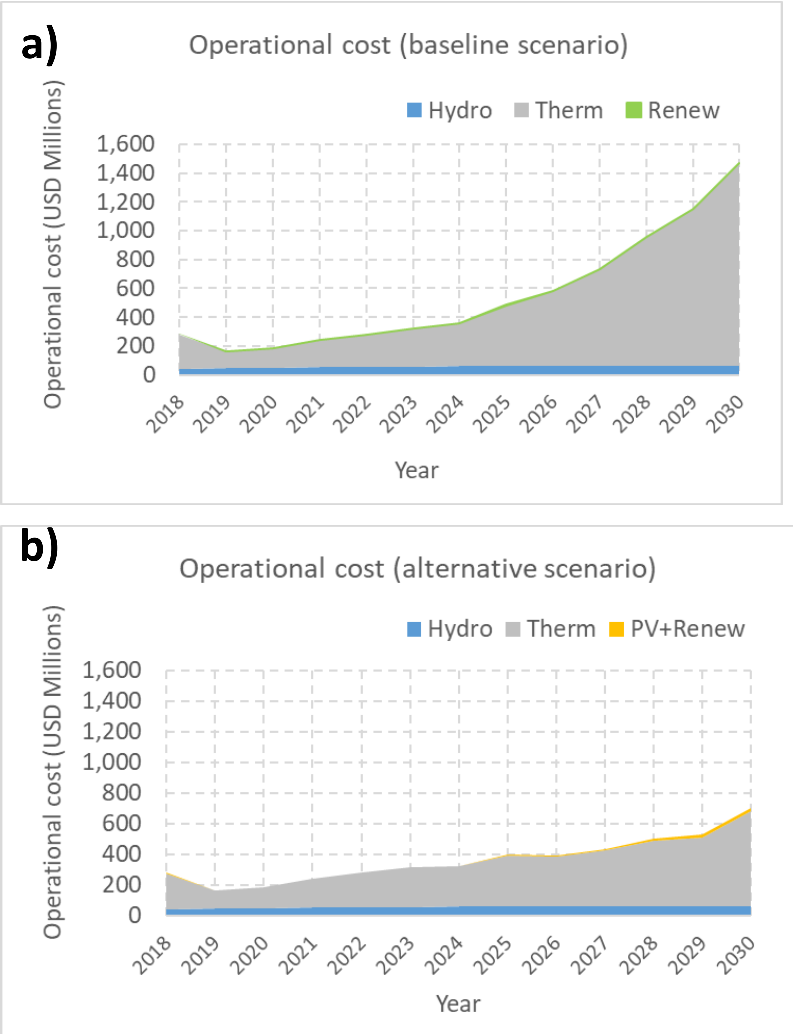


Figure 4.6 Operational cost a) baseline scenario, b) alternative scenario

4.2.3 Fossil fuel consumption

Figure 4.7 depicts fossil fuel consumption (i.e. natural gas, diesel, and fuel-oil) by thermoelectric power plants in the baseline and alternative scenario. At the end of the period (2030), there was a considerable reduction (69%) of the annual consumption of fuel oil in the alternative scenario (720,439 m^3) compared with the baseline scenario (2,327,598 m^3). However, diesel consumption had a considerable increment in the alternative scenario (84,997 m^3) compared with the baseline scenario (9,383 million m^3). The total consumption of natural gas was almost the same for both scenarios (Alternative scenario=490,815,090 m^3, Baseline scenario=505,624,781m^3) because this is a forced generation due to technical limitations of the power system. All in all, the overall consumption of fossil fuels was reduced by half in the alternenative scenario as a consequence of the integration of a high share of PV that displaced thermoelectric power to cover electricity demand growth, especially during the drought season when hydropower is low. The reduction of fossil fuel consumption has a positive economic advantage. The former relates with savings on fuel importation costs which are approximately 1200 USD millions at the end of the period (2030) considering a diesel, fuel-oil and natural gas price of 0.48 USD/Liter, 0.25USD/Liter, and 0.16 USD/m^3 respectively (MEER, 2016).

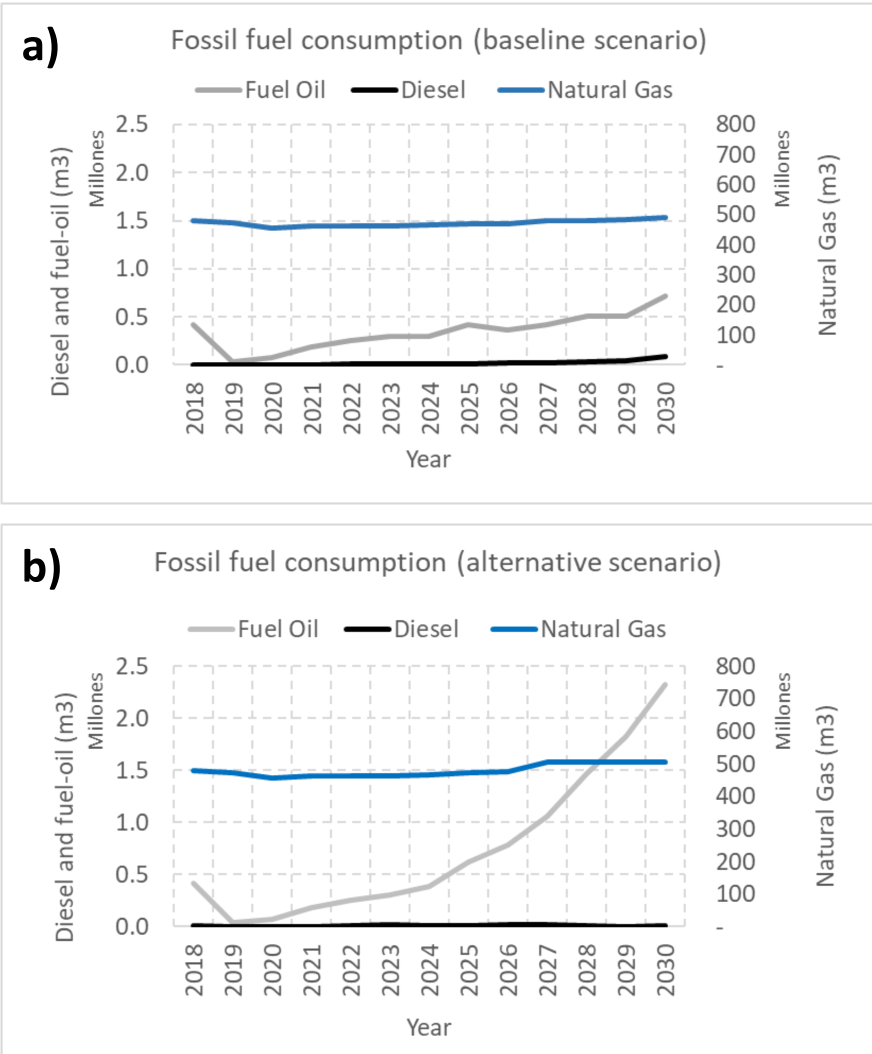


Figure 4.7 Fuel consumption a) baseline scenario, b) alternative scenario

4.2.4 Lifecycle greenhouse gas emissions

Figure 4.8 depicts the lifecycle GHG emission for each technology in both the baseline and alternative scenarios. The cumulative lifecycle GHG emissions were 63,144 and 42,599 GgCO_2eq for the baseline and alternative scenario respectively, which implies that a reduction of more than one quarter (33%) of the GHG lifecycle emission was achieved by integrating PV in the power system.

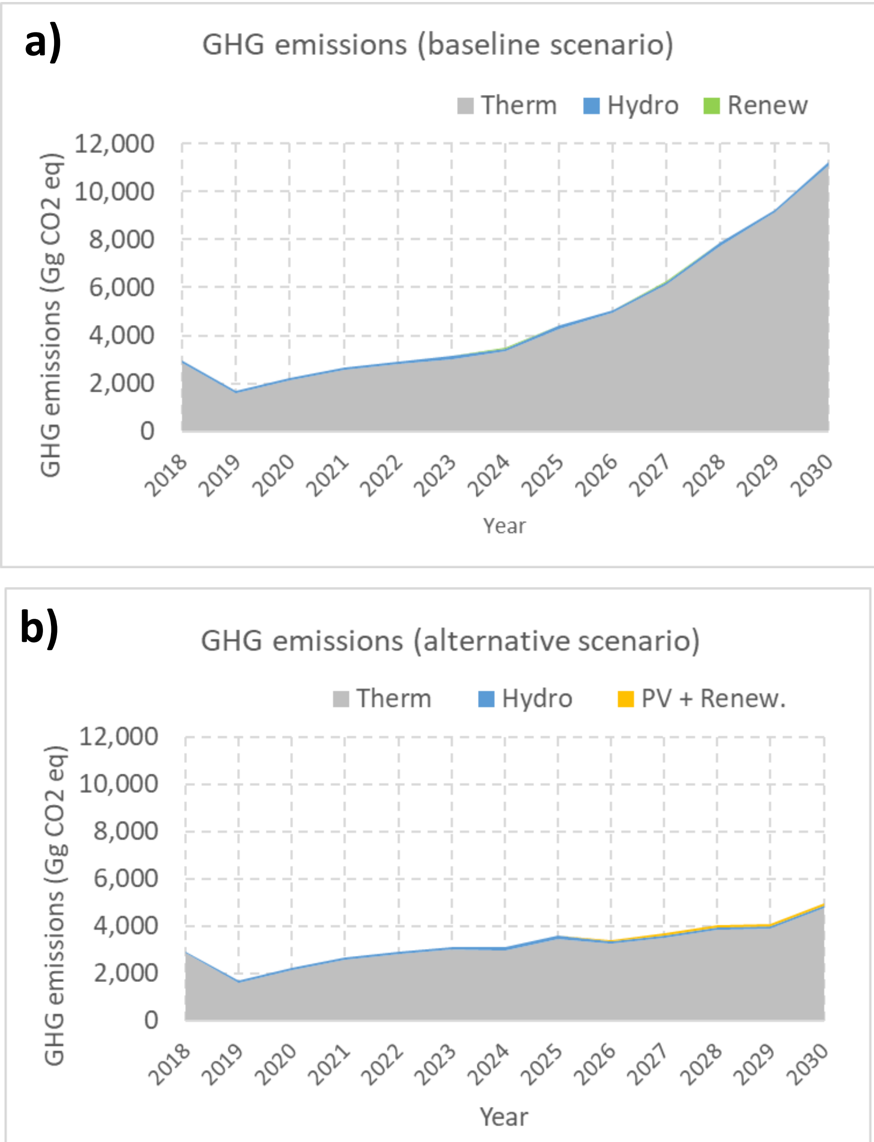


Figure 4.8 GHG emissions a) baseline scenario, b) alternative scenario

5 DISCUSSION

In order to answer research questions a discussion of the previous results follows:

Does an integrated, spatially and temporal explicit approach is capable of identifying and study the potential of complementary PV that could tackle the inter-annual variability of hydropower in Ecuador?

The framework of analysis presented in this thesis provides a participatory, spatially and temporal explicit approach for identifying the most suitable land areas for PV that has the highest ability to compensate the seasonality of hydropower, and to minimize the environmental impacts, investment and operational cost associated with large-scale PV. It fills the gap between GIS-based site suitability prospecting for PV and long-term power system expansion planning. Contributing, towards existing literature (see 2.1.1) with the novelty and added capacity to allow local experts' participation and perform an energy system analysis to evaluate long-term economic and environmental impacts of PV integration in power system expansion.

How much and where are located suitable land areas for PV in Ecuador considering land restrictions from local expert's viewpoint? And, how much and where are located the best suitable land areas for PV that can compensate seasonality of hydropower in Ecuador considering land suitability criteria from local expert´s viewpoint?

It is the first Ecuador-specific study to identify suitable land (Figure 4.1) and the best locations (Figure 4.2) for PV that can compensate hydropower seasonality using local expert's knowledge and a GIS-based multi-criteria model (i.e. AHP). Subsequently, research findings are not directly comparable to similar GIS-based models applied in other countries since they have their own specific criteria and model inputs (Arán Carrión et al., 2008; Charabi & Gastli, 2011; Sánchez-Lozano et al., 2013; Uyan, 2013; Watson & Hudson, 2015).

The study approach most similar to this thesis is presented by Watson & Hudson, (2015) who used local experts' knowledge to identify and evaluate suitable land for PV from a technical, economic and ecological viewpoint. However, they excluded the land restriction for PV called "complementary areas" (Table 3.2) which were used in this study to focus at locations where PV production is maximum during the dry season of hydropower. Thus, this thesis contributes towards GIS-based approaches for site suitability prospecting of complementary renewable energy areas (i.e. PV) at a regional scale, which is of special interest in South America countries (Paredes et al., 2017; Silva et al., 2016).

Looking at the selected criteria and weights provides an opportunity to understand the research problem from local experts' concerns and contrast with literature. Technical criteria (i.e. solar radiation, slope) are perceived as the most important criteria, meaning that maximizing electricity production is more important than maximizing the financial or economic performance of PV. A similar finding was obtained in alike studies (Arán Carrión et al., 2008; Charabi & Gastli, 2011; Sánchez-Lozano et al., 2013; Uyan, 2013; Watson & Hudson, 2015) focused in countries with liberalized electricity markets where economic performance is very important, which is opposite to Ecuador where power system expansion is on government hands and highly subsidized (Peláez-Samaniego et al., 2007; Ponce-Jara, Castro, et. al., 2018). Ecological criteria (i.e. land use, distance to inhabited areas) are perceived as the least important criteria because all natural and protected areas were excluded from the analysis (i.e. exclusion stage); thus, experts alleged that deploying PV plants in identified suitable land area will have a low environmental impact, a similar finding in reviewed studies (Sánchez-Lozano et al., 2013; Watson & Hudson, 2015). From a technical viewpoint higher solar radiation is most important than terrain slope. High slopes (steep terrain) could diminish electricity production; however, it can be amended with proper structures (Brewer et al., 2015). From an economic viewpoint distance to roads is perceived as the most important factor since their construction costs were considered much higher than the electric network; therefore, PV must be sited close to roads rather than electric networks, opposite than other studies (Uyan, 2013). From an ecological viewpoint land use is perceived as the most important factor to site a PV rather than being far away from inhabited areas to avoid visual impacts (Stoms et al., 2013). Thus, PV must avoid competition or disrupting existing land uses (e.g. agriculture) than producing a visual impact.

Above considerations provide the basis for an integrated assessment of land suitability for complementary PV in Ecuador. However, because of the time limit, this research was conducted only on a small size of local experts who have a long experience in energy planning but limiting experiences in PV. Thus, the study should have involved a larger group of experts and with experience on building large-scale PV power plants; the latter is not possible to perform with local experts because PV is still in an initial stage in Ecuador. Moreover, because of time and resources limitations for travel along the country this research did not include a field research to validate the suitability of land to deploy PV power plants. This thesis used the best available data from official sources; however, their uncertainty has not been evaluated, which should be studied in further research.

What are the installation capacity potential and expected energy production of complementary PV in Ecuador?

For the first time, this study presents a theoretical PV installation capacity potential in Ecuador, i.e. 35.7 GWp (Figure 4.3), which can produce 61,470 GWh/year equivalent to 2.6 times the total present electricity demand (23,500 GWh/year). This figure contributes to the knowledge gap of non-hydro renewable energy potential that has not been considered in official expansion plans of the Ecuador power system (MEER, 2016).

Most of similar GIS-based models of site suitability prospecting for PV (Arán Carrión et al., 2008; Charabi & Gastli, 2011; Sánchez-Lozano et al., 2013; Uyan, 2013; Watson & Hudson, 2015) provided figures of average or annual PV production but not hourly time series of PV production (Figure 8.3, Appendix 1); which are needed for modeling and planning the expansion of power system (PSR, 2017c). Other studies (Schmidt, et. al., 2016; Schmidt, et. al, 2016a) calculated time series of PV production for selected coordinates at a national scale using historical data from global and modeled datasets (i.e. atmospheric reanalysis). However, these studies do not confirm if the selected coordinates are within suitable land areas for PV. Thus, the proposed approach in this thesis contributed to the research of developing spatially explicit methods to approximate PV generation profiles in suitable lands using local and historical PV production. However, this approach has limitations on using available and short-term historical PV production of 2-3 years instead of at least 10 years (Schmidt, et. al., 2016a), averaging the calculated PV production times series to big zones of influence (Figure 3.6) and do not accounting the effects of cloud cover (Ineichen & Perez, 1999), atmosphere conditions (Louche, Peri, & Iqbal, 1986) and topography (Fu & Rich, 1999).

What are the economic and environmental impacts of complementary PV in the long-term operation of Ecuador´s power system?

This thesis confirmed that non-hydro renewable energy like PV can mitigate the seasonality of hydropower and avoiding the expansion and use of costly and polluting thermoelectric power especially during the dry season (see 4.2). This is a relevant finding and agrees with studies in other countries of South America with a high share of hydropower (Batlle, 2014; de Faria & Jaramillo, 2017; Paredes et al., 2017; Schmidt, et. al, 2016b). It provides valuable information for decision-makers who are seeking a sustainable expansion and maintain a high share of renewable energy in Ecuador's power system.

It was found that developing only 11% of the installation PV potential of Ecuador (i.e. 3900 MWp) avoids the construction of 1800 MW of thermoelectric power to cover projected demand by 2030 (see 4.2.1); and consequently, a reduction of 1,607,159 m3 of fuel-oil is achieved resulting in cumulative savings of approximately 2.5 USD billions by 2030 (see 4.2.3). Considering the projected investment cost for PV by 2025, i.e. 0.790 USD/MWp (IRENA, 2016c), 3.1 USD billions are needed to implement the proposed PV installed capacity. Thus, cumulative savings could cover most (81%) of this investment cost. Moreover, a cumulative reduction of the lifecycle GHG emission equivalent to 20,545 GgCO_2eq is achieved (see 4.2.4); which surpasses the committed goal of GHG emission reduction in the energy sector (electricity and transport) defined in the Intended Nationally Determined Contributions (INDCs) and communicated by Ecuador to the UNFCCC Conference of the Parties (COP21) in Paris in December 2015 (Ecuador, 2015a). However, obtaining these economic and environmental benefits depends on the ability of Ecuador's transmission system to integrate 3900MWp of PV. Since the proposed PV capacity is an intermittent generation and represents more than 35% of the installed capacity of the power system by 2030 (i.e. 11,036MW) electric problems in the power system can arise; which, have not been studied in this thesis (Becker et al., 2014; Urzua et al., 2016).

6 CONCLUSIONS

This thesis developed an integrated, spatially and temporal explicit approach capable of identify and evaluate the potential of complementary PV that could tackle the inter-annual variability of hydropower in Ecuador through the combination of a GIS-based participatory multi-criteria analysis (i.e. AHP) and an energy system analysis (i.e. SDDP). The proposed approach is able to explore and evaluate land suitability for PV at a national scale and assesses the economic and environmental impact of PV in the long-term operation of the Ecuadorian power system. Thus, contributing to progress towards participatory and integrated approaches to support decision-makers for a holistic energy planning.

A significant and untapped PV installation capacity potential of 35.7 GWp has been identified; which, is equivalent to 4.3 times the today power system capacity, and almost half of this potential is located in South of Ecuador. Developing a small percentage (10.9%) of this potential can compensate hydropower and reduce the need of expanding thermoelectric power to cover future electricity demand by 2030. This is traduced in a substantial reduction of operational cost of the power system (2.5 USD billions) and lifecycle GHG emissions (20,545 GgCO_2eq). Thus, PV can contribute to reaching an almost 100% renewable energy in the power system capacity of Ecuador by 2030, securing the supply of electricity at low cost and environmental impact.

Today hydropower still is seen as a political priority in Ecuador. However, its high seasonality and that hydropower plants with large reservoirs to store water for energy production during the dry season are not going to be built in the near future reduce the value of this renewable energy source to provide a firm power output in the long-term in Ecuador. Thus, using non-hydro and complementarity renewable energy like PV that can compensate hydropower seasonality is an economic and ecological solution that should be considered by decision-makers to maintain a firm power output with a high share of renewable energy in the long-term.

A further area that should be explored is to replicate this study to other renewable energy (i.e. wind, biomass, geothermal) and evaluate their complementarity and variability in order to find an optimal mix of non-hydro renewable energy that can compensate at a higher level hydropower seasonality and increase the security of supply in power systems. Moreover, though the proposed GIS-based model provided a flexible method that allows local expert participation to evaluate land suitability for PV, not always a participatory approach is possible and could limit the application of the proposed methodology. Therefore, other methods (e.g. ELECTRE) that do not rely on experts' expertise should be studied further.

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8 APPENDICES

8.1 Appendix 1: Literature statistics

The literature review was conducted in journal databases using the following keywords: GIS, suitability analysis, photovoltaic, renewable energy. The criteria used to select literature were: scientific articles and peer-reviewed, articles must be less than 25 years, and articles must focus on photovoltaic and do not other solar energy like concentrated solar power (CSP). Following a list of reviewed literature:

ID	Source	Technology	Spatial Extent
2001-1	Broesamle, H., Mannstein, H., Schillings, C., & Trieb, F. (2001). Assessment of solar electricity potentials in North Africa based on satellite data and a geographic information system. Solar Energy, 70(1), 1–12.	CSP	North Africa
2007-1	Domínguez Bravo, J., García Casals, X., & Pinedo Pascua, I. (2007). GIS approach to the definition of capacity and generation ceilings of renewable energy technologies. Energy Policy, 35(10), 4879–4892. https://doi.org/10.1016/j.enpol.2007.04.025	PV, CSP, Wind Biomass	Spain
2008-1	Arán Carrión, J., Espín Estrella, A., Aznar Dols, F., Zamorano Toro, M., Rodríguez, M., & Ramos Ridao, A. (2008). Environmental decision-support systems for evaluating the carrying capacity of land areas: Optimal site selection for grid-connected photovoltaic power plants. Renewable and Sustainable Energy Reviews, 12(9), 2358–2380.	PV	Spain
2008-2	Dahle, D., Elliott, D., Heimiller, D., Mehos, M., Robichaud, R., Schwartz, M., … Walker, A. (2008). Assessing the Potential for Renewable Energy Development on DOE Legacy Management Lands, (February), 1–163.	PV, CSP	USA
2009-1	Breyer, C., & Knies, G. (2009). Global Energy Supply Potential of Concentrating. SolarPACES 2009, 15–18.	CSP	World
2009-2	Fluri, T. P. (2009). The potential of concentrating solar power in South Africa. Energy Policy, 37(12), 5075–5080.	CSP	South Africa
2010-1	Charabi, Y., & Gastli, A. (2010). GIS assessment of large CSP plant in Duqum, Oman. Renewable and Sustainable Energy Reviews, 14(2), 835–841.	CSP	Oman
2010-2	Clifton, J., & Boruff, B. J. (2010). Assessing the potential for concentrated solar power development in rural Australia. Energy Policy,	CSP	Australia

	38(9), 5272–5280. https://doi.org/10.1016/j.enpol.2010.05.036		
2010-3	Gastli, A., Charabi, Y., & Zekri, S. (2010). GIS-based assessment of combined CSP electric power and seawater desalination plant for Duqum-Oman. Renewable and Sustainable Energy Reviews, 14(2), 821–827.	CSP	Oman
2010-4	Janke, J. R. (2010). Multi-criteria GIS modeling of wind and solar farms in Colorado. Renewable Energy, 35(10), 2228–2234.	PV, Wind	USA
2010-5	Wang, S., & Koch, B. (2010). Determining profits for solar energy with remote sensing data. Energy, 35(7), 2934–2938.	PV	Europe
2011-1	Charabi, Y., & Gastli, A. (2011). PV site suitability analysis using GIS-based spatial fuzzy multi-criteria evaluation. Renewable Energy, 36(9), 2554–2561.	PV	Oman
2012-1	Dawson, L., & Schlyter, P. (2012). Less is more: Strategic scale site suitability for concentrated solar thermal power in Western Australia. Energy Policy, 47, 91–101.	CSP	Australia
2013-1	Sánchez-Lozano, J. M., Teruel-Solano, J., Soto-Elvira, P. L., & Socorro García-Cascales, M. (2013). Geographical Information Systems (GIS) and Multi-Criteria Decision Making (MCDM) methods for the evaluation of solar farms locations: Case study in south-eastern Spain. Renewable and Sustainable Energy Reviews, 24, 544–556.	PV	Spain
2013-2	Stoms, D. M., Dashiell, S. L., & Davis, F. W. (2013). Siting solar energy development to minimize biological impacts. Renewable Energy, 57, 289–298.	PV, CSP	USA
2013-3	Sun, Y. wei, Hof, A., Wang, R., Liu, J., Lin, Y. jie, & Yang, D. wei. (2013). GIS-based approach for potential analysis of solar PV generation at the regional scale: A case study of Fujian Province. Energy Policy, 58(2013), 248–259.	PV	China
2013-4	Uyan, M. (2013). GIS-based solar farms site selection using analytic hierarchy process (AHP) in Karapinar region Konya/Turkey. Renewable and Sustainable Energy Reviews, 28, 11–17.	PV	Turkey
2013-5	Jun, D., Tian-Tian, F., Yi-Sheng, Y., & Yu, M. (2013). Macro-site selection of wind/solar hybrid power station based on ELECTRE-II. Renewable and Sustainable Energy Reviews, 35, 194–204.	Wind, PV	China
2014-1	Mahtta, R., Joshi, P. K., & Jindal, A. K. (2014). Solar power potential mapping in India using	PV, CSP	India

	remote sensing inputs and environmental parameters. Renewable Energy, 71, 255–262.		
2014-2	Merrouni, A. A., Mezrhab, A., & Mezrhab, A. (2014). CSP Sites Suitability Analysis in the Eastern Region of Morocco. Energy Procedia, 49, 2270–2279.	CSP	Morroco
2014-3	Mondino, E. B., Fabrizio, E., & Chiabrando, R. (2014). A GIS tool for the land carrying capacity of large solar plants. Energy Procedia, 48(0), 1576–1585.	PV	Italy
2014-4	Sánchez-Lozano, J. M., Henggeler Antunes, C., García-Cascales, M. S., & Dias, L. C. (2014). GIS-based photovoltaic solar farms site selection using ELECTRE-TRI: Evaluating the case for Torre Pacheco, Murcia, Southeast of Spain. Renewable Energy, 66, 478–494.	PV	Spain
2014-5	Ziuku, S., Seyitini, L., Mapurisa, B., Chikodzi, D., & van Kuijk, K. (2014). Potential of Concentrated Solar Power (CSP) in Zimbabwe. Energy for Sustainable Development, 23, 220–227.	CSP	Zimbabwe
2015-1	Brewer, J., Ames, D. P., Solan, D., Lee, R., & Carlisle, J. (2015). Using GIS analytics and social preference data to evaluate utility-scale solar power site suitability. Renewable Energy, 81, 825–836.	PV	USA
2015-2	Polo, J., Bernardos, A., Navarro, A. A., Fernandez-Peruchena, C. M., Ramirez, L., Guisado, M. V., & Martinez, S. (2015). Solar resources and power potential mapping in Vietnam using satellite-derived and GIS-based information. Energy Conversion and Management, 98, 348–358.	PV, CSP	Vietnam
2015-3	Watson, J. J. W., & Hudson, M. D. (2015). Regional Scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation. Landscape and Urban Planning, 138, 20–31.	PV, Wind	UK
2016-1	Anwarzai, M. A., & Nagasaka, K. (2016). Utility-scale implementable potential of wind and solar energies for Afghanistan using GIS multi-criteria decision analysis. Renewable and Sustainable Energy Reviews, (June 2015), 1–11.	PV, CSP, Wind	Afghanistan
2016-2	Jahangiri, M., Ghaderi, R., Haghani, A., & Nematollahi, O. (2016). Finding the best locations for establishment of solar-wind power stations in Middle-East using GIS: A review. Renewable and Sustainable Energy Reviews, 66, 38–52.	PV, Wind	Middle-East

2016-3	Merrouni, A. A., Mezrhab, A., & Mezrhab, A. (2016). PV sites suitability analysis in the Eastern region of Morocco. Sustainable Energy Technologies and Assessments, 18, 6–15.	PV	Morroco

Table 8.1 Literature statistics of restriction to develop large-scale PV plants

No	Restriction	Sources that mentioned the restriction	
		Number	% of the total
1	Built-up areas	11	58%
2	Waterbodies and rivers	11	58%
3	Protected areas	11	58%
4	Slope	11	58%
5	Natural Areas	9	47%
7	Historical and interest sites	6	32%
8	Road network	6	32%
6	Arable or planted land	5	26%
9	Solar Radiation	5	26%
10	Aspect	4	21%
11	Cattle trails	3	16%
12	Land with high socio-economic value	3	16%
13	Plot area	3	16%
14	Distance to the electric network	2	11%
15	Distance to the road network	2	11%
16	Distance to water bodies or rivers	2	11%
17	Railway network	2	11%
18	Risk zones	2	11%
19	Electric network	1	5%

Table 8.2 Literature statistics of evaluation criteria to develop large-scale PV plants

No	Evaluation Criteria	Sources that mentioned the criteria	
		Number	% of the total
1	Solar radiation	10	91%
2	Distance to roads	9	82%
3	Distance to residential areas	7	64%
4	Distance to the electric network	7	64%
5	Slope	6	55%
6	Average temperature	4	36%
7	Aspect	3	27%
8	Distance to substations	3	27%
9	Agricultural Lands	3	27%
10	Barren	3	27%
11	Plot Area	2	18%
12	Public acceptance	1	9%
13	Distance to water source	1	9%
14	Complexity to get the land for construction	1	9%
15	Geological and topographic conditions	1	9%
16	Rainfall height	1	9%

No	Evaluation Criteria	Sources that mentioned the criteria	
		Number	% of the total
17	Dryland herbaceous crops	1	9%
18	Federal Lands	1	9%
19	Herbaceous and woody crops	1	9%
20	Irrigated herbaceous crops	1	9%
21	Other land uses	1	9%
22	Rock outcrop	1	9%
23	Sand covered area	1	9%
24	Short vegetation	1	9%
25	Stable topography	1	9%
26	Subdued	1	9%
27	Woody crops	1	9%
28	Distance from historically important areas	1	9%
29	Distance from wildlife designations	1	9%
30	Energy savings pollutant reduction	1	9%
31	Pollution	1	9%
32	Visual impact	1	9%
33	Local resident attitude	1	9%
34	Population density	1	9%
35	Construction cost	1	9%
36	Electricity demand	1	9%
37	GDP	1	9%
38	Operation and Maintenance cost	1	9%

8.2 Appendix 2: Input for power system modeling in SDDP

Table 8.3 Hydropower plants characteristics

ID	Name	Installed Capacity (MW)	Year of operation
1	Agoyan	156	2017
2	Alazan	6.23	2017
3	Baba	42	2017
4	Calope	18	2017
5	Ccs1500	1200	2017
6	Chorrillos	4	2017
7	Delsitanisag	180	2018
8	Due	49.7	2017
9	Mazar	170	2017
10	San Francisco	212	2017
11	Hidroabanico	37.5	2017
12	Hidronacion	213	2017
13	Isimanchi	2.25	2017
14	Manduriacu	62.5	2017
15	Minas San Francisco	275	2018
16	Normandia	38	2018
17	Ocaña	26	2017
18	Palmira nane	10	2017
19	Paute	1100	2017
20	Pilaton	49	2019
21	Pucara	73	2017
22	Pusuno	47	2017
23	Quijos	50	2018
24	Rio verdechi	10	2017
25	San Jose Minas	5.95	2017
26	Sabanilla	30.9	2018
27	San antonio	7.19	2017
28	San Bartolo	48.1	2017
29	Santa Cruz	129	2023
30	Sibimbe	15	2017
31	Sigchos	18	2017
32	Sj tambo	8	2017
33	Sopladora	487	2017
34	Toachi	204	2019
35	Topo	22.8	2017
36	Victoria	10	2017

Table 8.4 Thermoelectric power plants characteristics

ID	Name	Installed Capacity (MW)	Year of Operation	Operational Marginal Costs (US$/MWh)
1	A. Santos 1	20.5	2017	218.07
2	A. Santos 2	20.5	2017	246.29
3	A. Santos 3	20	2017	214.81
4	A. Santos 5	18	2017	223.72
5	A. Santos 6	18	2017	229.76
6	A. Tinajero1	46.5	2017	159.51
7	A. Tinajero2	35	2017	201.49
8	Catamayo 1	1	2017	179.91
9	Catamayo 10	2.2	2017	193.46
10	Catamayo 2	1	2017	182.4
11	Catamayo 4	1.3	2017	209.05
12	Catamayo 5	1.3	2017	216.46
13	Catamayo 6	2.5	2017	172.73
14	Catamayo 7	2.5	2017	174.18
15	Catamayo 8	2.4	2017	194.38
16	Catamayo 9	2.2	2017	190.63
17	Cc machala	110	2017	41.548
18	Celso cas u1	1.8	2017	251.01
19	Celso cas u2	1.8	2017	251.01
20	Celso cas u3	1.8	2017	251.01
21	Celso cas u4	1.8	2017	251.01
22	Dayuma	2	2017	219.84
23	El descanso1	4.3	2017	59.82
24	El descanso2	4.3	2017	61.092
25	El descanso3	4.3	2017	59.544
26	El descanso4	4.3	2017	59.722
27	Enrique garc	96	2017	192.45
28	Esmeraldas	125	2017	69.768
29	Esmeraldasii	96	2017	74.91
30	G. Zeval.tv2	73	2017	143.92
31	G. Zeval.tv3	73	2017	94.823
32	G. Zevalltg4	20	2017	238.97
33	G.hernadez 1	5.2	2017	61.606
34	G.hernadez 2	5.2	2017	61.606
35	G.hernadez 3	5.2	2017	61.269
36	G.hernadez 4	5.2	2017	61.181
37	G.hernadez 5	5.2	2017	61.428
38	G.hernadez 6	5.2	2017	61.398
39	Generoca1	4.2	2017	82.633
40	Generoca2	4.2	2017	83.503

ID	Name	Installed Capacity (MW)	Year of Operation	Operational Marginal Costs (US$/MWh)
41	Generoca3	4.7	2017	83.353
42	Generoca4	4.5	2017	80.883
43	Generoca5	4.2	2017	82.633
44	Generoca6	4.2	2017	82.633
45	Generoca7	4.2	2017	82.633
46	Generoca8	4.2	2017	82.633
47	Guangopolo 1	5.1	2017	110.36
48	Guangopolo 3	5.1	2017	96.074
49	Guangopolo 4	5.1	2017	96.734
50	Guangopolo 6	5.1	2017	96.074
51	Guangopolo 7	1.4	2017	127.01
52	Guangopoloii	48	2017	73.88
53	Jaramijo	134.3	2017	74.474
54	Jivino i u1	1.9	2017	237.66
55	Jivino i u2	1.9	2017	236.76
56	Jivino ii u1	5	2017	92.614
57	Jivino ii u2	5	2017	92.614
58	Jivino iii 1	10.5	2017	76.994
59	Jivino iii 2	10.5	2017	76.909
60	Jivino iii 3	10.5	2017	76.909
61	Jivino iii 4	10.5	2017	76.909
62	Lligua 1	1.8	2017	182.5
63	Lligua 2	1.5	2017	188.48
64	Loreto	2	2017	218.33
65	Machala 1	64.1	2017	59.088
66	Machala 2	64.4	2017	59.093
67	Machala 3	70	2017	62.773
68	Manta 2	18.6	2017	77.388
69	Manta getg1	19	2017	205.91
70	Miraflores 7	2	2017	202.94
71	Miraflores 8	2	2017	212.5
72	Miraflores10	4.5	2017	212.36
73	Miraflores11	4.5	2017	163.07
74	Miraflores12	1.9	2017	89.195
75	Miraflores13	1.9	2017	213.46
76	Miraflores14	1.9	2017	212.36
77	Miraflores15	1.9	2017	212.36
78	Miraflores16	1.9	2017	212.46
79	Miraflores18	2	2017	212.46
80	Miraflores22	1.8	2017	211.33
81	Payamino	4	2017	238.73

ID	Name	Installed Capacity (MW)	Year of Operation	Operational Marginal Costs (US$/MWh)
82	Pedernales	3.3	2017	212.26
83	Propicia 1	3.3	2017	105.5
84	Propicia 2	1.8	2017	96.4
85	Propicia 3	93	2017	222.55
86	Quevedo	27.3	2017	75.886
87	Salegre	82.15	2017	79.116
88	Sta elena 2	13.9	2017	69.988
89	Sta elena3 1	13.9	2017	60.814
90	Sta elena3 2	13.9	2017	60.699
91	Sta elena3 3	16.4	2017	60.295
92	Sta. Rosa 1	17	2017	263.39
93	Sta. Rosa 2	17	2017	263.39
94	Sta. Rosa 3	17	2017	263.39
95	Termoguayas4	20.5	2017	103.63
96	Tgmach u1	21	2017	58.216
97	Tgmach u2	20.5	2017	58.216
98	Tgmach u3	21.5	2017	58.374
99	Tgmach u4	20.5	2017	58.087
100	Tgmach u5	20	2017	58.3
101	Tgmach u6	20	2017	59.102
102	Trinitaria	33	2017	82.677
103	V. A.santos	32	2017	106.61
104	Bloque termi_1	300	2024	92.614
105	Bloque termi_2	400	2026	92.614
106	Bloque termi_3	1100	2028	92.614

Table 8.5 Renewable energy power plants

ID	Name	Installed Capacity (MW)	Year of Operation	Type	Comment
1	GZE_1	54	2024	PV	Projected
2	VIR_1	5	2024	PV	Projected
3	LOJ_1	61	2024	PV	Projected
4	PAR_1	5	2024	PV	Projected
5	SCH_1	14	2024	PV	Projected
6	SPA_1	4	2024	PV	Projected
7	SPE_1	10	2024	PV	Projected
8	SRE_1	64	2024	PV	Projected
9	VIRT1_1	588	2024	PV	Projected
10	VIRT2_1	95	2024	PV	Projected
11	Ecoelectric	35.2	2017	Biomass	Existing

ID	Name	Installed Capacity (MW)	Year of Operation	Type	Comment
12	Ecudos	27.6	2017	Biomass	Existing
13	Fotovolt < 1MW	25	2017	PV	23 existing plants
14	San carlos	75	2017	Biomass	Existing
15	Villonaco	16.5	2017	Wind	Existing
16	GZE_2	73	2026	PV	Projected
17	VIR_2	6	2026	PV	Projected
18	LOJ_2	81	2026	PV	Projected
19	PAR_2	7	2026	PV	Projected
20	SCH_2	18	2026	PV	Projected
21	SPA_2	4	2026	PV	Projected
22	SPE_2	14	2026	PV	Projected
23	SRE_2	86	2026	PV	Projected
24	VIRT1_2	785	2026	PV	Projected
25	VIRT2_2	127	2026	PV	Projected
26	GZE_3	72	2028	PV	Projected
27	VIR_3	6	2028	PV	Projected
28	LOJ_3	81	2028	PV	Projected
29	PAR_3	7	2028	PV	Projected
30	SCH_3	19	2028	PV	Projected
31	SPA_3	5	2028	PV	Projected
32	SPE_3	14	2028	PV	Projected
33	SRE_3	85	2028	PV	Projected
34	VIRT1_3	784	2028	PV	Projected
35	VIRT2_3	127	2028	PV	Projected
36	VIRT1_4	600	2029	PV	Projected

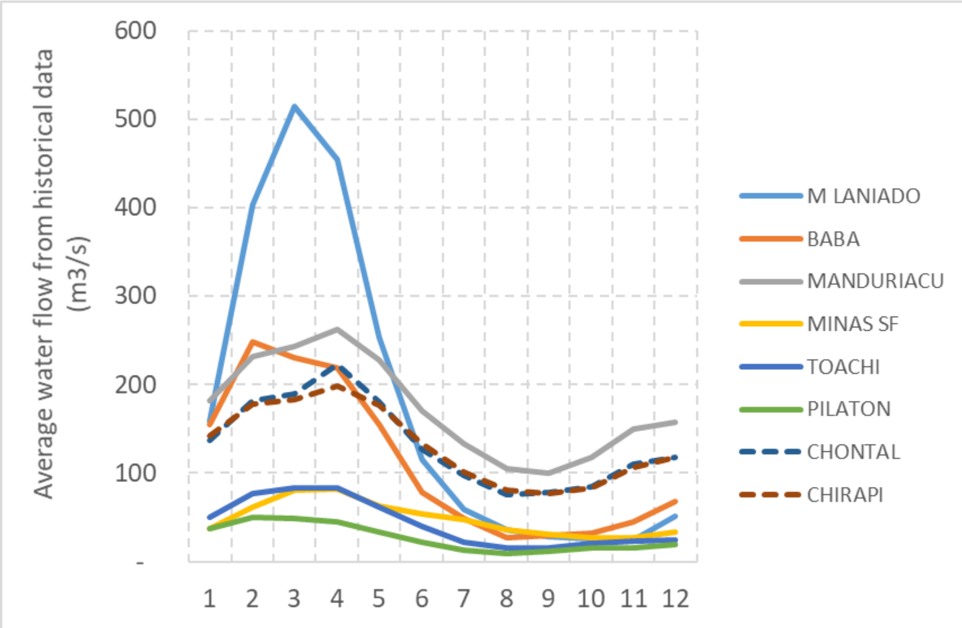


Figure 8.1 Average water flow hydropower plants located in the Pacific water basin, calculated from historical data 1950-2014

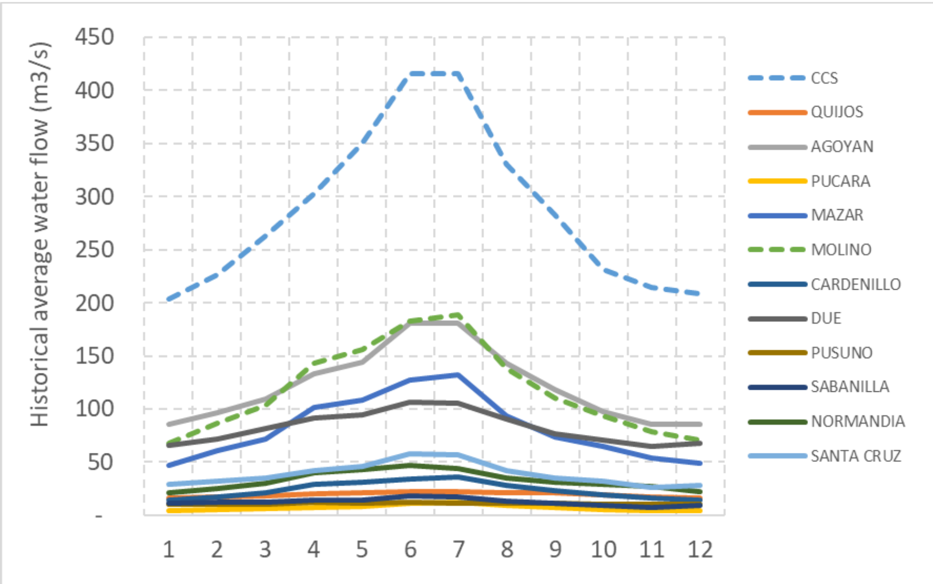


Figure 8.2 Average water flow hydropower plants located in the Amazon water basin, calculated from historical data 1964-2014

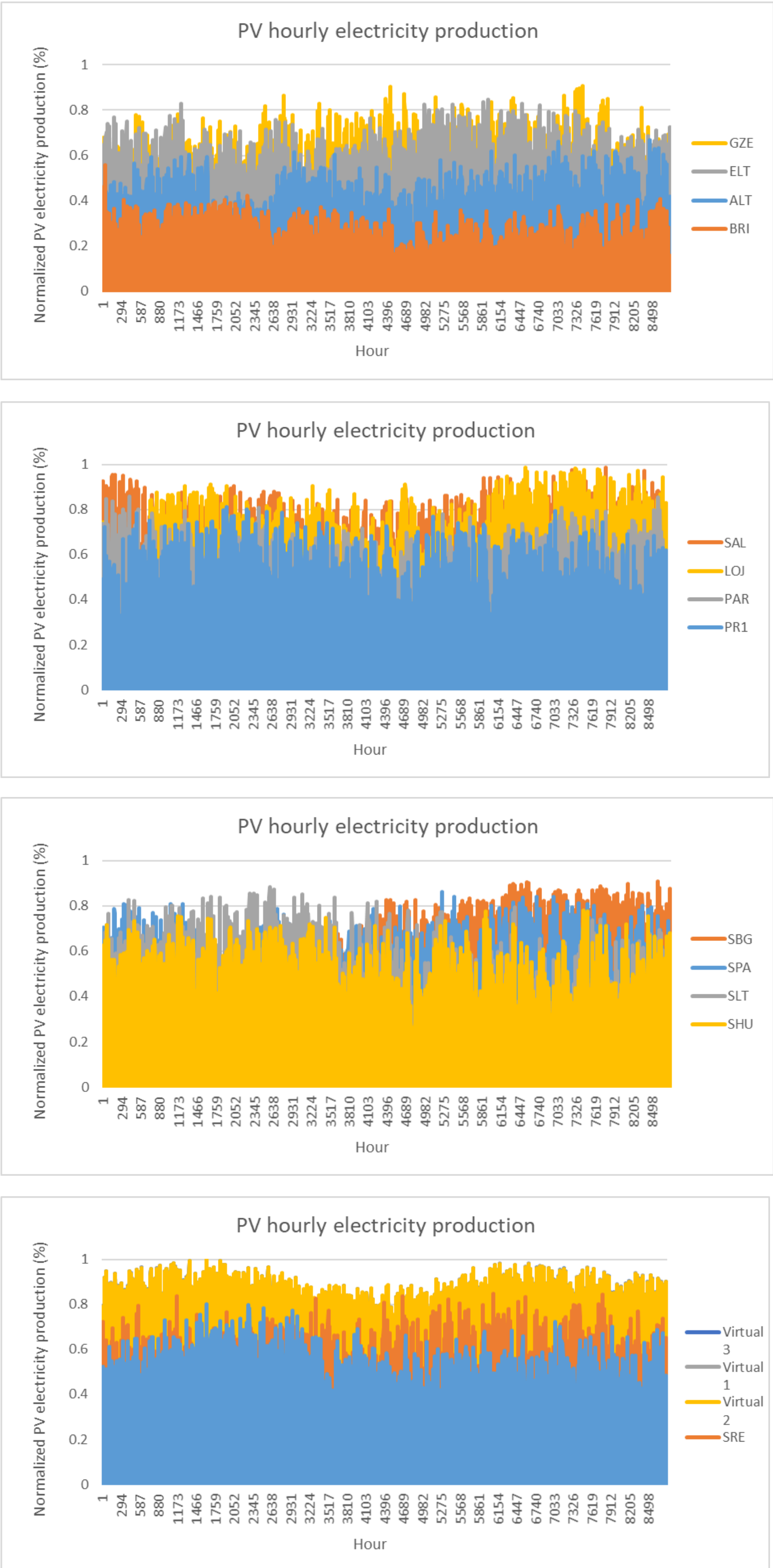


Figure 8.3 Calculated synthetic time series of hourly electricity production of selected PV sites

8.3 Appendix 3: Restrictions maps for PV deployment

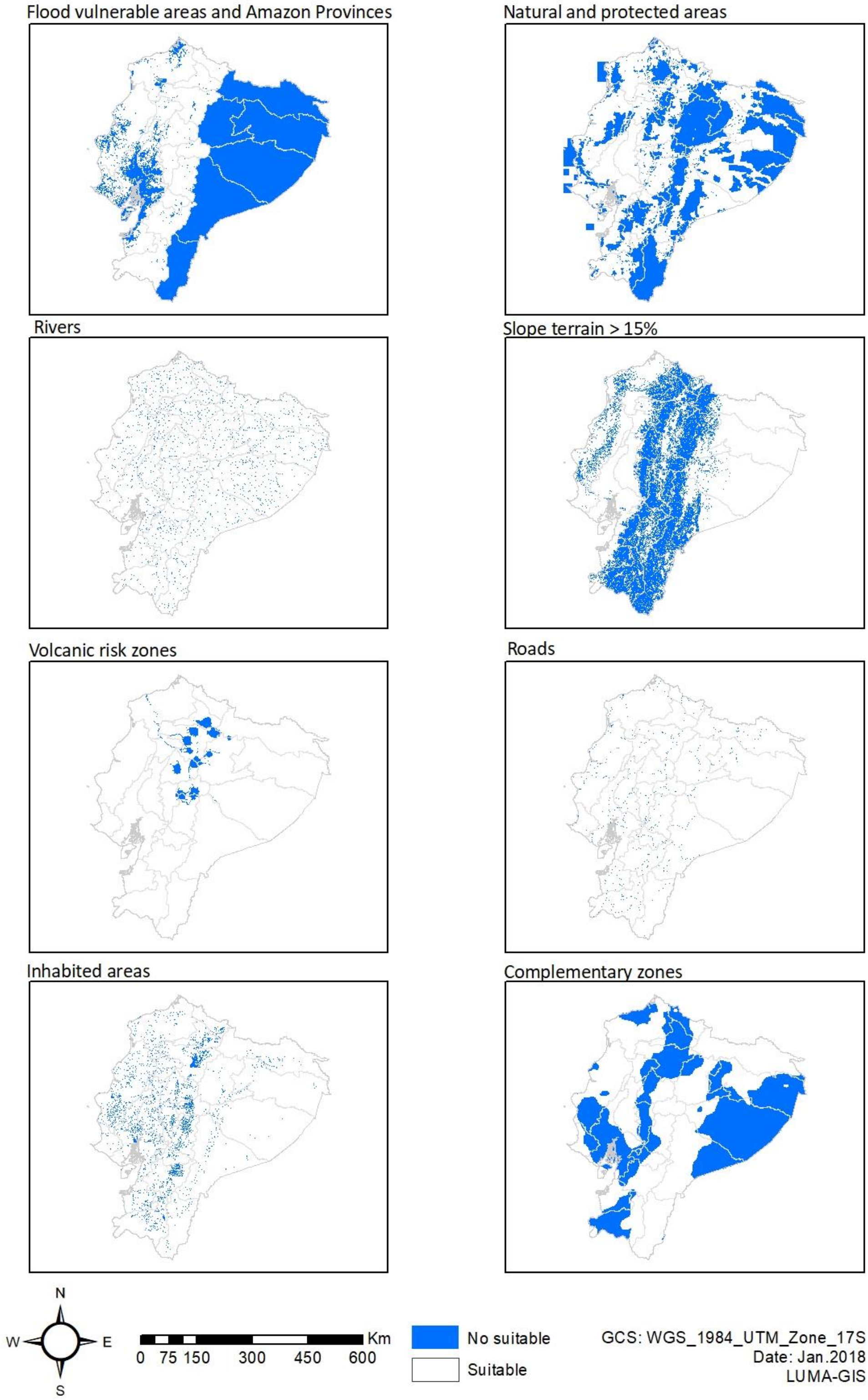


Figure 8.4 Restrictions maps used to identify non-suitable land for PV deployment

8.4 Appendix 4: Workshop results

Table 8.6 Pairwise comparison, normalization and consistency checking of technical sub-criteria

	Solar Radiation	Slope
Solar Radiation	1	9
Slope	0.11111	1
TOTAL	1.11111	10

NORMALIZATION			ROW SUM	WEIGHTS	Consistency Measure
Solar Radiation	0.9	0.9	1.80	90.0%	2.00
Slope	0.1	0.1	0.20	10.0%	2.00
TOTAL SUM MUST BE 1	1	1			
				CI	0.00
				RI	0
				CR	-

Table 8.7 Pairwise comparison, normalization and consistency checking of economical sub-criteria

	Distance to roads	Distance to electric networks
Distance to roads	1	6
Distance to electric networks	0.16667	1
TOTAL	1.16667	7

NORMALIZATION			ROW SUM	WEIGHTS	Consistency Measure
Distance to roads	0.85714	0.85714	1.71	0.857	2.00
Distance to electric networks	0.14286	0.14286	0.29	0.143	2.00
TOTAL SUM MUST BE 1	1	1			
				CI	0.00
				RI	0
				CR	-

Table 8.8 Pairwise comparison, normalization and consistency checking of environmental sub-criteria

	Land use	Distance to residential areas
Land use	1	8
Distance to residential areas	0.125	1
TOTAL	1.125	9

NORMALIZATION			ROW SUM	WEIGHTS	Consistency Measure
Land use	0.88889	0.88889	1.78	0.889	2.00
Distance to residential areas	0.11111	0.11111	0.22	0.111	2.00
TOTAL SUM MUST BE 1	1	1			

CI	0.00
RI	0
CR	-

Table 8.9 Pairwise comparison, normalization and consistency checking of criteria

	Technical	Economic	Ecological
Technical	1	3	5
Economic	0.33333	1	3
Environmental	0.2	0.33333	1
TOTAL	1.53333	4.33333	9

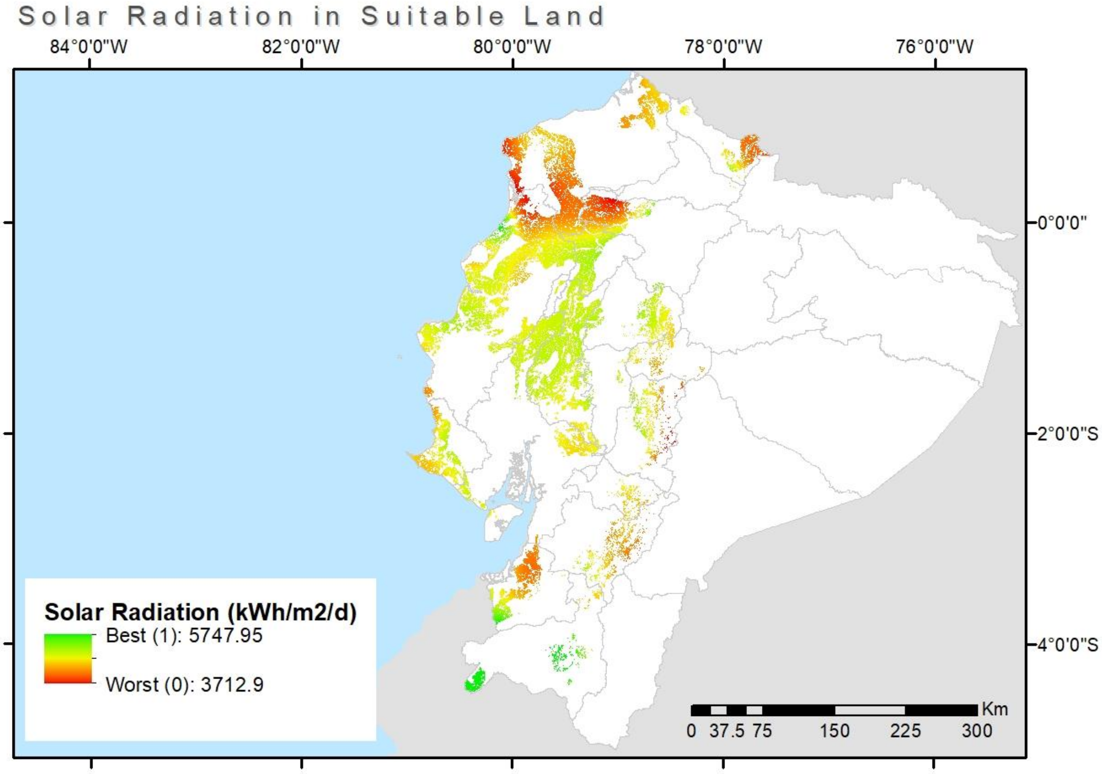
NORMALIZATION				ROW SUM	WEIGHTS	Consistency Measure
Technical	0.65217	0.69231	0.55556	1.90	0.633	3.07
Economic	0.21739	0.23077	0.33333	0.78	0.260	3.03
Environmental	0.13043	0.07692	0.11111	0.32	0.106	3.01
TOTAL SUM MUST BE 1	1	1	1		1.000	

CI	0.02
RI	0.58
CR	0.03

Table 8.10 List of local experts

Expert	Years of experience	Institution
Power system planning	15	CELEC EP
Renewable energy	10	CELEC EP
Environmental manager	10	CELEC EP
Researcher	20	University of Cuenca

8.5 Appendix 5: Sub-criteria and criteria maps to evaluate land suitability for PV



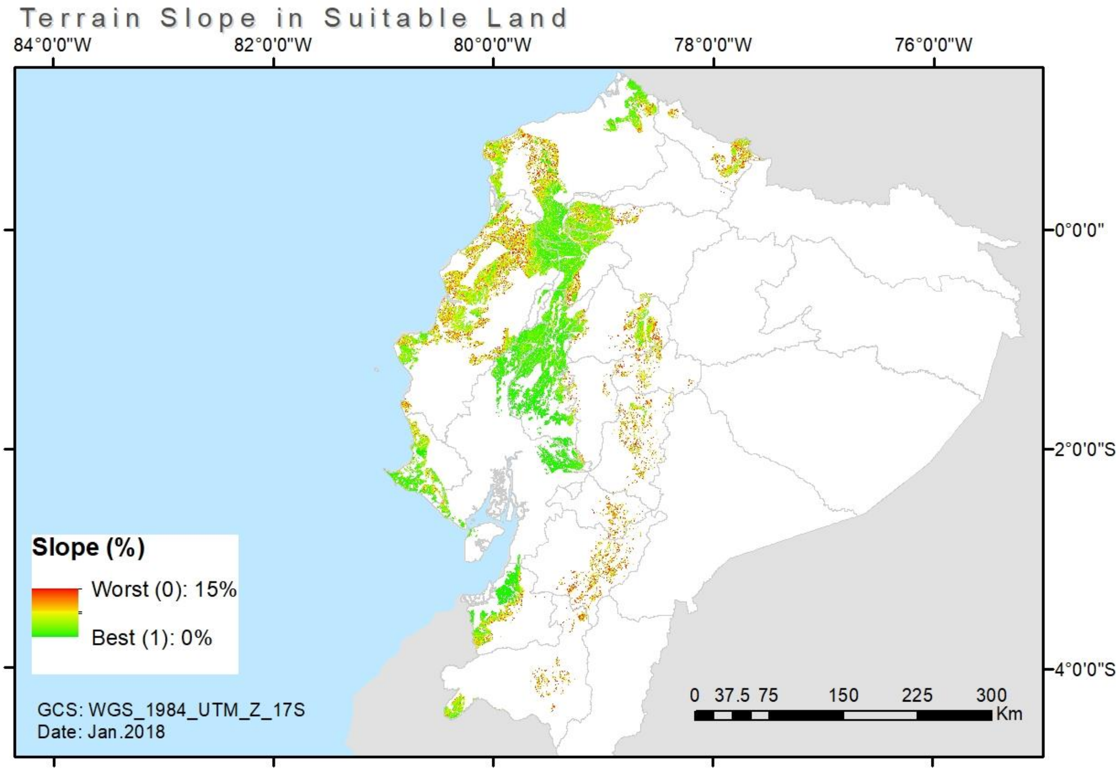


Figure 8.5 Technical sub-criteria for land suitability analysis of PV deployment

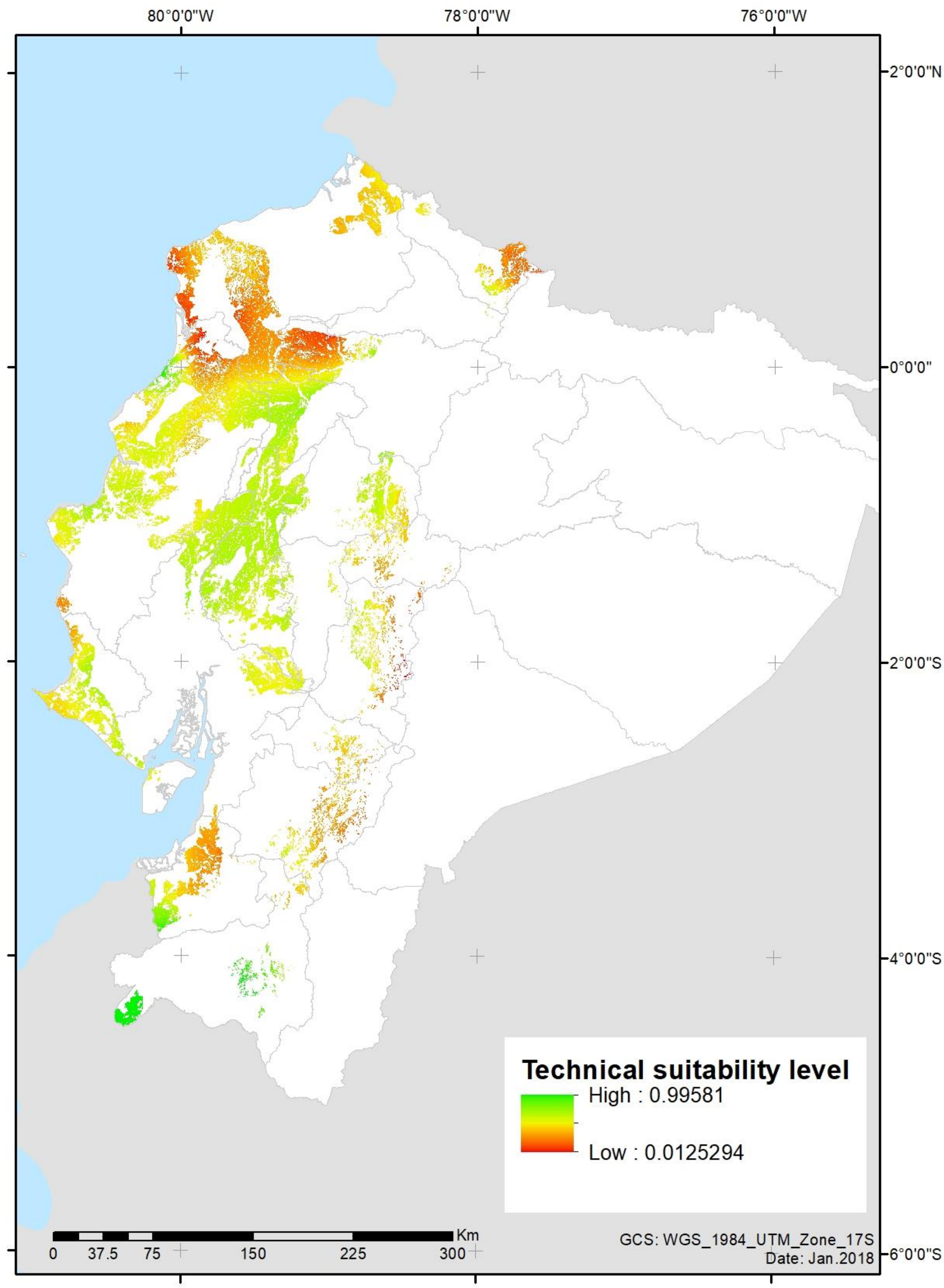


Figure 8.6 Technical land suitability for deploying PV in Ecuador

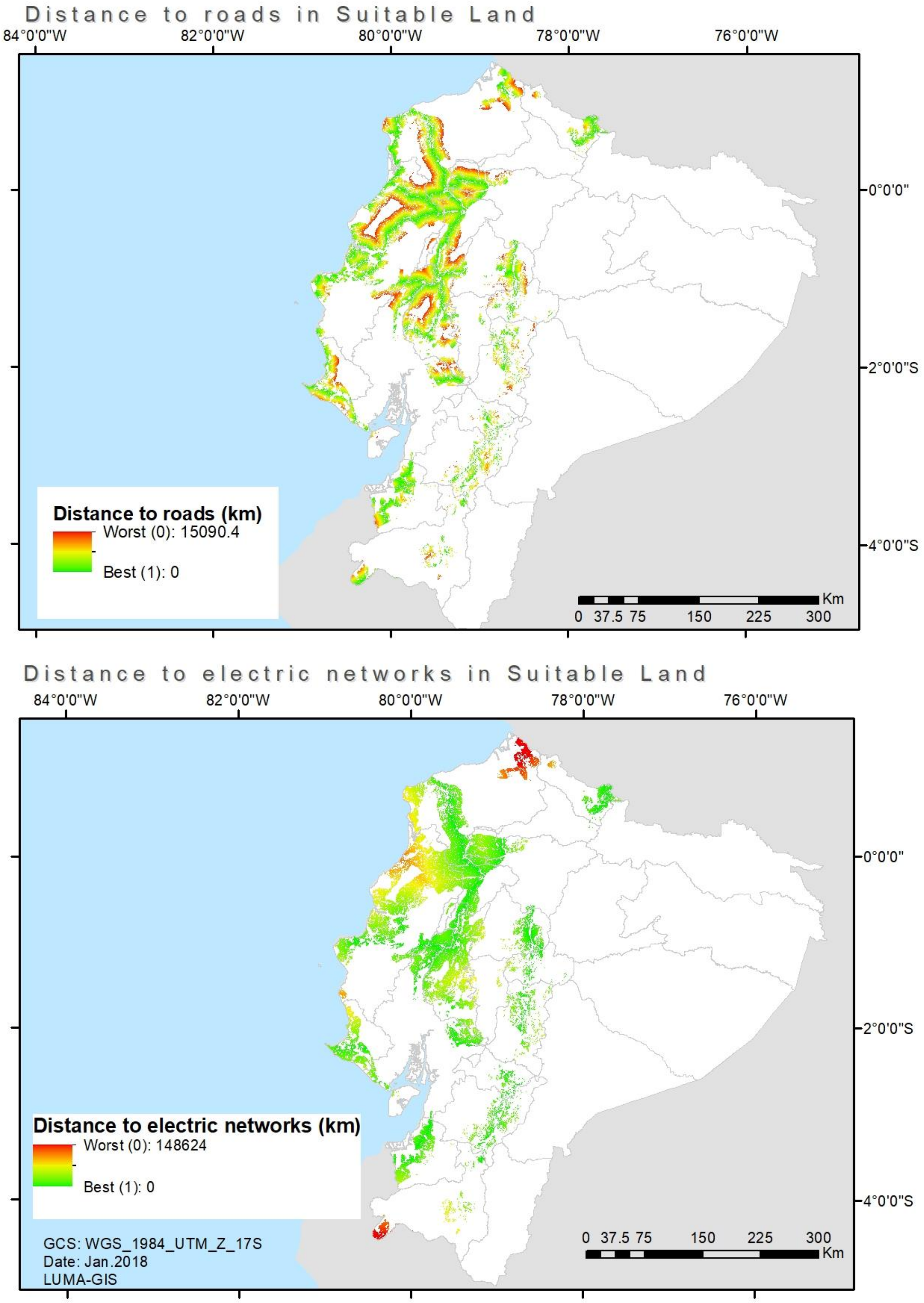


Figure 8.7 Economic sub-criteria for land suitability analysis of PV deployment

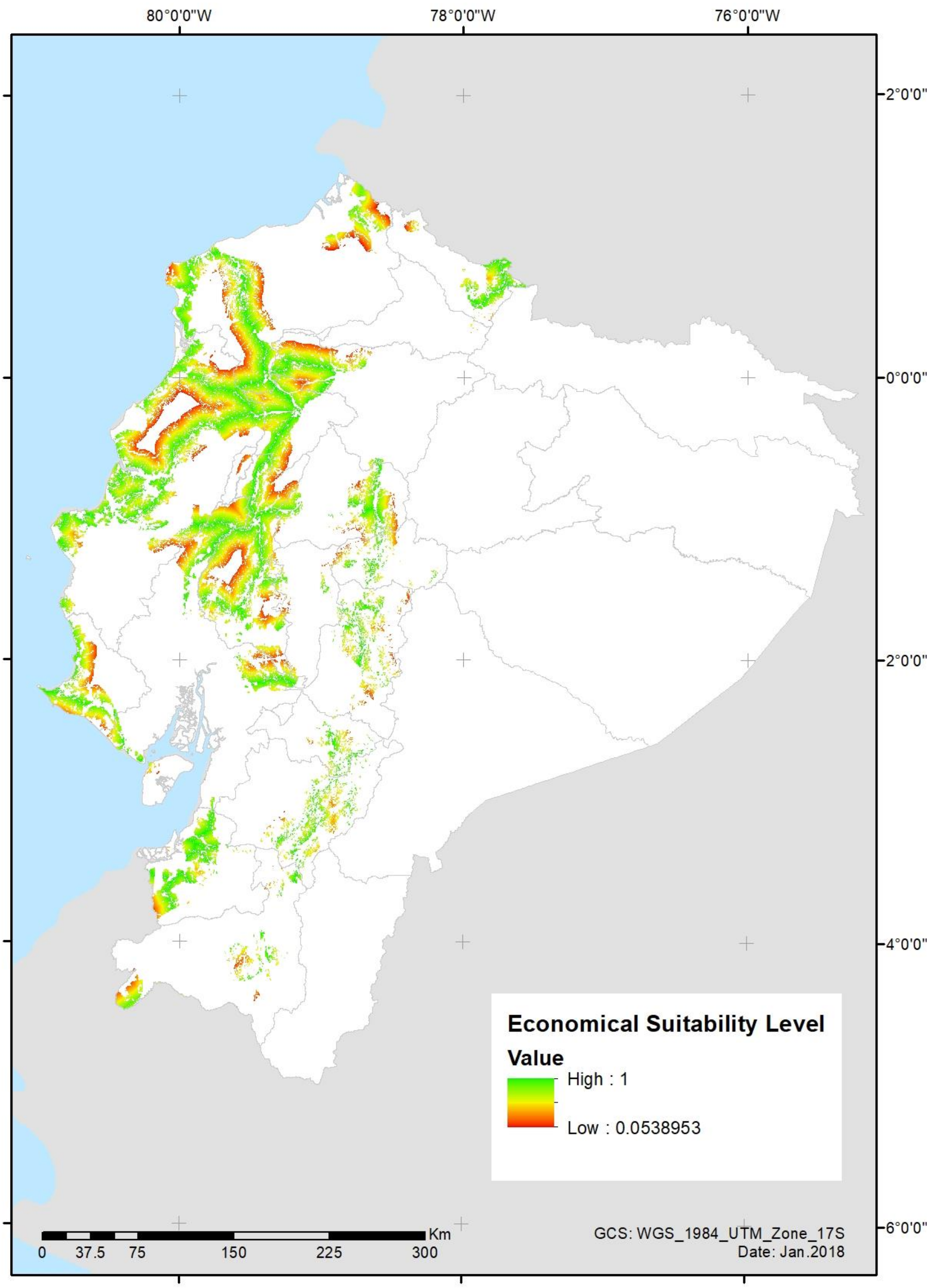


Figure 8.8 Economic land suitability for deploying PV in Ecuador

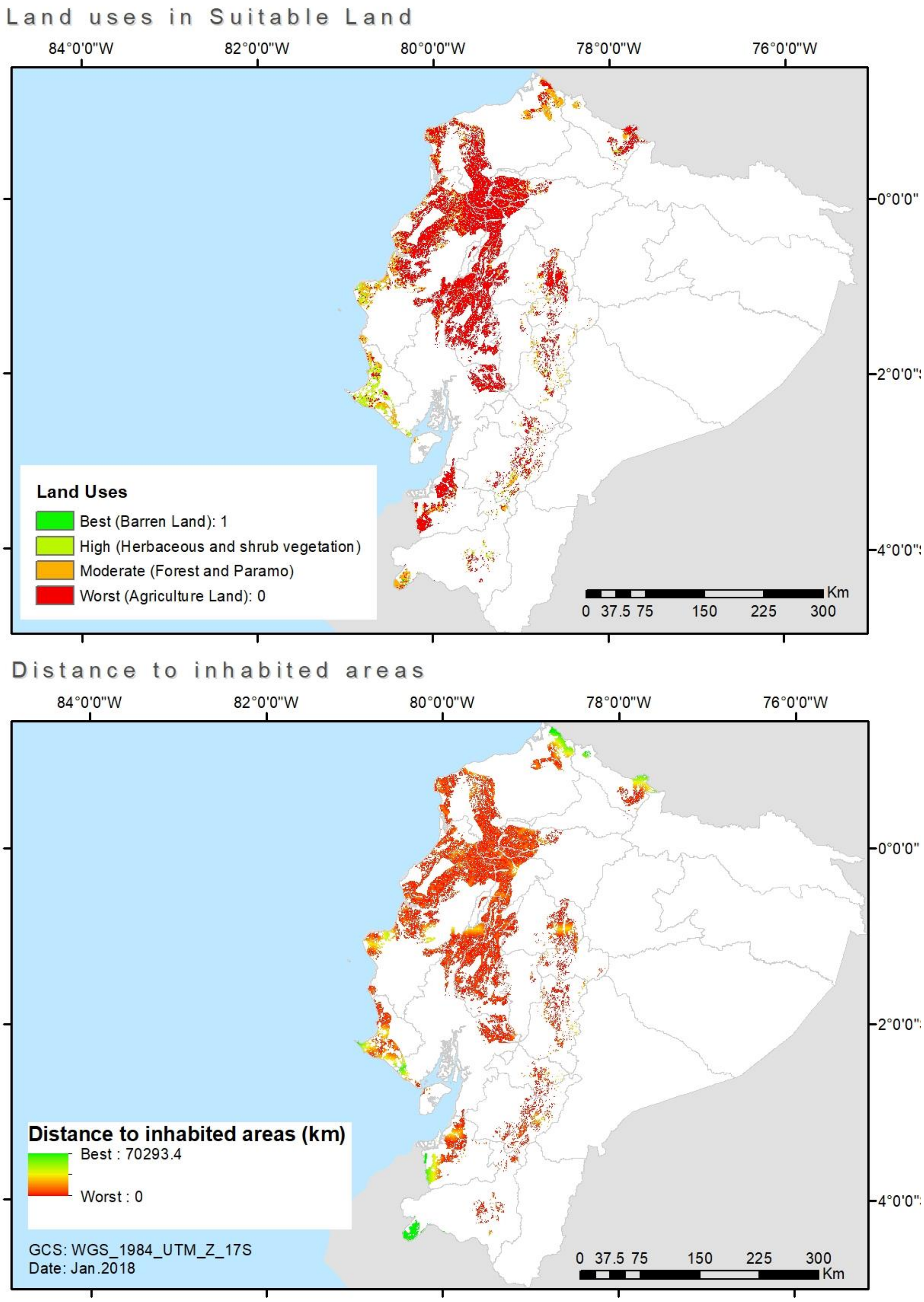


Figure 8.9 Ecological sub-criteria for land suitability analysis of PV deployment

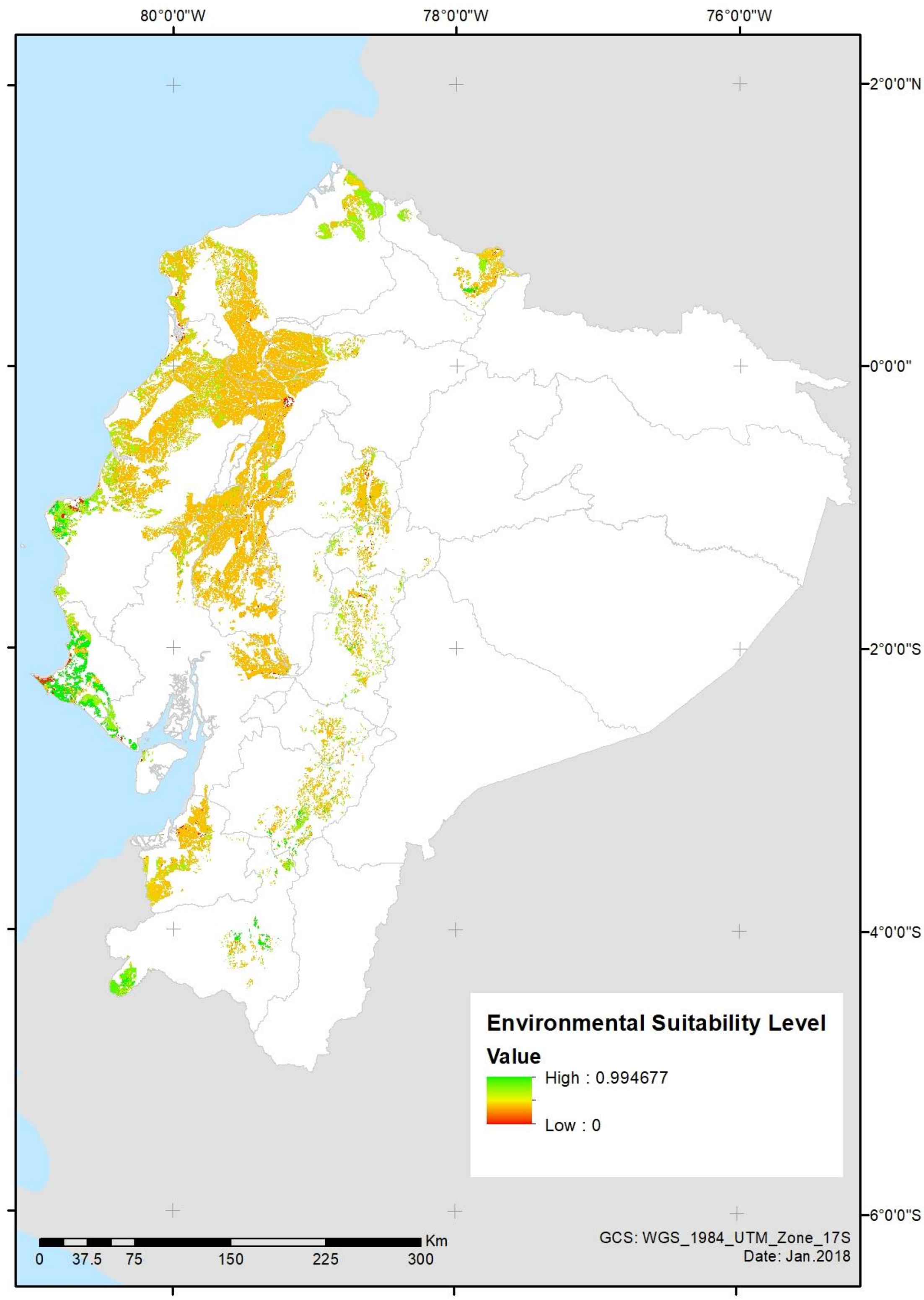


Figure 8.10 Ecological land suitability for deploying PV in Ecuador

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