AALBORG UNIVERSITY
STUDENT REPORT

MSc. Sustainable Energy Planning and Management
MASTER THESIS

Concentrating solar power potential of Peru

Analysing Peru's potential for CSP technology with geographical, technical and economic approaches.

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January 24, 2019

AALBORG UNIVERSITY
STUDENT REPORT

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Title:

Concentrating solar power potential of Peru

Study:

MSc. Sustainable Energy Planning and Management

Project:

Master Thesis

Period:

October 2018 - January 2019

Supervisor:

Steffen Nielsen

Report pages: 92
Appendix pages: 10
Completed: 24-01-2019

Synopsis:

Concentrating Solar Power is a renewable energy technology with interesting prospects in countries with high levels of solar radiation in a context where conventional fossil fuel electricity generation has to be replaced by carbon neutral technologies to fight against climate change. Peru is one of those countries receiving a large annual radiation, however the electricity sector is dominated by natural gas and hydropower. Therefore, the introduction of the technology is evaluated, establishing the following research question:
Is Concentrated Solar Power with thermal storage a techno-economically feasible option for Peru?
To answer the question, a comprehensive study of the potential of technology in Peru has been carried out, including a geographic analysis with GIS software to identify the most favourable locations; and economic optimization of a 50 MW solar tower molten salt CSP plant. The results suggest a promising future for the technology in the country with a competitive LCOE compared with the dominating solutions. The report aims to establish a point of departure to attract greater attention to CSP technology from institutions and companies in Peru .

Preface

This report is composed by Francisco Pliego Ruiz during the period from 24^{th} October 2018 to 24^{th} January 2019. The theme of the project is *Master's Thesis*, the requirement of the fourth semester concluding with the graduation of the Master program in Sustainable Energy Planning and Management.

Acknowledgements

I would like to express my acknowledgment to my supervisor Steffen Nielsen for his guidance throughout the long process of writing this thesis. I also would like to thank the fruitful collaboration of the professors Eunice Villicaña, Julien Noel and Elmer Ramirez in arranging interviews and providing useful data and methods for the report. I hope the results can entail a small contribution to improve the Peruvian society. Thank you to Jitka Klingerová for giving me the opportunity to live and work in the Czech Republic for one semester and fulfill one of my dreams.

Finally, I would like to express my appreciation to all the people who walked together with me during this two year journey. To my parents Paco and Elena, for their support even in difficult times; to my old and new classmates and friends from all over the world who broadened my limits and enjoyed the gratifying experience of living in a different country, and to Ivana for your support in this last part of the journey, when I needed it the most.

Gracias. Tak. Děkuji. Ďakujem. Thank you!

Reading guide

For referencing literature and sources the Harvard method is followed. It consists on an alphabetical list of items the end of the report. The references are written as [Author, Year], with Author as the surname of the writer or the complete name if it deals with an institution.

Figures and tables are numbered according to the chapter where they are embedded, a dot and the correlative number of the item inside the chapter. For figures in the second chapter, it would start by 2.1, and then 2.2, 2.3... An explanatory text is placed under all figures and tables. Figures and tables without references are created by the author.

The report uses the International System of Units (SI). The decimal numbers are separated with commas (,), and miles in currency values are divided by a point (.). Examples: 5,75% or 160.000 USD.

Currency values are expressed in United States dollars (USD = $) for reasons of simplicity and to allow worldwide monetary comparisons. However, the official currency in Peru is the Peruvian sol (PEN = S/). The following conversion rates apply:

$$1 \text{ USD} = 3{,}33 \text{ PEN} = 0{,}88 \text{ EUR} = 6{,}56 \text{ DKK}$$

Francisco Pliego Ruiz

Contents

List of Figures

List of Tables

Nomenclature

CF	Capacity Factor
$COES$	Comité de Operación Económica del Sistema Interconectado Nacional
COP	Conference of the Parties
CSP	Concentrating Solar Power
DGE	Dirección General de la Electricidad
$DGER$	Dirección General para la Electrificación Rural - National Rural Electrification Office
DTU	Denmark Technical University
EU	European Union
EUR	Euro
GCF	Green Climate Fund
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiation

GIS	Geographical Information Systems
IEA	International Energy Agency
$INDC$	Intended Nationally Determined Contribution
$IRENA$	International Renewable Energy Agency
LA	Latin America
LCE	Ley de Concesiones Eléctricas - Electricity Concessions Law
$LCOE$	Levelized cost of electricity
$LULUCF$	Land use, land-use change, and forestry
$MCDM$	Multicriteria Decision Making
MEM	Ministry of Energy and Mines
$NREL$	National Renewable Energy Laboratory
$OSINERGMIN$	Organismo Supervisor de Inversión en Energía y Minería - Energy and Mining Investment Supervisory Body
PEN	Peruvian sol
$PPPGDP$	Purchasing Power Parity GDP
RES	Renewable Energy Sources
SAM	System Advisor Model
$SEIN$	Sistema Eléctrico Interconectado Nacional - National Electricity Office
SRS	Spatial Reference System

TES	Thermal Energy Storage
$TFEC$	Total Final Energy Consumption
$TPES$	Total Primary Energy Supply
TSO	Transmision System Operator
USA	United States of America
USD	United States dollar
$UTEC$	Universidad de Ingeniería y Tecnología

1 Introduction

The global temperature of the Earth is alarmingly rising during the past decades, jeopardizing biodiversity and human life, including the cities where we live and economic activities. Following decades of controversy on the topic of whether climate change is happening or not and whether it is caused by human action or not, a general scientific consensus exists nowadays and only the difficulties of the economy transition that has to be faced can explain the voices against climate change. (Friends of the Earth, 2018) The last Assessment Report presented by the Intergovernmental Panel for Climate Change (IPCC) in 2014 concludes that global warming is unequivocal, with CO_2 concentrations unprecedented at least in the last 800 000 years and the human influence is extremely likely, on the range 95%-100%. (IPCC, 2013) Moreover, it states that the risks associated with climate change can be reduced if the magnitude of warming is mitigated. As the path was showing an increase of around 4ºC by 2100, new policies had to be taken by the international community. (IPCC, 2015)

With this purpose, the United Nations Framework Convention on Climate Change (UFCCC) called the international leaders to reach an agreement at the COP21, in 2015. The Paris Agreement includes the commitment to hold the increase in the global average temperature below 2ºC, aiming to limit it to 1,5ºC. To achieve the commitment, countries had to submit a so-called INDC (Intended Nationally Determined Contribution), establishing goals for the reduction of GHG emissions and deadlines. Funding for investment in developing countries was also approved. (*Adoption of the Paris Agreement* 2015)

Despite being a developing region, Latin America (LA) has been through a deep transformation during the last two decades, growing faster than high-income countries. However, LAC still presents the highest ratio of inequality in income in the world. (IRENA, 2016) The priorities in the energy sector are thus fulfilling the rising demand, energy security and adapting to the consequences of climate change. In this context, economic growth drives the energy policy and INDC consider a growth in CO_2 emissions, putting the efforts in the reduction compared with the case where no action is taken.

LA is rich in energy sources, both renewables and non-renewables. Fossil fuels dominate the energy sector, yet hydropower is dominant in the electricity mix, turning the electricity into the most renewable in the world. Wind, solar and other renewable sources are, in opposite, far from large deployment, even though LA's diverse geography presents a good potential of non-conventional RES. (IRENA, 2016)

Problem analysis

2

The intention of this chapter is presenting the problem to be analyzed within the thesis. The information presented flows from the general problematic of global warming in Peru to the description of the specific problem. At last, the research question is formulated with the related delimitations.

2.1 Peru and the energy sector

Peru is a state of Latin America, a region with abundant potential for renewable energy sources but also region with the highest share of conventional sources in the energy mix.

The capital and biggest city of Peru is Lima, and the country is divided in 24 administrative regions (named *departamentos*, see Figure 2.1). Peru has a wide geographical variety, which can be divided in three areas: coast or *costa* (to the East in the Pacific, orange in the map), highlands or *sierra* in the Andes range (brown in the map) and rainforest or *selva*, the Western region also denominated *Amazonía* (green in the map). Due to the geography, Peru presents a wide variety of climates.

Fig. 2.1.: Regions of Peru (Flickr, 2018)

Peru has a population of over 32 million inhabitants in 2018. (United Nations, 2017) Its gross domestic product (GDP) in 2017 was 211 billion USD. Peru's per capita PPP GDP is 13,434 USD, being ranked as upper middle income with the neighbouring countries Colombia, Brazil and Ecuador; and behind the regional leader and also neighbour country Chile. (The

World Bank, 2018a) The economy in Peru is stable and with a continuous growth, one of the highest in LAC. The GDP has increased at an average of 6,1% yearly, over the average in LA. (The World Bank, 2018b) Peruvian economy relies heavily on the exports of commodities, i.e. natural gas and fish. Among them, the mining sector is critical for the economy, as it makes the 10% of GDP (El Peruano, 2018), providing 67% of exports, therefore it attracts an important part of the foreign direct investment (OEC, 2018). Peru is the world's second producer of silver, copper and zinc, fourth of lead, mercury and molybdenum and sixth of gold and tin (MINEM, 2018). The mining sector has an important influence in the energy mix, as it is an important driver for the construction of generation projects and consumes an important share of fossil fuels.

Considering the whole energy sector, Peru has a large share of 79% of non-renewable sources in its energy mix, meanwhile renewable sources account for only 21% of the mix, mainly for its important hydropower structure (2 Mtoe). (IEA, 2018) Fossil fuels dominate the transportation sector, with the highest consumption by sector in the country. For heating, biomass is used and in rural areas, kerosene and coal is used at households, with important risks for human health and air. On a first approach, the project will focus on the electricity sector to identify the problem to study.

2.1.1 Electricity in Peru

The national electricity grid is called SEIN (Sistema Eléctrico Interconectado Nacional) and the TSO is denominated COES (Comité de Operación Económica del Sistema Interconectado Nacional), a private entity without economic interest representing generators, transmitters, distributors and users. (COES, 2018) An updated map of the grid is shown in the Appendix A.1. SEIN, unfortunately, does not cover the whole population and even though important efforts were made by the government during the last decade, 5% of the population still does not have electricity access, due to geographical remoteness. (The World Bank, 2018a)

Hydropower is the base for electricity generation in Peru. However, since 2004, the natural gas share has increased in the country, covering the demand growth for the following years. Currently, with 47% and 46% share in the electricity mix, these two sources dominate the market. Other types of renewables like solar or wind (denominated unconventional renewables) have a very small share in the mix with wind power generating 1063 GWh and photovoltaics even less, 241 GWh in 2016. The evolution of the electricity mix is showed in the Figure 2.2:

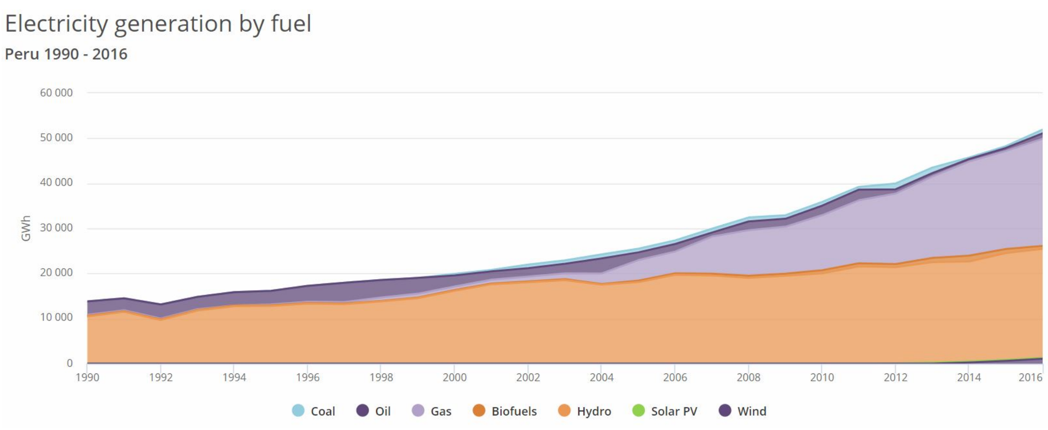


Fig. 2.2.: Electricity generation by fuel in Peru (IEA, 2018)

Peru is a country with a great potential for hydropower. Water flows from the high Andes to the wide rainforest of Amazonas, producing large flows which have been traditionally exploited for the generation of electricity. Peru had 4190 MW of installed hydropower capacity in 2016. (World Energy Council, 2018) The largest hydropower plant in Peru is Mantaro facility with 900 MW, proving one-third of the total electricity supply.

Natural gas in Peru had a sharp growth since beginning of the extraction in the Camisea Gas Field in 2004. Since 2007, new thermal power plans have been installed in the nearby area of Chilca to use up the extracted gas. This field is located in the Urubamba river basin, with gas reserves of up to 373 Mtoe. (World Energy Council, 2018)

2.1.2 Goals and policy

As a signatory country of the Paris Agreement, Peru submitted its INDC in 2016. The country committed to a 20% decrease of its CO_2 emissions compared to the business as usual scenario, and further to 30% in case of external funding by the year 2030. (Republic of Peru, 2015). The Business as Usual estimation given in the report is presented in the Table 2.1:

	Emissions ($MtCO_2eq$) including LULUCF	Emissions ($MtCO_2eq$) excluding LULUCF
2010 (base)	170,6	78,0
2030 (BaU)	298,3	139,3
2030 (INDC)	208,9	97,5

Tab. 2.1.: GHG emissions of Peru, (IEA, 2018)

Which means that Peru commits to reduce by 30% its total level of emissions accounting for 298,3 MtCO_2eq, resulting in a maximum of 208,8 MtCO_2eq in the year 2030, which means increasing the reference emissions in 2010 by only 22,4%; allowing economical development of the country while adhering to the fight against global warming.

Peru's legislation for renewable energy started in 2008 with the legislative decree n°1002 for the promotion of investment in RES. The regulation opened a period of auctions for renewable capacity, including wind, solar power and small hydro. This paper also establish an obligation of 5% generation of electricity with non-conventional RES (discarding hydropower) and this index should be reassessed every year. (Government of Peru, 2008) A small index of 5% and the development of infrastructure to exploit the natural gas of Camisea have driven to the electricity sector to a path where it is dominated by fossil fuels and RES are not competitive. The government presents the natural gas as a clean and local source of energy, without considering its CO_2 emissions linked to its fossil fuel nature and the long-term depletion of the gas. Important reforms are needed to change the path, and after more than 7 years, the index of 5% RES should be increased. The new share will be 15% by 2030, as the government stated. (Singh, 2018)

2.2 Solar energy: an unused potential

Peru is one of the countries with the largest potential for RES. The country has important potential for wind energy, geothermal, wave energy and biomass. (Energy Monitor Worldwide, 2018b) However, in this project only solar energy technologies will be discussed. Peru has an expected high potential for solar energy, due to its location near the Tropic of Capricorn. Currently, two technologies based on solar energy can generate electricity: using solar radiation to produce electricity (photovoltaics), or using the thermal effect of the radiation to heat water in a power cycle (CSP).

Fig. 2.3.: Photovoltaics vs CSP technologies
(InvestChile, 2017) (Scribbler, 2017)

Photovoltaics

In the photovoltaic technology, or PV; the electricity is produced by light absorption in semiconductor material forming PV modules. The systems using the technology are usually flat panels which can be placed on rooftops or gathered in large surfaces forming a solar plant. (Delft University, 2018)

PV technology can harvest a large range of the solar spectrum, therefore its potential is strongly related to the Global Horizontal Irradiation (GHI). A map with the Global Horizontal Irradiation (GHI) in a year in Peru is showed in the Appendix A.2. In some parts of the country the GHI reaches above 2500 kWh/m^2, and over 2000 kWh per kWp installed per year. To compare the results, the highest GHI in Spain is below 1900 kWh/m^2. The cost of the technology has falling dramatically over the last decade. From being one of the most expensive technologies, it can now compete with fossil fuels even without the help of subsidies. The average investment costs fell from 4394 USD/kW installed in 2010 to 1388 USD/kW in 2017. Currently, Peru has only 7 photovoltaic plants, most of them in the southern regions of Arequipa and Moquegua. (Delta Volt, 2018) In 2013, PV plants generated around 200 GWh of electricity, a figure which remained steady till 2018 when Rubí 145 MWp plant was opened, with a generation forecast of 415 GWh per year. (Energy Monitor Worldwide, 2018a) This plant was awarded with a price of 48 USD/MWh, the lowest for solar energy and close to the values awarded for wind and hydropower. The awarded value also represents one of the best prices for PV worldwide (IRENA, 2018).

The main disadvantage is the seasonality of the source, which is not available during the night and varies significantly depending on the weather. Therefore, it cannot fulfill the required conditions for firm power delivery, which means having a reserve whenever is needed in the grid. As a consequence of this, PV cannot participate in the wholesale electricity market, and it is only penetrating through tenders offered every two years and with limited capacity. Due to this restriction, CSP technology should be considered as it has the potential to overcome this barrier.

Concentrating Solar Power (CSP)

In CSP technology, electricity is generated by concentrating the sunlight in a small surface using mirrors, through different configurations: parabolic through, solar tower, Fresnel or stirling dish. Given that the technology uses reflection to concentrate solar energy, only beam (or direct) irradiation can be harvested. Thus, large amounts of thermal energy in the collector serve to heat water for use in a steam turbine. (Boerema et al., 2013) An advantage of this technology is the possibility of storing the surplus energy produced during the day to be used during the night, with high temperature fluids like molten salt or mineral oils. In this case, reducing the typical fluctuation nature of solar energy is possible. Another important advantage of CSP is the possibility of cogeneration or trigeneration, in other words, producing heat or other forms of energy for industrial processes, district heating or desalination, among others. As CSP output only depends on Direct Normal Irradiation (DNI), higher differences regarding the location exists. Taking a look in the world map of DNI (see Apendix A.3), it is remarkable that the region of Peru, Bolivia and Chile presents the highest yearly DNI. The map of DNI in Peru is showed in the Figure 2.4.

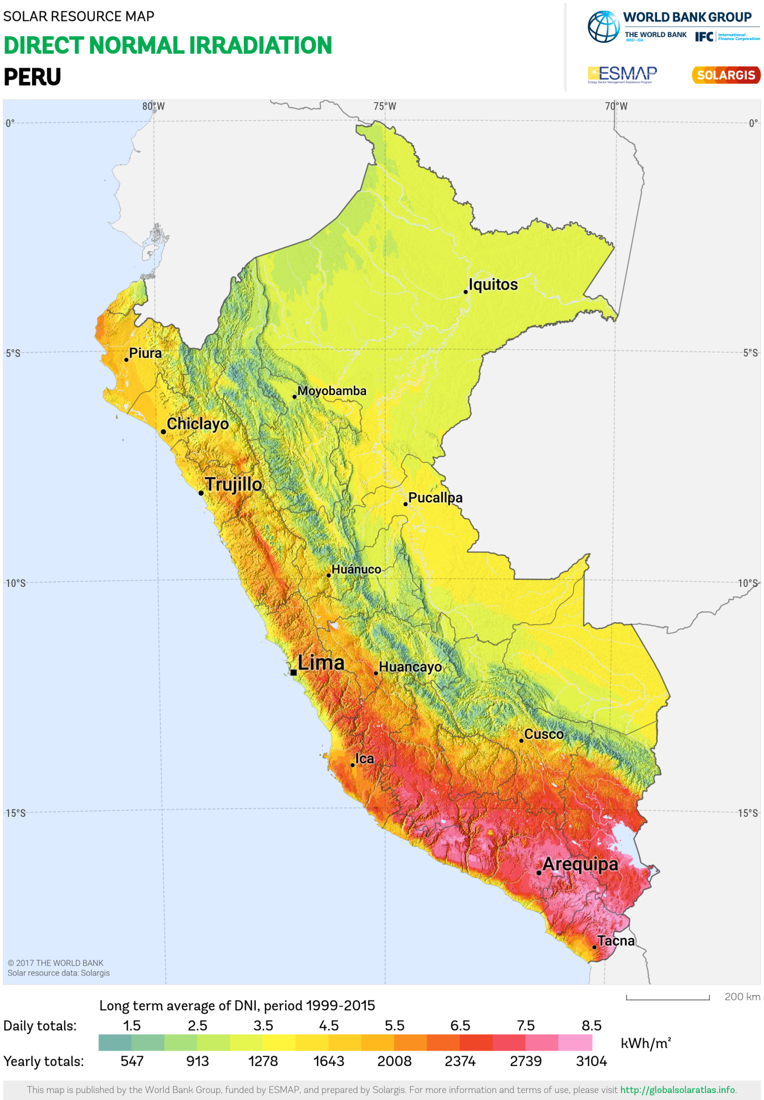


Fig. 2.4.: Direct Normal Irradiation in Peru, (World Bank Group, 2018)

The average investment costs for CSP fell from 7583 USD/kW installed in 2010 to 5564 USD/kW in 2017. The average cost of electricity generation with CSP technology is 250 USD/MWh. (IRENA, 2018) Therefore, it can be assumed that currently CSP is more expensive than PV.

Currently, there are no CSP-based power plans in Peru but the technology can be found in the neighbouring Chile. The high direct radiation in the south of the country predicts a high production with this technology. Even though CSP technology is old and traditionally used in few locations: Spain and USA; a recent deployment trend is appreciated around the world, with projects in China, South Africa and Australia among others. The evolution of cost in the last years indicates that learning effects and technology improvement have not yet affected the price, leaving room for significant potential reduction on the cost of CSP in the future. (IRENA, 2018)

Barriers for solar energy

However, the current electricity sector in Peru shows a low penetration of solar technologies in the market and the framework conditions might be hindering the deployment of the resource in the coming years. The large infrastructure created for the exploitation of Camisea gas, provides the resource with important incentives as tax exemptions despite the fossil fuel nature of the natural gas. Moreover, policy limitations currently prevent fluctuating sources to enter the spot market under the context of prioritization of security of supply, therefore the space for renewable energies is limited to the spectrum of tenders, which are based in the national goals for RES and by the time, only set a 5% penetration in the market. As it was previously stated, Concentrating Solar Power technology with storage can constitute a renewable energy solution satisfying the firm power requirement and delivering clean energy with a local resource, as well as integrate different energy supplies, for example through cogeneration of heat for industrial processes. But large-scale solar thermal power technologies are currently ignored by Peruvian energy planners, one of the main reasons being the lack of information about the possibilities and costs of this technology, as they are considered expensive compared with natural gas or hydropower solutions, which strongly dominate the electricity market.

2.3 Research question

Global warming urges societies to take responsible action and curb the emission of GHG. The electricity generation is traditionally dominated by the combustion fossil fuels, which not only depletes the resource but contributes in a large extent to global warming. The focus country is Peru, which can also represent a good picture of Latin America. Peru has its electricity generation divided nearly equally between natural gas fuelled thermal generation and hydropower generation, while the rest of RES have a negligible share. The local availability of natural gas counts with the support of the government and a good infrastructure, positioning Peru in a fossil fuel dependency path, with only 5% share of RES. Natural gas is even considered clean energy by the authorities, as it is compared with oil and coal, meanwhile other options including renewable energy are disregarded for being expensive and fluctuating in time. Yet the reality shows that not many studies have been conducted to assess the potential of alternative technologies in the country.

Following the Paris Agreement, Peru committed to reduce the expected GHG emissions by 30% in 2030. Concentrating solar power is presented as a possible solution to cut down emissions, when including storage to allow electricity production at any time and integrate several energy supplies. The proposed research question is then as follows:

Is Concentrated Solar Power (CSP) with thermal storage a techno-economically feasible option for Peru?

Subsequently, several subquestions have been formulated to structure the research and set the goals of the research in order to resolve the research question:

1. *How is electricity currently generated in Peru?*

   Before the analysis of the potential for CSP technologies in Peru, it is necessary to conduct an analysis of the current situation in the electricity sector. This analysis allows to find challenges and opportunities, which are decisive in the selection of the configuration for the appropriate CSP technology.

2. *Where are the most suitable locations in Peru to build large-scale concentrating solar power installations?*

   The first goal to assess feasibility of CSP addresses the geographical potential of CSP technology in Peru. Technology performance is heavily dependant on the Direct Normal Irradiation received. However, other it is essential to consider additional factors: suitable land use, flat terrain, water availability and proximity to the grid, transport networks and points of demand, like cities, industry or mines. The outcome should identify the best hot spots for CSP projects in the country

3. *What is the techno-economical feasibility for CSP-based electricity generation in Peru?*

The second goal is to model a CSP plant including thermal storage in an optimal location as found in the first subquestion. The model should include technical and economical parameters to obtain the Levelized Cost of Electricity for the plant and the Net Present Value of the investment. The results can be then compared with the typical values for conventional electricity generation in Peru (hydropower and natural gas).

2.4 Structure and research design

In this section, the correlation of chapters in the report is presented. Chapters follow a progressive path to answer sequentially the proposed subquestions, ending with the conclusions drawn from the research.

Chapter 3 sets the theoretical background of the project, presenting the worldview that has been taken by the researcher. It is linked with **Chapter 4**, where the methods used in the research are developed. Chapter **Chapter 5** analyzes the current situation of the electricity generation in Peru, setting a baseline for techno-economic goals to be fulfilled by the designed alternatives, hence answering subquestion 1. Subsequently, **chapter 6** shows the results of the geographical analysis to select the location of the proposed plant, as an answer to subquestion 2. Later, **chapter 7** presents the outputs of the modelled CSP plant, estimating the techno-economical feasibility to answer subquestion 3. Furthermore, in the **chapter 8** sensitivity analyses are performed to evaluate the relevance of the estimated parameters as well as to establish comparisons with the alternative fossil fuel technologies, as searched by the subquestion 3. Finally, a discussion of the results is presented in the **chapter 9** and the conclusions in the **chapter 10**.

The graph showed in the Figure 2.5 details the logic flow of the project from the elaborated subquestions to the corresponding analysis, from input data to processing methods and output results, constituting the basis of the designed research:

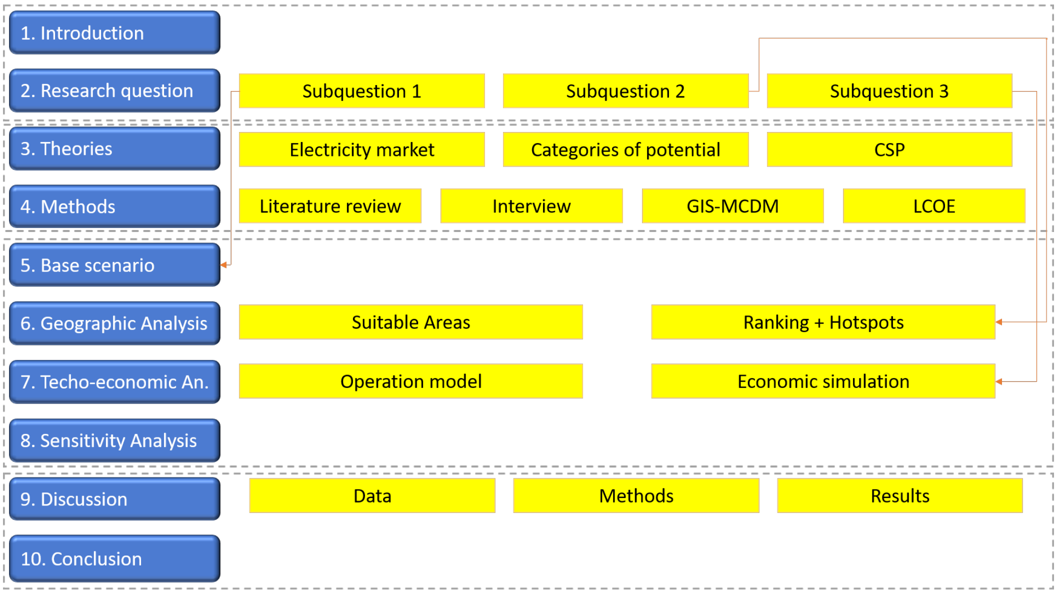


Fig. 2.5.: Structure of the report

3 Theoretical framework

The theoretical framework shows the worldview with which the researcher approaches to the reality. The chapter aims to create the background for the study, defining key theories and concepts that will enlighten the research process.

3.1 Liberalized electricity markets

National power markets worldwide have undergone significant development, from a public monopoly structure with vertical corporations to the liberation (privatization in many cases) of the majority of organizations in the market. The aims behind the transformation consist in improvements in the efficiency as imposed free market regulation and the introduction of a variety of technologies to compete for supplying inexpensive and reliable electricity to the consumers. In Peru, the process started in 1992 with *Ley de concesiones eléctricas* (LCE), a reform of the electricity sector which ruled the separation of the activities in the supply change, the introduction of competition and the corresponding regulation for each activity (Dammert et al., 2011).

After the reform, the vertically structured companies went through a profound change to open the market to competition. The most important step was dividing the electricity market services in three parts (Dammert et al., 2011):

1. **Generation**. The first part of the electricity market process, consisting in the transformation of different forms of energy (mechanical, chemical, radiation) into electricity. The electricity is generated in power stations which are classified in two groups: fossil fuel based (mainly thermal generation fired by coal, oil or natural gas) and renewable energy (hydro, wind or solar, among others). In a liberalized electricity market this sector is open to competition, in order to reduce the generation costs.

2. **Transmission**. It is the second part of the productive chain consisting in the transport of electricity from the generation site to the points of demand using a high voltage electricity grid. The transmission has an important impact in the generation and it impose a limitation on the capacity which is put on the

grid. The transmission activity is a natural monopoly, therefore is controlled by the Transmission System Operator, whose goal is not economic but to keep the balance between supply and demand, as the electricity cannot be stored and has to be consumed when it is generated.

3. **Distribution.** The distribution system has the function of delivering the electricity from the transmission system to the individual consumers. This sector has also been liberalized, allowing the competition before companies; even though in Peru the process of liberalization is not completed and each generator controls its area of operation and the customers cannot select the distribution company.

On the other hand, the consumers are divided in two groups: regulated consumers and free consumers. Regulated consumers receive the electricity by establishing a contract with a distributor, which ensure that electricity is delivered to the consumer. The prices are regulated. However, big consumers with a demand over 200 kW have the opportunity to become free consumers and thus they can negotiate the contracts with the generators. This is the case for industries, especially mines which are the largest electricity consumers in Peru. A grah showing the structure of the market is shown in the Figure 3.1:

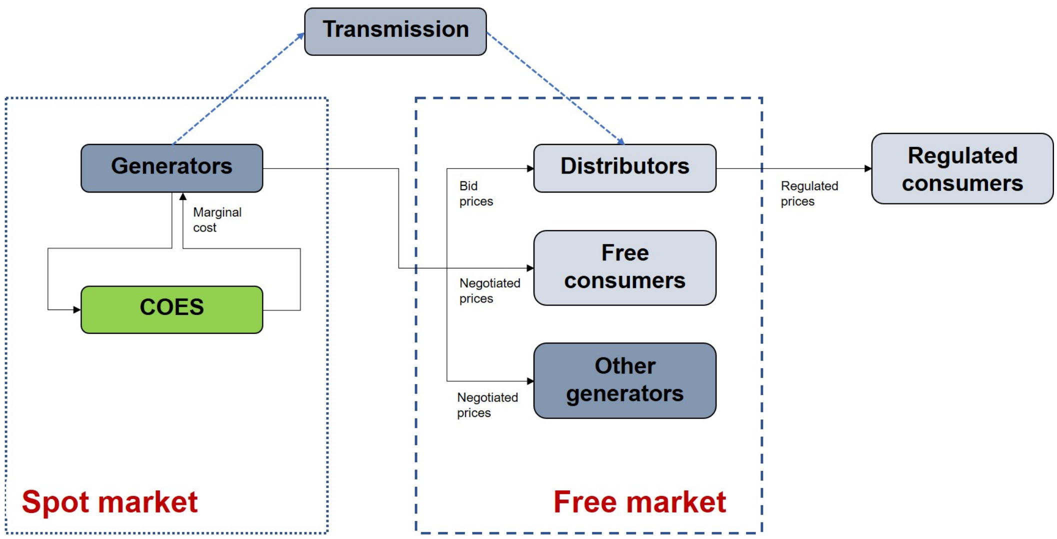


Fig. 3.1.: Diagram of electricity market in Peru, (Yaneva, 2018)

In the free or wholesale market, the electricity transfers are negotiated between generators, distributors and free consumers. The signed contracts have an economic nature, establishing a capacity agreed and a price. However, the physical transference of electricity have to be balanced at the moment. For that purpose, COES controls that generation "dump" to the grid as much electricity as demanded by the distributors and free consumers at a given hour. If generated electricity has a surplus or is missing, COES compensate generators for reducing or increasing their production. This is called the spot market.

One of the consequences of the competition in the generation sector was the incentive to reduce the operation costs to maximize the benefits. To ensure the maximum efficiency of the electricity generation, COES dispatch the capacity needed at a certain time frame from the generators with the lowest marginal cost until fulfilling the demand. The marginal cost is the cost of production of the next unit, and it is linked with the operational and fuel cost of the plant, therefore it is lower for renewable technologies than traditional technologies. The spot price is then based in the marginal cost of the last unit that enters in the dispatch of electricity. The plants also receive a payment for the installed capacity to cover the capital investment costs. An index that takes into consideration both operational costs and capital investment costs is the Levelized Cost of Electricity (LCOE) over the lifetime of the plant

When the supply of a generator is linked to the production cost, the most important factor to ensure the feasibility of the plant is presenting a low cost of production per unit of electricity. Therefore, the competition is based on the LCOE. The theory of minimizing the LCOE is used in the project to evaluate the feasibility of the selected technology, to ensure the competition in the liberalized energy market and generate profit.

3.2 Three categories of potential

To evaluate the electricity potential using a renewable energy source, it is important to consider three different categories of potential (Sun et al., 2013). This theory is based on the nature of RES, which are geographically located and require to be harvested on the site (with the exception of biomass based technologies). The three categories are hierarchical, and follow a determined sequence, as shown in the Figure 3.2:

3.2.1 Geographic potential

Geographical potential is based on the identification of suitable areas for the deployment of the technology, taking into consideration geographical constraints. (Sun et al., 2013) For CSP technologies, the most important geographical variable is the Direct Normal Irradiance that land receives along the year. However, important geographical restrictions apply. The land used for building up the installation will be restricted to any other land use. Therefore, areas covered by cities, agriculture uses, forests or wetland are not available for CSP projects. It is important to consider

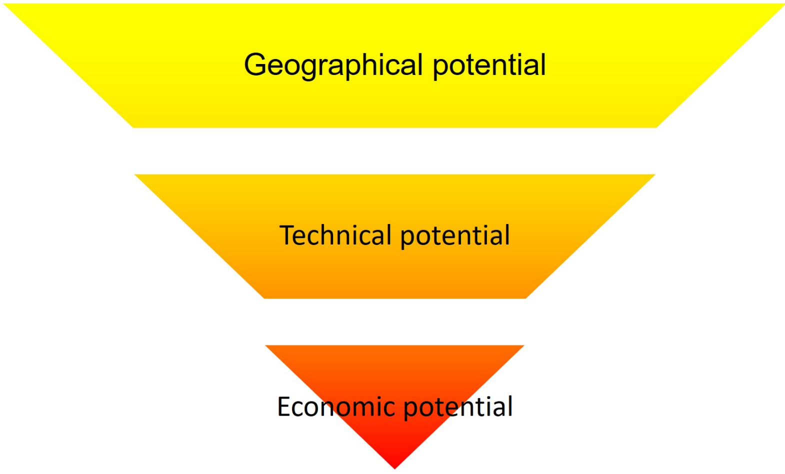


Fig. 3.2.: The three categories of potential. Created by author

available infrastructure on the neighbouring lands as road network in order to reduce the cost and the environmental impact. For the same purpose, environmentally protected areas must not be taken into consideration. The result of geographical potential is a map of the suitable areas ranked in regards of established criteria. This prioritization leads to using the method of Multiple Criteria Decision-Making (MCDM), which will be developed in the chapter 4. The second possible output is the overall natural resource (in kWh) in the study region which is possible to convert into power.

3.2.2 Technical potential

Technical potential evaluates the electricity output that is possible to harvest from the estimated geographical potential. This category takes into consideration the technical characteristics of the CSP system. (Sun et al., 2013) As Concentrating Solar Power presents a process of two different types of energy conversion: radiation-thermal (through the solar field) and thermal-mechanical-electrical (through a Rankine cycle), the efficiencies of the conversion steps are relevant to estimate the electricity output. Moreover, different configurations of CSP exist with distinct performance values. The various possibilities and elements they present are discussed in the next section 3.3

3.2.3 Economic potential

Economic assessment is the last and most essential part in the potential assessment of renewable energy technology. Even with good geographical and technical performance, the project must be attractive for investors and have acceptable profitability. To study the economic potential, costs and benefits are taken into account. Costs are split in initial investment and operation and maintenance costs. In CSP projects the operation cost is nearly null but they have large capital investments previous to the operation. On the other hand, revenues are accounted through the sale of electricity (and heat when cogeneration is used). Other financial measures to be looked at are taxation, incentives, cost of the debt and inflation. As it is a temporal study a discount rate is applied.

For the economic potential assessment of the project three financial parameters are calculated:

- Net Present Value (NPV): summary of cash flows during the lifetime of the project expressed in present value (with time correction through discount rate). This is a central tool in profitability assessment.

- Pay-back time (PBT): express the time when the initial costs of the project are covered, and the project starts to be profitable. It is an important value for investors, as private funds are requesting for quick returns of investment

- Levelized Cost of Electricity (LCOE): is the unitary cost of producing electricity in the proposed installation. The main functionality of this parameter is to serve for comparison with other alternatives for power generation. In this project the objective is to achieve an acceptable LCOE to compete with dominating technologies, i.e. natural gas and hydropower.

3.3 Concentrating solar power technology framework

Concentrating Solar Power technologies capture energy from incident Direct Solar Irradiation by optic reflection, transform the energy into heat and generate electricity using steam turbines, gas turbines or Stirling engines (Viebahn et al., 2011). Therefore, the structure of the CSP plants can be divided into the following subsystems: a solar block, a conventional power block, and an optional thermal storage which in case of existing connects the solar and the power block. Depending on the configuration of the solar block, four different categories of the technology exist: parabolic trough, solar tower, Fresnel collector and Stirling dish. The next paragraphs develop a short review of each technology and present their main advantages and disadvantages to set a comparison.

3.3.1 Parabolic trough

In a parabolic trough CSP system, the solar collectors are shaped like a U and form large rows of collectors with a single-axis tracking system. The radiation is focused in a pipe located in the focal point of the U, with a thermal fluid flowing inside the pipe and receiving the thermal energy reflected by the collector. The fluid flowing in the pipelines can be mineral oil or molten salt, with a high heat capacity to transport the heat to the power cycle where steam is generated. In this system, the sun radiation is concentrated up to 100 times, which produces a temperature in the fluid between 350-550ºC. The overall efficiency of the conversion solar energy-electricity is 15%. In these systems, the heat contained in the fluid can be stored to be used under the conditions of no incident radiation. Parabolic trough technology is the most widely implement CSP technology and moreover, the technology with a lower capital investment. However, the land utilization of the technology is the largest of all possible configuration, as a consequence of presenting the lowest concentration rate. (Islam et al., 2018)

3.3.2 Solar tower

In solar tower technology, a large field of flat mirrors, called heliostats, which are displayed around a high tower. The heliostats have a two-axis tracking system to focus the solar radiation in a single point in the top of the tower, which contains the denominated solar receiver, a high temperature heat exchanger that transfer the concentrated heat to a heat transfer fluid, in most cases molten salt. Molten salt is the denomination for a mixture of 60% sodium nitrate and 40% potassium nitrate, which is able to work at high temperatures in the range from 260 to 550ºC. An image of an operating solar tower is shown in the Figure 3.3:

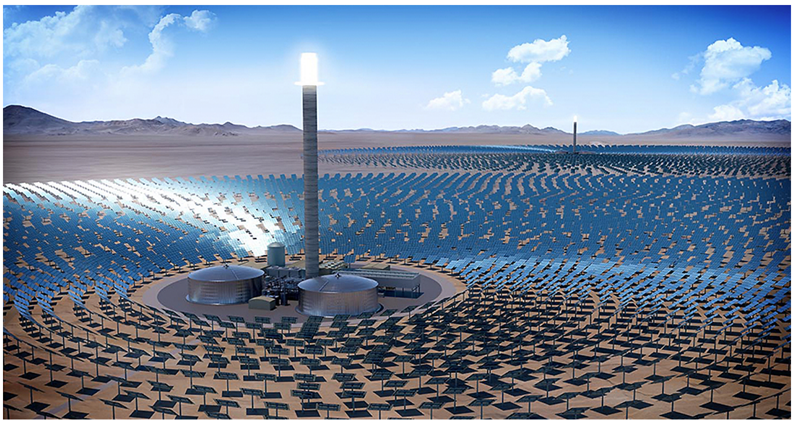


Fig. 3.3.: Solar tower CSP plant example, (Port, 2016)

The high level of concentration in the solar receiver allows high temperatures and high rate of production of heat. Therefore, the efficiencies achieved in the power cycle range up to 42%; and an important amount of energy is produced and can be stored. These systems have been the first to produce a 24 hours operation, using the stored heat to generate electricity at night or when sun is not shining. The molten salt acts as a transfer fluid between the solar receiver and the power cycle. The storage is divided in two tanks with different temperatures. The molten salt circulates from the cold tank to the solar receiver, where is heated by the concentrated radiation and transported to the hot tank. There, it can be used instantly to produce steam or it can be stored to produce steam later. The Figure 3.4 illustrates the process of electricity generation with solar tower molten salt technology.

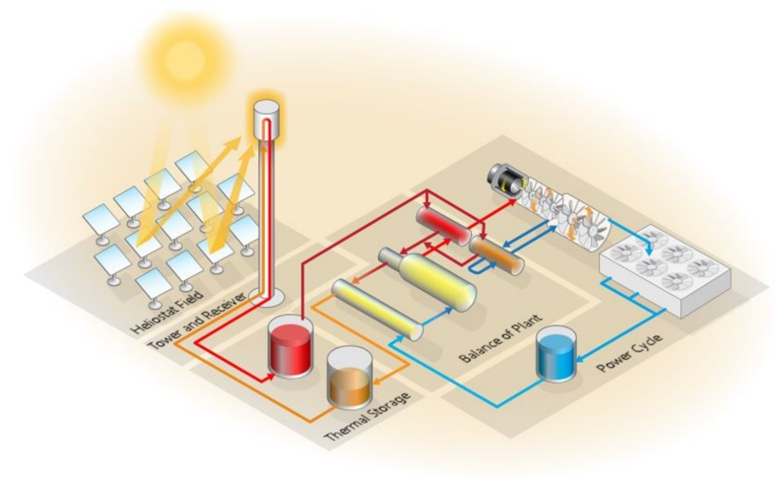


Fig. 3.4.: Solar tower diagram, thermal storage in two tanks of molten salt (NREL, 2019b)

To summarize, the systems the components of a solar tower plant are:

- Solar field: heliostats, tower and solar receiver
- Thermal storage with molten salt: hot tank, cold tank
- Power cycle: steam turbines, condensator and pumping system

The configuration of solar tower plants combined with molten storage is optimal for the production of continuous output in large-scale facilities. Moreover, as the power cycle is not directly connected to the solar tower; it is possible to hybridize with a back-up boiler to produce steam in case if it is necessary to maintain the electricity generation. The overall solar-efficiency of the system is between 20-35%. (Islam et al., 2018) The main advantages is the functionality as firm power generators and the possibility of implementing large-scale power plant with a high efficiency on the conversion of radiation into electricity. The disadvantages are the use of large areas of field and a high capital investment upfront.

3.3.3 Linear Fresnel

The mechanism of linear Fresnel is analog to a Fresnel lens. The solar radiation is reflected through lines of reflector with different inclinations to focus on one line. The system works in a similar way than parabolic trough, when the heat transfer fluid is heated in a pipe passing through the focal line of the mirrors; is used to heat steam for a power cycle. The advantage of the technology is a low capital cost compared with other types of CSP technologies. However, it has not been currently implemented in large scale at the time of writing this report.

3.3.4 Dish systems

In a CSP dish system, the radiation is concentrated in a single point through a collector with the shape of a dish. The system has a two-axis tracking system to follow the sun. The concentration rate is high, with values above 2000 times concentration, which allow the plant to run a high temperature cycle. The heat is transported in fluids working at high temperatures like helium to be used in a Brayton or Stirling engine. The configuration of the technology allows capacities around 0,5 MW per dish, therefore the systems are modular, likewise for instance PV modules or wind generators. This feature make dish systems suitable for distributed generation. The solar-electricity efficiency can be up to 30%, becoming the highest among CSP technologies. However, the technology has not reached yet a commercial production with only 2 units existing at the time of the study. (Islam et al., 2018)

The Figure 3.5 shows the configuration of the solar field for each CSP subtype of technology and presents the relative value of penetration in the market, based on the number of existing projects of each category:

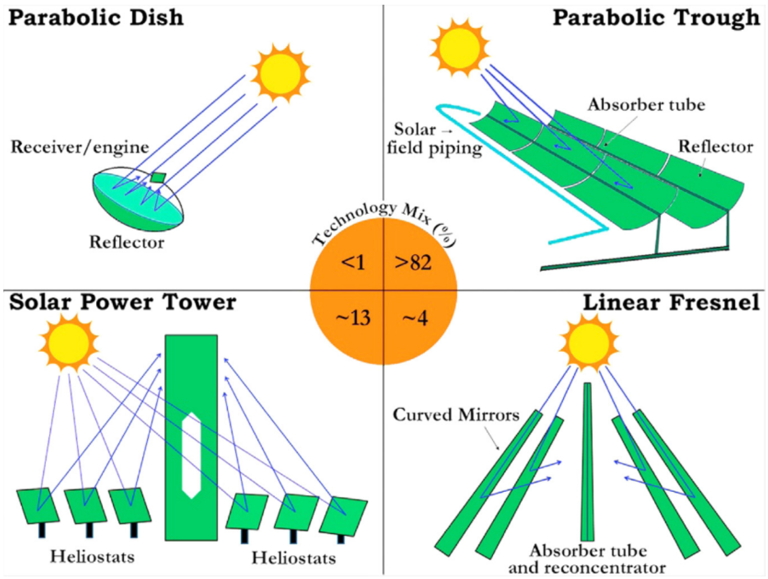


Fig. 3.5.: Four types of CSP plants along with their ratios of current number of projects, (Islam et al., 2018)

According to (Konstantin and Kretschmann, 2010) "Due to the lowest specific thermal energy storage costs, high capacity factors and firm output and dispatching capabilities, which also supports the grid stability, molten salt central receiver technology is expected to be the leading technology for solar power plants with high capacity factors" (Konstantin and Kretschmann, 2010)

Methodology

4

The following chapter presents the methods that have been used to answer the formulated research question. A variety of methods have been considered, from literature study for the first phase of the project, including interviews, simulation tools like QGIS and Excel and specific methods as multicriteria decision making.

4.1 Literature study

A comprehensive literature study is essential in the start-up phase of the project. It gives the research a point of departure and constitutes the background of the study. The process of literature research followed was, in a geographical approach, from a worldwide research to a focus in the specific situation of Peru. A wide variety of papers constitutes the body of studied literature:

- Energy statistics portals: IEA, World Bank group, IRENA and INEI (Peruvian Institute for Statistics).

- Institutional reports: Studies and analyses of the situation conducted by OSINERGMIN, COES or MINEM

- Press media: Articles in the national media describing the latest news about energy generation projects in Peru. Includes *El Peruano* and *El Comercio*.

- Specialized scientific articles on the topic of Concentrating Solar Power technologies. They were at the first stages of the process to define the methodology for the quantitative analyses. Two articles in the topic of the report are highlighted: (Aly, Jensen, et al., 2017) and (Aly, Bernardos, et al., 2018)

4.2 Interview

The interview is a powerful strategy to gather data in qualitative research. The objective of the interviews is to gain knowledge on a topic from the answers of experts in the field. The interview method is used when not much is known in a specific area and, a conversation with a knowledgeable person sheds light to start the process of acquiring the necessary information. In the start-up part of the project, the interview has proved to be a more time-efficient data collection method. For this reason two interviews have been arranged during the research process. Both interviews had as interviewees professors from the Universidad de Ingeniería y Tecnología (UTEP), which were interested and collaborative with the study topic.

The environment of the interviews was a telephonic conversation due to the geographic distance with Peru. From the researcher point of view, a telephone interview is not the most advantageous for the communication as it can produce interference in the communication and the settlement tend to force short interviews because of the lack of closer personal intercommunication. On the other hand, they are a faster method and allow a certain degree of personal contact (Valenzuela and Shrivastava, 2006)

The methodology chosen was semi-structured interviews. This method was an effective way to control the topic of the conversation through questions prepared before the interview, although a space is given to the interviewee to diverse the conversation and add relevant topics that might have not been considered at first hand by the interviewer. (Gill et al., 2008)

The first interview was conducted with the professors **Julien Noel** (PhD Electrical engineering) and **Elmer Ramirez Quiroz** (MSc in Energy Management and Audit in Business). The objective of the interview was set to get familiarize with the electricity sector in Peru. The first part of the interview was a background speech about the functioning of the liberalized electricity market in Peru and the main problems at the moment, highlighting excess of supply, sinking of prices and increase of the number of free users. Subsequently the interview covered the topic of renewable energy tenders in Peru. The second part of the interview, questions were asked to clarify different concepts about the Peruvian market: *potencia firme* (firm power), *precios en barra* (fixed generation costs) which substitutes the spot price of the European systems. The last part of the interview treated specific successful projects of solar power in Peru: individual solar systems for off-grid zones as part of the Plan for Rural Electrification and the recent connection of the largest PV plant of the country: Rubi.

The main conclusions obtained was his impression that fluctuating technologies cause disruption on the congested electricity grid, generation capacity will not increase during the next 3 to 4 years due to excess of supply, except if new large mining project are developed. Firm power is a regulation which forces the generation to present large capacity factors to fulfill the demand, of at least 40% or signing contracts with other generators. Private funded projects with renewable energy have not been developed because of the limitations of firm power. Natural gas is subsidized for electricity generation, since generators do not pay the real value of the natural gas like industry does. The findings of this interview constitute the starting point for the analysis of the current situation of the electricity sector, which is presented in the Chapter 5

A second interview was arranged after a recommendation by the first interviewee Julian Noel, with to the professor **Eunice Villicaña** (PhD. in Technology, Sustainability, Quality and Energy Efficiency), an expert and instructor of Concentrating Solar Power technology in Peru. The interview was likewise the first one semi-structured, with questions designed to investigate the main factors for the calculation of LCOE for a CSP power plant in Peru. The interview was conducted after a visualization of the intervention of the professor in the Global Energy Forum of Peru about the feasibility of CSP plants in Peru. She explained the calculation and introduced a methodology for the comprehensive calculation of parabolic troughs power plants and solar tower plants, obtaining monthly productions and calculating the corresponding LCOE. The method was an important imput for the project but had to be modified, to change the time steps of the process from monthly values to hourly values.

In the last part of the interview, a discussion on the Peruvian electricity market was carried out to study the fit of renewable energy projects in the market. It was identified the difficulty to compete with natural gas, which in many cases presents costs nearly equal to 0. The problem with firm power was also identified by the professor, who additionally identified lack of regulation for renewable energies and blamed the dominance of natural gas and hydropower in the market. Subsequently, she described the geographical asymmetry of the grid due to the energy planning of the country. Financial parameters for economic calculations were given during the interview. To conclude, she established a threshold for the feasibility of the CSP on a LCOE of 80 USD/MWh, which will be used for the validation of results.

4.3 Geographic potential analysis

The first part of the analysis lies in the identification of suitable areas and hot spots for large-scale CSP installations in a national scale. Suitable locations are not only linked with a high level of direct normal irradiance, but to other essential factors such as adequate land use, proximity to demand, flat terrain and presence of water among others. Therefore, it is considered a complex problem. In order to solve the problem, a methodology consisting in two tools was followed:

- **Geographical Information Systems (GIS)**. GIS systems are designed to create, manage and analyse geographic data. (Maliene et al., 2011) The information provided is location-based, i.e. it is referred to a Spatial Reference System (SRS). As the area of study corresponds to a large country, the project used the global SRS. The information was handled in two different data formats:

  – **Vector**: a vector file contains geographical datasets organized in vectors, representing geometrical shapes: points, lines or polygons. It is used primarily for discrete information as sociological features or administrative borders. Formats used: shapefiles (*.shp*).

  – **Raster**: a raster file is a database contained in a grid, with pixel as the minor entity in analogy with digital photography. Each pixel contains a different value, while the whole dataset represents a specific attribute. It is ideal for representation of continuous information, as elevation maps or suitable areas. Formats used: *.jpeg*, *.tiff*.

  The geographical potential analysis was performed in the GIS-based software Quantum GIS (QGIS: *qgis.org*), an open source applications run by different contributors, with the objective of making geographical information and analysis publicly available.

- **Multicriteria Decision Making (MCDM)**. MCDM is a method aimed to address the decision-making process when multiple objectives are pursued. In sustainable energy assessments, it is important to determine the relative importance of each criteria in the final decision. This is generally a qualitative process which should be led by rationality, as the risk on falling in the subjectivity of the author exists. Because of the lack of time to conduct interviews with more experts in the field in Peru, weights have been taken from (Aly, Jensen, et al., 2017) and adapted following guidelines suggested by interviewees and available data. Each criteria is ranked on different tiers, giving points gradually from the highest to the lowest impact. Subsequently, the set of criteria is weighted to obtain an individual ranking of suitable areas, which allows the identification of the best hot spots, or the best possible decisions according to the desired objectives.

  The application of GIS-based MCDM is a powerful tool in the planning science for a decision making process, especially when the focus is put in natural resources. (Greene et al., 2011) Assessments of geographical potential for renewable energies using GIS-based MCDM have been carried out in different regions of the planet, for example (Bravo et al., 2007) in Spain and (Ramachandra and Shruthi, 2007) in India. However, not many examples can be found in Latin American region, where renewable energies are expected to have an important potential. Only one recent assessment for Ecuador was identified among LA countries (Cevallos-Sierra and Ramos-Martin, 2018). Furthermore, most MCDM studies are applied to small regions within provinces. The few previous reports using MCDM methodology to assess a whole country's CSP potential were made in Jordan (Fichter et al., 2014), Australia (Dawson and Schlyter, 2012) and Tanzania (Aly, Jensen, et al., 2017). The methodology of the latter article, especially criteria and weighting of ranking criteria has been closely considered in the analysis.

The analysis is set in the whole territory of Peru. The first step is the identification of relevant criteria for the suitability of CSP. Two types of criteria are selected: exclusion criteria (EC), in case the geographical features make it unfeasible to establish a CSP installation in the area; and ranking criteria (RC), selecting the factors that enhance the feasibility of the installation. Subsequently, GIS layers representing identified criteria are downloaded from national and international databases, in order to create a GIS database. Layers expressing EC will be processed to constitute excluded areas. For the RC, layers are reclassified giving points in a scale from 0 to 100, and then assigned a weight according to the relative relevance of the criterion compared with others. The result is a layer with different values showing the suitable areas ranked according to RC. Finally, the best 10 ranked areas are assigned as hot spots, in other words, as the best locations for a large-scale CSP installation in the country. The process to follow is represented in the graph of the Figure 4.1:

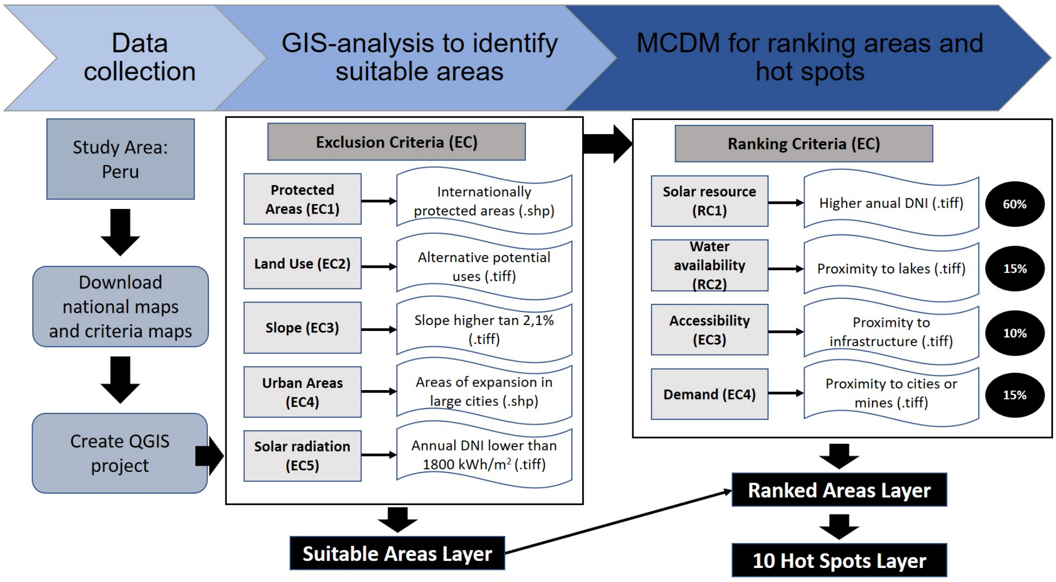


Fig. 4.1.: Methodology for geographic analysis

4.3.1 GIS-analysis to identify suitable areas

The suitable areas layer obtained is the combination of the complete surface of Peru with the removal of all areas which do not fulfill any of the established exclusion criteria (EC). In order to be able to overlap different layers, only the SRS system WGS 84 has been used for the projection of every GIS-based map. Information regarding administrative limits, urban nucleus and infrastructure in Peru have been downloaded from the official authorities Geodata dataset insfrastructure (GEOIDEP) (Government of Peru, 2019). Exclusion criteria are technology specific, as they contain the necessary geographic features that a CSP installation needs, and at the same time excludes areas which for environmental or human impact reasons cannot be considered for energy utilities. Compared with analogue studies (Aly, Jensen, et al., 2017), the range of selected EC is comprehensive. The next paragraphs will elaborate on the studied EC.

Protected Areas (EC1)

Protected areas are according to the International Union for Conservation and of Nature (IUCN) "*a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long term conservation of nature with associated ecosystem services and cultural values*. The GIS dataset is provided by the World Database on Protected Areas (WDPA). (IUCN and UNEP-WCMC, 2018) It is possible to download the dataset for Peru. All the protected areas marked in the map were excluded.

Land Use (EC2)

The CSP installation will occupy a large area of land, therefore it is important that this area does not have potential productive uses. Among others, forests, agriculture lands, cities or wetlands should be excluded as they have a social utility. The dataset containing land use is provided by the European Space Agency's (ESA) GlobCover Database 2009 (European Space Agency, 2009). The information is presented in a raster classified in 23 categories, from which only 4 have been considered suitable for CSP installations: 30 (primarily terrestrial vegetation), 140 (herbaceous closed to very open vegetation), 150 (herbaceous sparse vegetation) and 200 (bare areas).

Slope (EC3)

Large-scale CSP power plants must be constructed on flat terrain to allow appropriate reflection. According to consensus, areas with a slope higher than 2,1% should be excluded when considering the implementation of a CSP project. (Trieb et al., 2009) The slope map is derived from a Digital Elevation Model (DEM) using the QGIS tool GRASS. DEM information was provided by the NASA Shuttle Radar Topographic Mission (SRTM) through CGIAR-CSI GeoPortal (A. Hiraneg Jarvis, 2008) The map is downloaded in a tile format of 30x30 degrees to contain the whole surface of Peru. The information is contained in a raster with values of altitude for every pixel, with a spatial resolution of 90 meters.

Urban Areas (EC4)

This exclusion criteria is not only aimed to remove the urban areas but also the areas which are expected to be urbanized by the end of the lifetime of the project (20-30 years), following the urban expansion in a country with a growing population. Peru's Population in 2018 was 32.551.815 inhabitants, which is expected to rise up to 41.620.307 by 2050, which means a population growth of 28%. (United Nations, 2017) Only large cities will be considered, setting the threshold in 100.000 inhabitants. Three tiers were created (see Table 4.1): Lima (7.737.002 inhabitants), constitutes a tier itself; cities over 250.000 inhabitants (11 cities), and cities over 100.000 inhabitants (9 cities).

Cities > 1m pop	**Cities > 250k pop**	**Cities > 100k pop**
Lima	Arequipa	Ica
	Trujillo	Juliaca
	Chiclayo	Sullana
	Iquitos	Chincha Alta
	Huancayo	Huanuco
	Piura	Ayacucho
	Chimbote	Cajamarca
	Cusco	Puno
	Pucallpa	Tumbes
	Tacna	
	Santiago de Surco	

Tab. 4.1.: Large cities in Peru, (INEI, 2018)

Urban areas are then compared with the population of the cities, setting averages areas for each tier. Each tier average area has been multiplied by the population growth, considering an uniform urban area expansion. It is a very conservative assumption, as population can also growth vertically, with higher buildings. Urban areas have been assumed to be circular, so an average radius can be calculated based on the area. The radius of the extended area for each tier will be used to calculate urban areas exclusion layer. Areas and radius considered for the creation of the layers are summarized in the Table 4.2:

Tier	Av. Area (km^2)	Av. Exp. Area (km^2)	Radius (km)
1	700	896	17
2	80	102,4	6
3	40	51,2	4

Tab. 4.2.: Radius of exclusion for urban areas

Solar Radiation (EC5)

Solar radiation is the most decisive factor in the performance of solar technologies. For Concentrating Solar Power, only Direct Normal Irradiance (DNI) produces energy. Therefore, a CSP installation should be built in an area with high values of DNI. With that purpose, areas with annual DNI values of less than 1800 kWh/m^2 are excluded as suitable options. (Aly, Jensen, et al., 2017) The information about the annual DNI is taken from the Global Solar Atlas provided by Solargis for the World Bank Group (World Bank Group, 2018). The Global Solar Atlas is based on information gathered through the combination of sensors at meteorological stations and satellite-based meteorological models. The results are based on the last 10 years, and represent a Typical Meteorological Model (TMY), which can be used for the preliminary assessment of solar power projects.

The layers produced by the exclusion criteria are processed with the tool GRASS for QGIS. With this tool, vector files are transformed in raster files, with which it is possible to perform algebraic operations to create a mask with the superposition of all excluded areas, obtaining with the difference a map of **suitable areas** for a large-scale CSP installation.

4.3.2 MCDM analysis to rank suitable areas and identify hot spots

After excluding unsuitable areas for CSP technology in Peru, a MCDM analysis has been carried out to rank the suitable areas and identify the hot spots for CSP installations. In the next paragraphs, the ranking criteria considered are presented, justifying why they are important for the ranking and establishing the thresholds which mark a significant change in the suitability of the project. Subsequently, criteria are organised in tiers and each tier is given a quantitative score from 0 to 100 (0 for the least-favourable tier and 100 for the most-favourable tier).

Solar Resource (RC1)

The DNI is the primary resource of a CSP installation, therefore the electricity generation is directly linked with the amount of DNI the plant is receiving (see section 7.1). Sites with higher direct irradiation will have a positive impact in the feasibility of a CSP facility. The information about the annual DNI is taken from the Global Solar Atlas provided by Solargis for the World Bank Group (World Bank Group, 2018), using the layer generated for EC5. As the values for annual DNI range from 1800 to 3149 kWh/m^2 (note that values lower than 1800 kWh/m^2 were excluded), a threshold is set in 150 kWh/m^2 to establish 10 tiers, from the highest to the lowest annual DNI.

Water availability (RC2)

CSP technology uses the concentrated direct radiation to generate steam to run a Rankine cycle. Like a standard Ranking cycle, a condensation step is present which has a high water requirement for cooling. A smaller amount of water is also necessary to wash the mirrors of the heliostats (see chapter 3). The information is taken from the Global Database of Lakes, Reservoirs and Wetlands (Lehner and Döll, 2004) and clipped to save only information regarding Peru. Only data with the value 1, representing lakes have been considered as scarcity of water is a rising social problem in Peru, therefore the water in flowing streams will be left for the use of the population. Departing from the information of GLWD a layer showing proximity to the considered water sources is created. Due to the high cost of pipeline and pumping installations a threshold of 2 km has been established to originate 4 tiers. Locations located further than 9 kilometers from a lake are considered unfavourable.

Accessibility (RC3)

The proximity to the existing infrastructure is an important factor which will determine the initial investment for the project. For power transmission, a transmission line must be built to link the facility with the closest substation. Moreover, road infrastructure is necessary to transport massive equipment to the location. As transport in large trucks is necessary, only national roads from the *Red Vial Nacional* will be considered. The state of the roads in Peru is diverse, due to the lack of renovation, altitude and geographical remoteness of many of them. The majority of national roads are paved, therefore are considered appropriate for the transport. The information about RVN is provided by the Geodata dataset insfrastructure of Peru (GEOIDEP). (Government of Peru, 2019) A GIS-based file of SEIN (electricity grid) has not been found, therefore proximity to the grid will not be considered in the analysis. As many transmission lines are built in parallel to the roads, a higher weight factor will be given to road network to represent the RC3. A threshold of 5 km of distance to the closest national road has been established to create 4 tiers. Locations further than 20km to the road network will be considered unfavourable, as a new road must be built in these cases.

Demand (RC4)

The demand criterion studies the proximity of the future installation to centres of supply. There are several reasons for taking this factor into account. On one hand, if the electric supply area is close to the generation, losses in transmission decrease. On the other hand, it is interesting to study the possibility of cogeneration of heat and power in a CSP plant, a case in which the proximity to a city with relevant industrial sector is important to sell the heat. Therefore, the urban nucleus calculated in EC4 are used establishing different thresholds depending on the size of the city. For Lima, a threshold of 10 km from the edge of the expansion area is used to create 4 tiers, considering areas with more than 60 km distance unfavourable. For cities bigger than 250000 inhabitants (excluding Lima), 5 tiers with thresholds of 5 km were created with 30 km limit to be considered favourable. Analogically, cities bigger than 100000 inhabitants present 3 tiers with thresholds of 4 km and a limit of 16 km to be considered favourable. As a very important client and promotor of large generation projects in Peru, the mining sector has been considered as a potential demand of electricity. For that reason, proximity to areas with mining license has also been considered. Information has been provided by the Mining Cadastre information system (GEOCATMIN) (INGEMMET, 2018). 3 tiers with a threshold of 5 km have been created, with a maximum of 15 km to the mine to be considered as favourable.

With each criterion ranked from 0 to 100, it is important to weight the relative relevance of one criterion compared with the other ones, to assign a weighed percentage to each criterion. This information has a qualitative nature which must be quantified, so it is subjected to the individual criteria of the researcher. A good experience in CSP technology and economy is important as well as notions of the peculiar features of the considered region. As the size of such a broad research exceeds the scope of this thesis, the weight factors that have been taken into consideration are those ones used in a similar study of geographical feasibility for Tanzania (Aly, Jensen, et al., 2017), including certain modifications based on the objectives of the research and information obtained in the interviews. The Table 4.3 compares the values proposed for CSP in (Aly, Jensen, et al., 2017) and the values finally selected for the analysis:

RC	(Aly, Jensen, et al., 2017) (%)	Weight factor (%)
RC1	61,8	**60**
RC2	20,3	**15**
RC3	13,4	**10**
RC4	4,5	**15**

Tab. 4.3.: Values for weighting ranking criteria

The relative relevance of water availability has been diminished, considering the social problems that water scarcity presents in Peru and have been represented by conflicts with mining companies and the government (Bedoya and Lozada, 2010). In case no water resource is available, dry cooling could be a valid option. Accessibility criteria have also reduced its relative importance because of the lack of geodata for SEIN and uncertain conditions of roads for transport. It can be considered a demand-driven geopotential scenario, as the weight factor for demand has been raised from 5 to 15%. Proximity to populations have been considered important, also admitting the relevance of the mining sector in Peru when it comes to investments in electricity generation. The idea of analysing the possibilities for generation gives also a good reason to increase the factor for demand.

In order to apply the assigned weighting factors, the ranking scores have been multiplied by the corresponding factor, and the results are combined with the suitable areas layer to study only the areas which were not excluded in the first part of the analysis. Theoretically, it would be possible to obtain scores of up to 10000 points (100 score on each criterion). However, the analysis produced overall scores ranging from 2400 to 8500 points. Finally, the results are presented in the layer ***Best CSP*** in the form of a heat map according to the scores obtained. Then, the best 10 scoring areas are selected as hot spots.

4.4 Techno-economic potential analysis

In this study a CSP solar tower with molten salt storage plant has been modelled in the location of one hotspot found in the geographic potential analysis. The analysis is based on hourly modelling of energy systems and economic simulation of the project, which have been carried out in Excel spreadsheets, using parameters given by the software System Advisor Model (SAM) provided by (NREL, 2019b); and using methods and parameters designed by professor Eunice Villicaña Ortiz from UTEC (Ortiz, 2018b), an expert in CSP analysis in Peru (see interview part of the methodology). The method is divided into three parts: solar resource modelling, annual operation modelling, and economic simulation.

4.4.1 Solar resource modelling

Solar power technologies concentrate the Direct Normal Irradiance (DNI) incident on the mirrors of the heliostats by reflection towards a receiver to heat a heat transfer fluid (HTF) based on molten salts, which is afterwards use to run a Rankinke cycle. Therefore, the solar resource and concretely the DNI plays the most important role in the performance of a CSP plant. However, the solar radiation natural variability entails a degree of uncertainty in forecasting the overall performance of the plant, therefore a proper radiation assessment is necessary. After having carried out the geographical assessment of the resource, it is important to assess the temporal variability of the resource, which is also significant. Solar radiation is seasonal depending on the latitude, with striking differences between summer and winter (especially in regions closer to the poles). Moreover, it depends on the time of the day, with no radiation values from the sunset to the next sunrise and normal distribution during the sun hours, with a maximum around noon. Lastly, the irradiance incident in the surface depends also on the weather, as clouds or other phenomena can act as barriers.

To generate annual DNI hourly values, a Typical Meteorological Year (TMY) dataset has been downloaded from NREL's National Solar Radiation Database (NSRDB) for the closest measuring point to the used area. (NREL, 2019a) A TMY represents weather conditions for an average year, as a result of the analysis of a multiyear period. The annual DNI value is taken from the result of the geographical potential analysis, and subsequently distributed according to the TMY dataset, using the following equation 4.1:

$$DNI_i^* = \frac{DNI_{TMY,i}}{\sum DNI_{TMY}} \cdot AnnualDNI \tag{4.1}$$

where:

DNI_{TMY}, the hourly values of the TMY dataset.
annual DNI, value of annual DNI for the selected location (see Table 6.9).
*DNI**, hourly values calculated for the annual operation analysis.

4.4.2 Annual operation modelling

For the technical feasibility analysis, a 50MW solar tower with molten salt storage has been modelled using Excel to run hourly simulations to estimate the electricity generated by the plant. The technical parameters of the components of the CSP plant have been obtained from SAM and UTEP slides by Eunice Villicaña. The complex system of a solar tower plant (summarized in the section 3.3) has been divided into 3 main subsystems as shown in the Figure 4.2:

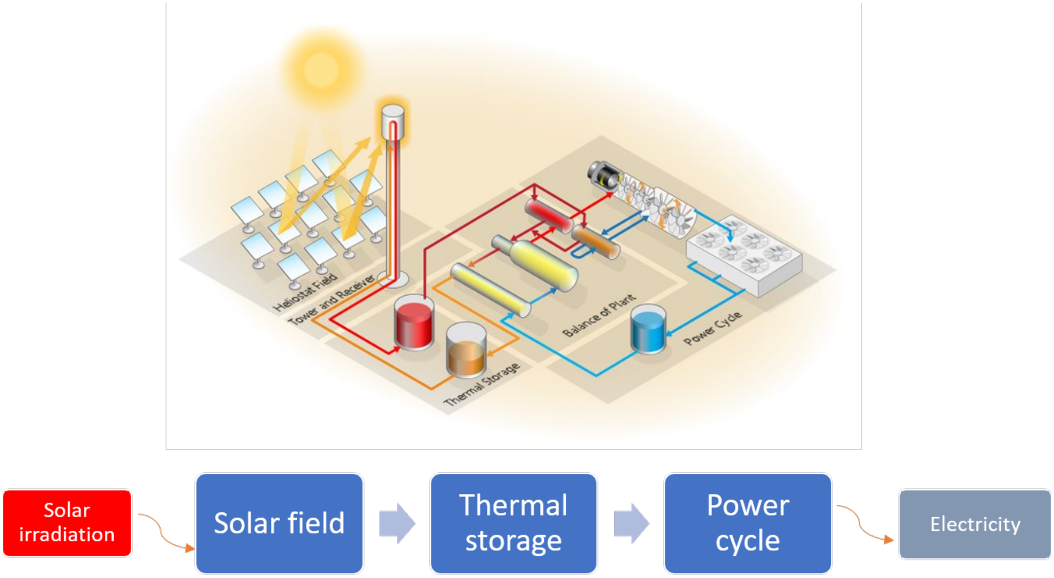


Fig. 4.2.: Solar tower molten salt facility diagram. Source (NREL, 2019b)

The goal of the analysis is a economic optimization of the CSP plant. With that purpose, the technical model has been designed on two basic parameters, which allow to modulate solar field and thermal storage:

- The **Solar Multiple (SM)** is a parameter that controls the solar field. It is the rate between the solar field area (A_{sf}) and the solar field area needed to produce the firm power at the DNI design point, i.e. at the time with the highest radiation.

$$SM = \frac{A_{sf}}{A_0} \tag{4.2}$$

$$A_0 = \frac{P_{th} \cdot 1000000}{DNI_0 \cdot \mu_{sf}}$$

- The **hours of thermal storage (HTS)** is a parameter that shows the hours that a full storage can supply the necessary thermal power to run a full load power cycle. It is the rate between storage capacity and the capacity to store energy to supply the necessary thermal power for 1 hour.

$$HTS = \frac{C_{TS}}{C_0} \tag{4.3}$$

$$C_0 = P_{th}$$

The technical parameters have been selected from default values of the state of the art model included in the CSP power tower molten salt package of SAM. Efficiencies are provided by the UTEP slides supplied by the interviewee Eunice Villicaña. It is necessary to note that efficiencies depend on the exact setting of the plant, fluctuate during the day and among a wide range of technical parameters, which are out of the scope of this study. But it is important to highlight that variations in the considered parameters have a crucial impact on the output. In the Table 4.4, the parameters used to define the systems of the plant are specified, attaching the source or the formula from which have been calculated

After defining the technical parameters in the plant, the hourly operation for a year is implemented in an Excel spreadsheet. The operation is based on a set of parameters which are calculated hourly and quantify the use of incident solar irradiance by the system. The parameters established are:

- **Potential heat to be transferred to molten salt**. Each hour the solar irradiance is reflected by the heliostats field into the solar receiver where molten salt is circulating. Through heat exchange, the heat can be transferred to the molten salt migrating to the hot tank. It is named potential heat because in case hot tank is full, the heat cannot be transferred to the molten salt. The hourly heat to be transferred to the salt is calculated as the product of the incident DNI, the helistats area and the efficiency of the solar field, removing radiation losses.

$$Q_{salt,i} = DNI_i^* \cdot A_{sf} \cdot \mu_{sf} \cdot (1 - Q_r) \tag{4.4}$$

- **Thermal input**. The power plant is designed to generate a firm power of 50MW uniformly along the year, therefore it needs 135MW of thermal input. For that reason, a thermal input of 135MW is necessary in order to ensure that power cycle runs the plant. The thermal input is covered by heat exchange with molten salts, which can be heated either by irradiance harvested on the calculation hour or thermal energy stored.

Item	Symbol	Value	Unit	Source/Equation
POWER CYCLE				
Firm Capacity	P_0	50	MW	Input
Cycle efficiency	μ_{RC}	41,2%	-	SAM
Alternator efficiency	μ_e	90%	-	UTEP
Thermal input	P_{th}	135%	-	$\frac{P_0}{\mu_{RC} \cdot \mu_e}$
HELIOSTAT FIELD				
Cosine efficiency	μ_{fc}	80%	-	UTEP
Shadowing & blocking eff.	μ_{sb}	95%	-	UTEP
Reflection efficiency	μ_r	80%	-	UTEP
Flux distribution eff.	μ_{fi}	90%	-	UTEP
Atmospheric attenuation	μ_{aa}	93%	-	UTEP
Solar field eff.	μ_{sf}	62%	-	$\mu_{fc} \cdot \mu_{sb} \cdot \mu_r \cdot \mu_{fi} \cdot \mu_{aa}$
DNI Design	DNI_0	1060	W/m^2	$max(DNI_i^*)$
Area solar field	A_{sf}	Calc.	m^2	$\frac{P_0 \cdot SM \cdot 1000000}{DNI_0 \cdot \mu_{sf} \cdot \mu_{RC} \cdot \mu_e}$
Heliostat Area	A_h	144	m^2	SAM
Number heliostats	n_h	Calc.		$\frac{A_{sf}}{A_h}$
Non-solar field Area	A_{nsf}	180000	m^2	SAM
Total Area	A	Calc.	m^2	$A_{sf} + A_{nsf}$
THERMAL STORAGE				
Heat Capacity	c_e	1519	J/kg· K	SAM
Density	ρ	1808	kg/m^3	SAM
Cold tank temperature	T_{cold}	290	ºC	SAM
Hot tank temperature	T_{hot}	574	ºC	SAM
Storage Capacity	C_{TS}	Calc.	MWh	$\frac{HTS \cdot P_{th}}{c_e \cdot \rho \cdot (T_{hot} - T_{cold})}$
Volume	V	Calc.	m^3	$\frac{C_{TS} \cdot P_{th} \cdot 3600000000}{c_e \cdot \rho \cdot (T_{hot} - T_{cold})}$
Initial content	E_0	Calc.	MWh	$\frac{C_{TS}}{3}$
Radiation losses	Q_r	0,3%	-	UTEP

Tab. 4.4.: Values for weighting ranking criteria

- **Storage content**. It is the energy in MWh stored in the molten salt hot tank which is ready to be transferred to the power unit when necessary to generate electricity. It is initiated with a third of its capacity.

- **Dumped energy**. It is the energy in MWh that cannot be used for electricity generation or stored, therefore has to be dissipated in the plant. It acts as an indication of the incident radiation which is not used.

- **Auxiliary production**. It is the thermal energy in MWh which has to be produced through an external heater in order to maintain the power production at the design capacity, in case that there is no solar irradiance hitting the heliostat field and the molten salt storage is empty. It is an indication of the production of a back-up boiler if installed in the plant, or an indication of the amount of electricity which is not produced otherwise (if there is no back-up system). in MWh that cannot be used for electricity generation or stored, therefore has to be dissipated in the plant. It acts as an indication of the incident radiation which is not used.

The objective of the technical scenario is to run the power cycle at full capacity (50MW) during the year, reaching a capacity factor of 1. In case this is not possible with only the solar system and the storage, there is an option to install a back-up boiler or not. The operation strategy consists on producing thermal energy for the power cycle with the incident radiation, otherwise with the storage content; and by last, with an auxiliary heater or not producing to full capacity. The storage content is increased if there in an excess of incident radiation until the storage is full, and the storage discharge is forced when there is not enough incident radiation to run full load until the storage is empty. The algorithm implemented in Excel to operate the CSP plant follows the process diagram represented in the Figure 4.3. Circled forms represent actions and rectangles represent checkings.

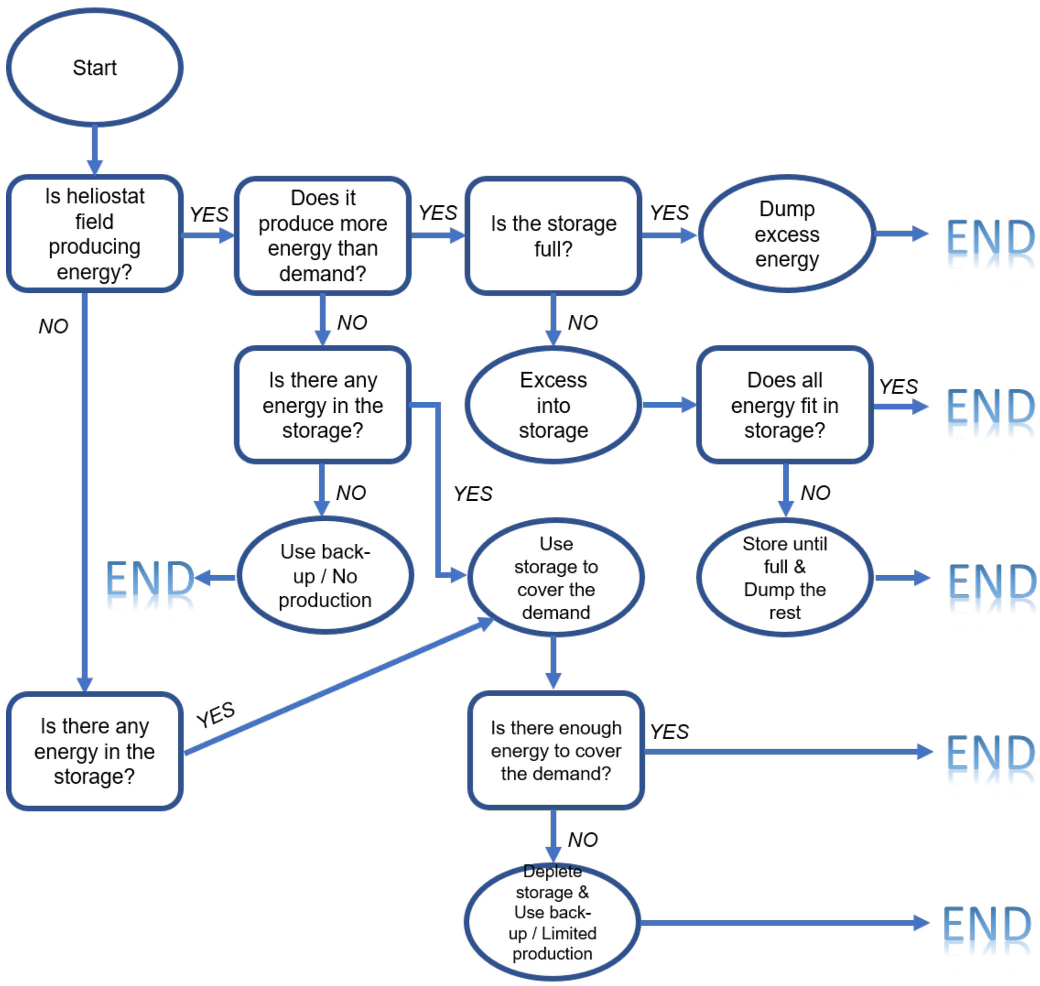


Fig. 4.3.: Hourly operation mode of the 50MW CSP plant

After running the process for the 8760 hours of the year, it is possible to produce the following overall outputs in a year base:

- **Electricity production (MWh)**. The electricity generated along the year is the sum of the hourly values of the field firm power. If there is a back-up with enough capacity, the plant will produce electricity every hour, reaching a production of 438000MWh (maximum production). The study does not consider back-up, so it is necessary to deduct the field *Back-up production* to calculate the electricity production.

- **Capacity factor**. It shows the rate between the actual electricity production and the maximum possible output, i.e. in the case the plant is running full load for the whole year.

- **Solar production (MWh)**. In case no back-up is considered it will correspond to electricity production. Otherwise, it is the total production minus back-up production

- **Hours with no full production**. It is the count of hours when the plant has not been running full load in case of no back-up existent.

The aforementioned outputs allow to discuss the technical feasibility of the plant, and become an essential output of the economic feasibility analysis.

4.4.3 Economic simulation

The main aim of the economic simulation is to minimize the LCOE (Levelized Cost of Electricity) over the lifetime of the CSP installation. The optimal design will be the pair of Solar Multiple and storage capacity that maximize the economic benefit, thus requiring a lower price of electricity to make the project economically feasible. The model considers for the calculation of LCOE two categories of inputs. The capital investment at the beginning of the project is the dominant cost in CSP technologies , as they are installations with high upfront investment. On the other hand, operation expenditures are also considered, including recurrent costs which have their origin in the electricity generation. Operation and management costs are included in this category as well as possible fuel costs.

The different costs have been parameterized to make them dependant on the results of the operation of the plant. The parameters have been provided by the default data for solar tower molten salt CSP plants in the software SAM (NREL, 2019b). They are presented in the Table 4.5:

Cost item	Value ($=USD)
CAPITAL INVESTMENT	
Site improvement	16 $\$/m^2$
Heliostat field	140 $\$/m^2$
Tower	15.000.000 $/unit
Receiver	50.000.000 $/unit
Thermal storage	22 $\$/kWh_t$
Power cycle	1.330$\$/kW_e$
Land cost	2,5$\$/m^2$
Sales tax	5%
OPERATION AND MAINTENANCE	
Fixed cost by capacity	66$/kW
Variable cost by generation	3,5$/MWh

Tab. 4.5.: Cost input parameters for economic assessment

LCOE considers the project costs for the total lifetime. In this case, a life cycle of 30 years has been considered but solar tower CSP plants can continue its operation even longer; as it is the case with the first commercial plants commissioned in California, USA. To calculate the LCOE the total costs are divided by the total amount of electricity generated by the plant on the whole lifetime. Due to degradation effects, mainly in the mechanical parts of the plant, a degradation factor of 0,5% has been selected. The factor decrease this amount the production of one year compared with the previous one (see Equation 4.5. (Aly, Bernardos, et al., 2018)

$$Q_n(n > 1) = Q_{n-1} \cdot (1 - degradation) \tag{4.5}$$

The real LCOE is a constant value as it adjusted with the inflation of the currency, so it describes the project as a whole. The reason for using LCOE is that it allows the comparison with other types of technologies in purely economic terms. The formula used for the calculation of LCOE is:

$$LCOE = \frac{C_0 + \frac{\sum_{n=1}^{30} C_n}{(1+d_{nom})^n}}{\frac{\sum_{n=1}^{30} Q_n}{(1+d_r)^n}} \tag{4.6}$$

where:

Q_n (MWh) electricity generated by the installation in year n as calculated in the operation model.

C_0 ($) initial investment ($).

C_n annual operation and management cost. d_r real discount rate. d_{nom} nominal discount rate (includes inflation).

The discount rate is the index to actualize future payments or revenues in order to assess an investment. It represents opportunity cost, in other words, alternative projects or saving the money of the investment. For private companies, discount rates are often high because the investments are used to have a fast payback. In case of Peru, the discount recommended during the interview with Eunice Villicaña was between 7%-9%. To confirm with another source, the discount rate suggested in the report of 2008 about state of the art of natural gas was in a range between 7 and 10%. (OSINERGMIN, 2008) Therefore, a real discount rate of 7% has been chosen. The nominal discount rates considers additionally the impact of inflation, combining both indexes for an investment evaluation. The relation between nominal and discount rate, knowing the inflation is shown in the equation 4.7:

$$d_{nom} = [(1 + d_r) \cdot (1 + inf) - 1] \tag{4.7}$$

According to the last data for 2018, the annual inflation of Peru was 2,48%. (INEI, 2019) Using the Equation 4.7, a nominal discount rate is calculated to 10,68%.

After calculating the LCOE, there are three methods to assess the economic feasibility of the project. All three are correlated. The first one suggest that any price for sale of electricity higher than LCOE will make the project feasible, as interest rate and the rest of financial parameters are included in the LCOE formula. The most common evaluation method is the Net Present Value (NPV) of the project, which is the sum of the present values of the cash flows for each year during the life time of the project. The equation for the calculation of NPV is the following:

$$NPV = \sum_{n=1}^{30} \frac{B_n}{(1 + d_{nom})^n} - C_0 \tag{4.8}$$

where:

B_n (\$) cash flow of the year n, calculated as revenues on the sale of electricity minus operation and management costs.

When NPV is used, a result higher than 0 concludes that the project is feasible according to the economic parameters used; being not feasible when the result is a negative value.

5 Base scenario for electricity generation in Peru

The first part of the analysis draws on the current scenario of the electricity generation in Peru. With the assistance of the consulted sources, including technical reports by national institutions, press articles and the information gathered on two interviews with professors who are experts in the Peruvian energy sector, the situation is analysed.

The main aim of the base scenario is to identify the current problems in the electricity sector in Peru, especially when they are concerning the implementation of non-conventional renewable energies. On the other hand, another point of interest of the analysis is to identify scenarios where CSP technologies can add value, taking advantage of its specific features. The chapter helps in that way to the choice of the CSP technology which will be analysed in the next parts of the analysis. The chapter is divided into the identified problems: declaration zero, centralization of generation, excess suply and firm power.

5.1 Firm power

The most decisive factor for the renewable energy situation is the concept of firm power, which needs to be fulfilled to participate in the wholesale market of energy with free consumers and distributors. Firm power is a concept that refers to the capacity that the plant can potentially supply when it is required, for instance in case that after the hourly balance COES identifies a new generator has to generate an additional amount of electricity to cover an unforeseen demand. As the main objective of the electricity market in Peru is the security of supply, the power plants have the requirement to have a reserve of firm power, or in other words, ensure to be able to dispatch an uniform flow of energy. In case, this cannot be ensured, the only alternative is signing a contract with another generator to cover that firm power, contracts which in many cases make financially unfeasible the already high capital investment RES projects

The nature of renewable energies is in most cases fluctuating, as they depend on nature forces that are variable on weather and seasonality. This is the case wind wind power and solar PV. In these cases, the technologies can enter through processes of tenders, bidding a price per MWh. The tenders are organized approximately every two years, with the goal to cover the national objective of 5% generation with non-conventional RES; which is expected to rise up to 15% during 2019. When winning a tender, the project is awarded with preferential dispatch to the grid and a premium tariff, as the TSO covers the difference between the spot price earned in the market and the established tariff. To the date of writing this project three tenders have been organized including solar energy projects. The information of the result of the tender process is shown in the Figure 5.1:

Tecnología	Proyecto	Potencia central (MW)	Precio monómico (USD/MWh)	Fecha subasta	Inversión estimada (MM USD)
Solar	Panamericana	20.0	215.00	2009	94.6
	Majes	20.0	222.50	2009	73.6
	Repartición	20.0	225.00	2009	73.5
	Tacna	20.0	223.00	2009	9.6
	Moquegua	16.0	119.90	2011	43.0
	Rubí	144.5	47.98	2016	-
	Intipampa	40.0	48.50	2016	-

Fig. 5.1.: Technical and economical parameters of solar projects awarded in the tenders, (Cordano, 2017)

According to the graph, awarded prices for solar projects have decreased in the subsequent tender, proving the success of the policy. Yet it does not allow a complete deployment of solar power, because on one hand the installed capacity is limited to the tender and on the other hand, it excludes projects with higher LCOE like CSP.

However, the advantage of CSP technologies in relation with the firm power requirement is the possibility of thermal storage which allows the plant to modulate the generation. The technology with the best possibilities for base load generation with thermal storage is solar tower technology, with a molten salt storage. By increasing the concentration factor in relation with parabolic through, it is possible to produce a higher amounts of heat which not only supply the instant demand but are available for storage with a high thermal capacity fluid as the molten salts.

5.2 Declaration zero

An important disruption of the liberalized electricity market is the phenomenon called *declaration zero*. This name refers to the situation in which the natural gas based power plants declare they variable costs as 0, to ensure they pass the filter of the hourly dispatch by COES. The reason for this action is that the contracts with the natural gas suppliers established in Camisea fields are in most cases *take or* *pay*, in other words, they are paying for the natural gas supply regardless whether they consume it or not. The reaction of the gas power stations to this contract is declaring null marginal costs in order to ensure they will produce at a certain hour. As a domino effect, this repeated action sink artificially the marginal cost of the electricity, which is translated to a higher premium tariff payment for the renewable technologies supported by tenders. And as a consequence, the willingness to launch new tender processes is affected, as they are seen as a heavy financial load for the system and the tariffs of the consumers.

5.3 Excess supply

During the last decade, especially after the beginning of natural gas supply from Camisea fields; large new capacity was installed in Peru. The main reason for that was expected beginning of operations in numerous large mining projects. Yet many of these projects were not eventually opened and that created a system with excess of supply, that combined with the declaration zero effect, contributes to sink the marginal cost of the electricity, which is a barrier for the breakout of renewable energy large-scale installations. The current system has an installed capacity of 11GW and an average demand of 6MW. However, still peak points of demand exist, and new mining projects are expected to appear for the coming years. Those factors combined with a high population growth and increase of the living conditions, create expectations for a rise in the electricity demand in the next years, which will shed light on the approval of new investments in generation.

5.4 Centralization of generation

The electricity generation in Peru is highly asymmetric. The presence of the capital Lima and the close Camisea field have led the electricity generation of the country towards the center, with a striking difference between the north and the south. This concentration in the generation is the cause of problems of congestion in the transmission grid, if the demand rises in one of the extremes of the country. An important mining sector is present in the South, with the largest free consumers in the country. For that reason, it is important to generate competitive electricity in the south of the country. However, a decisive barrier prevents generation capacity of the south to increase gradually when compared to the centre and the north. There is currently no natural gas distribution to the south of Peru, even though a concession was assigned in 2014 to build a gas pipeline connecting with the cities of Arequipa and Tacna (*Gasoducto Sur Peruano*). (El Peruano, 2014) A breach in the contract obligations was the cause to withdraw the concession, and as a result the project will be delayed. Regardless of the future connection of the south with natural gas, given the high solar radiation in the south of Peru, where the majority of the PV installations are present; the construction of a large-scale CSP facility would solve problems of congestion in the grid and would allow new projects which will affect positively the economy.

In conclusion, the analysis of the current situation in Peru shows an opportunity for the implementation of CSP technology, which up to date has been disregarded in Peru. The best possibilities exist for a large-scale CSP power plant, which allows firm power dispatchability and could potentially obtain the license without even entering in a tender process. A necessary geographic distribution of the generation in Peru gives an additional value to CSP technology, whose expected higher potential in the south gives this region a competitive advantage despite of the lack of natural gas.

As expected disadvantages, it is found the low number of new generation projects expected for the next years as a consequence of excess in supply and electricity market with sinking marginal costs. However, the urge of decarbonization of the energy sector materialized in the national contributions for the Paris agreement should be a strong argument in favour of the implementation of sustainable energy projects when a need for new generation appears.

6 Geographic feasibility analysis

The geographic feasibility analysis has been carried out in the application QGIS, creating a project file ***LocationCSP.qgz***. The goals of the analysis are identifying the areas in Peru which are suitable for the installation of a large-scale CSP facility, ranking the suitable areas and selecting hot spots for CSP in the country. The results of the geographic analysis serve as an input for the techno-economic feasibility analysis in Chapter 7. The analysis is divided in two parts: GIS-based suitable areas identification and MCDM area ranking.

As a base background, layers with administrative borders of Peru have been loaded. Peru is divided in 24 departments and 2 autonomous provinces (Lima and Callao), which do not belong to any department. The next level of division is the province. And provinces are divided into districts, which act analogically to Danish municipalities. A map showing the territory of Peru, with its biggest and smallest administrative divisions is shown in the Figure 6.1:

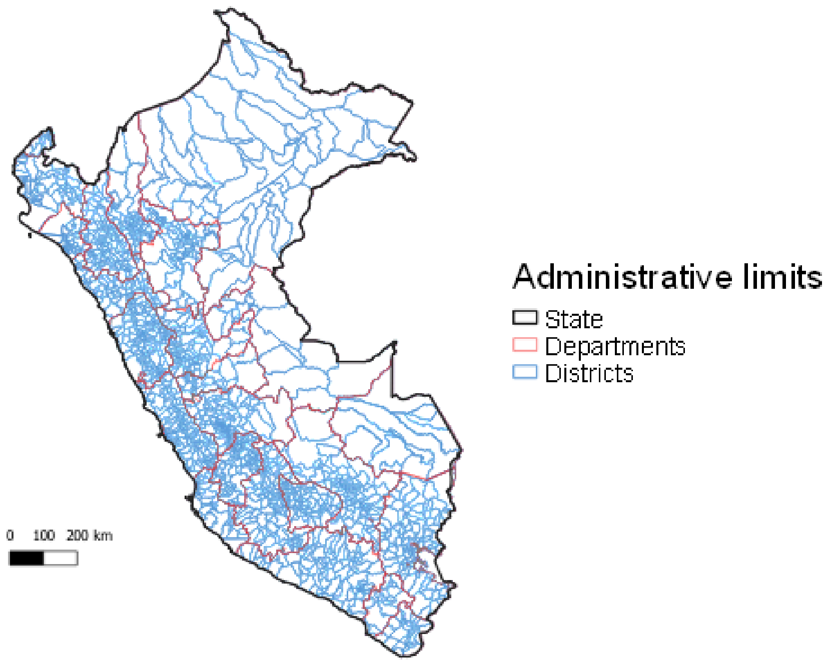


Fig. 6.1.: Administrative divisions in Peru

6.1 GIS-analysis to identify suitable areas

Five criteria have been selected to exclude unsuitable area for the placement of a large scale CSP plant: protected areas (EC1), land use (EC2), slope (EC3), urban areas (EC4) and solar radiation (EC5). The reasons for these choices and methods used are detailed in the section 4.3.1.

For the **EC1**, the database of protected areas of Peru is contained in a vector file, containing the shapes of the areas (see Figure A.2 in the Appendix). All protected areas will be excluded, therefore the layer is transformed into raster data in GRASS using the process: importing vector in GRASS (*v.in.ogr.qgis*) and transforming the vector into raster (*v.to.rast.constant*), assigning a value of 1 to points within protected areas.

For the **EC2**, the database of land use (see Figure A.3 in the Appendix) in Peru is contained in a raster with values representing a land use class. Only areas the following classes correspond with no productive potential uses and have been considered as suitable areas: 30, 140, 150, 200. The definition of each class can be consulted in (European Space Agency, 2009). It can be noted that big areas represented as light yellow in the Peruvian coast correspond mainly to deserts, a potentially interesting location for CSP. To process suitable land use areas, the raster is imported to GRASS tool (*r.in.gdal.qgis*) and subsequently reclassified with the module *r.reclass*, converting the classes of interest in value 1 and the rest to 0.

For the **EC3**, the slope map of Peru is obtained as a derivation from a Digital Elevation Model (DEM). DEM file is a raster dataset containing values ranging from -13 to 6685, which correspond to the altitude in kilometres on each pixel (see Figure A.4a in the Appendix). Importing DEM file to GRASS it is possible to calculate a slope raster file for the country using the module *r.slope*. The result is a slope raster with values in %, ranging from 0% to 69,2% (see Figure A.4b in the Appendix).

For the **EC4**, the cities considered for the study are extracted from the urban nucleus dataset of the Peruvian authorities. They are grouped in 3 classes according to the population (see Figure A.5 in the Appendix). To exclude the areas occupied by the possible expansion area of the city during the lifetime of the project the option buffer is used in the GRASS tool (*r.buffer*). Buffer distance of each city class is the radius calculated in the section 4.3.1: 17km for class 1, 6km for class 2 and 4km for class 3.

For the **EC5**, the database of annual DNI (see Figure A.6 in the Appendix) is contained in a raster with values representing the annual DNI in kWh/m_2. Data range from

408 to 3149 kWh/m_2, showing the wide geographical variation of solar radiation in the country. For the processing with the rest of layers, the database is imported into GRASS using *r.in.gdal.qgis*. The Figure 6.2 shows the results of applying the different exclusion criteria on the area of Peru:

(a) EC1: Protected Areas

(b) EC2: Land Use

(c) EC3: Slope

(d) EC4: Urban areas

(e) EC5: Low solar radiation

Fig. 6.2.: Layers for exclusion criteria. White means suitable, black is excluded

Observing the different maps, it is noticeable that land use and slope are the two more restrictive criteria. Usable lands are located preferentially near the coast or spread in the mountain range. On the other hand, terrain is flat in the Amazonas basin; but slopes are higher in the mountains, where the radiation is high, than in the coast. To calculate the final map of suitable areas for CSP projects, a combination of the five exclusion criteria is made. The combination is performed with the GRASS module *r.mapcalc* or map algebra. The logic conditions necessary for the calculation of the suitable areas layer are introduced in the tool by a graph, which is shown in the Figure 6.3:

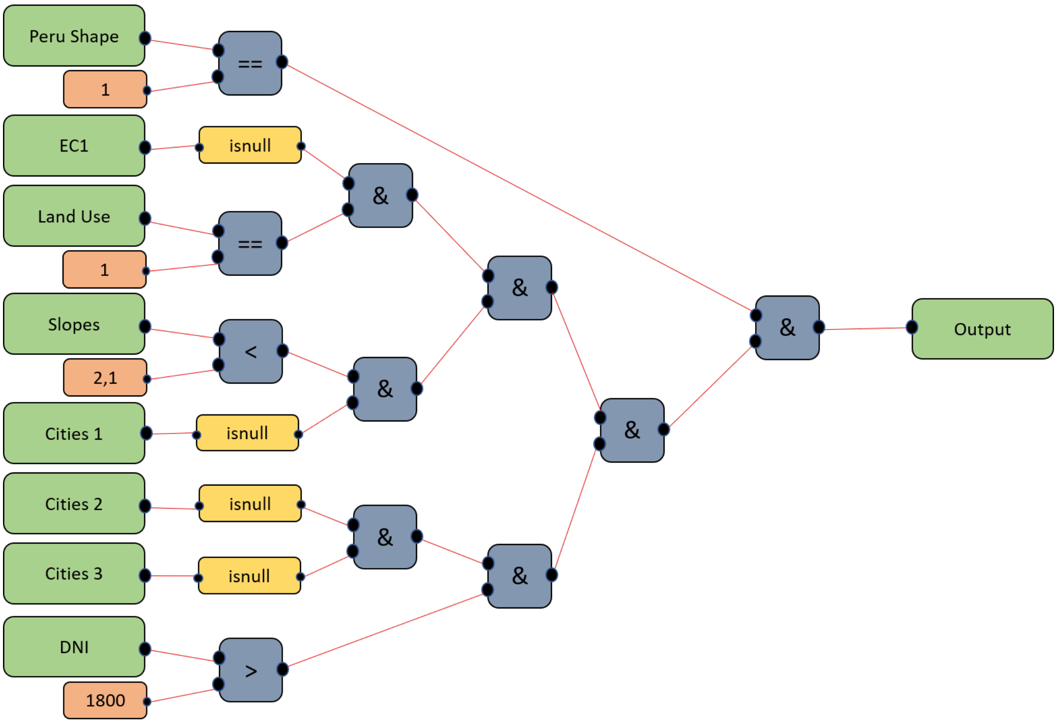


Fig. 6.3.: Algebraic equation to calculate suitable areas map

The equation applies criteria established in chapter 4.1. Algoritm *isnull* returns a value of 1 when no value is found in the layer, i.e. in the points which are not excluded by the corresponding layers. The logic funcion & returns a value of 1 if both factors of the operation are 1. In the last step, the result is operated with the Peru Shape map, to make sure all points resulting belong to the territory of Peru. The algebraic solution is a binary layer where values 1 represent the areas which are suitable for the installation of large-scale CSP plants.

The Figure 6.4 shows the solution of the exclusion areas analysis. The red surfaces represent areas where the installation of the CSP plant is theoretically possible:

The result shows that there is a higher potential for CSP technology in the south of the country, especially in areas near the coast where broader suitable areas are found. Moving inwards the country, the areas are more spread with smaller surface, mainly due to the fact that it is a predominantly mountain area with sharp changes of slope.

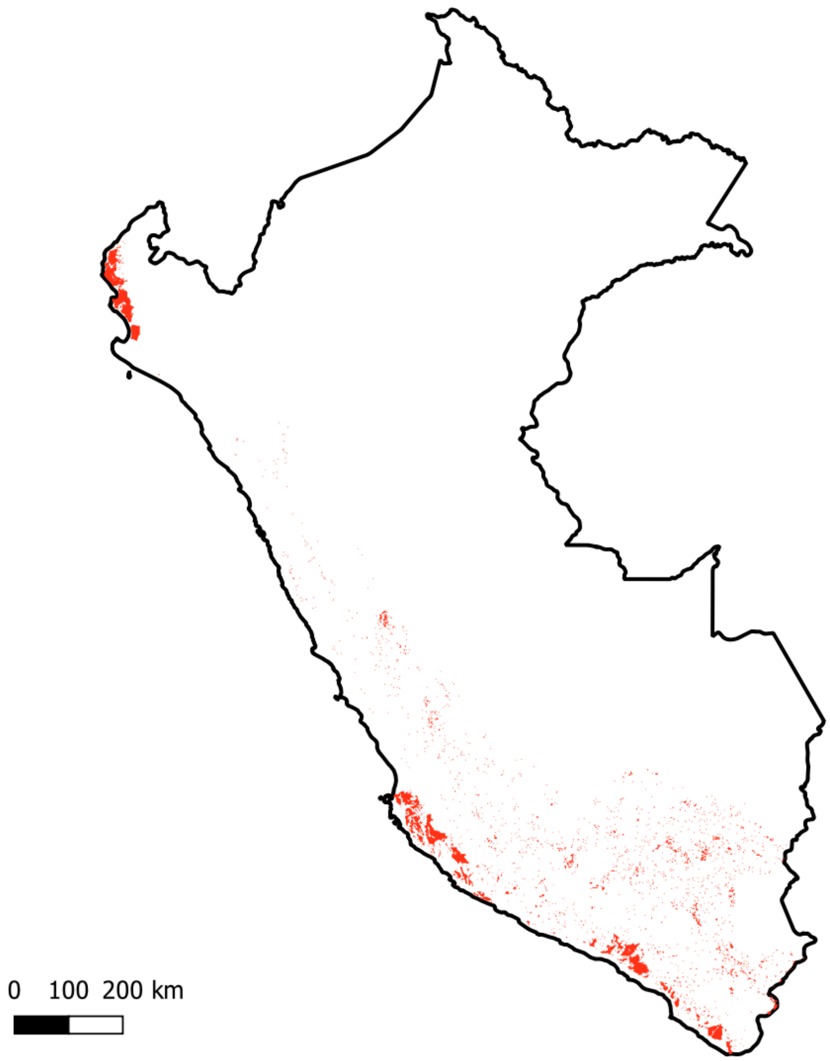


Fig. 6.4.: Suitable areas for large-scale CSP installations in Peru

In the northwestern tip of Peru, another broad area near the coast appears to be potentially available for CSP installations. When compared with the apparently high radiation of the annual DNI map of Peru, the actual suitable areas map might seem quite small. However, there are still an important number of locations which fulfill CSP requirements and still the received DNI is expected to be high. Determining the qualitative potential of each area is the purpose of the next part of the analysis.

6.2 MCDM analysis to rank suitable areas

After defining the areas which are suitable for large-scale CSP installations, the next step is to analyze which ones are more favourable than the other ones. Therefore, a ranking of areas has been created based on Ranking Criteria (RC), which are those factors which favour the overall performance of a potential CSP installation. Four ranking criteria were considered: high level of annual DNI (RC1), proximity to water resources (RC2), proximity to infrastructure (RC3) and proximity to demand (RC4). Regarding infrastructure, the national road network has been chosen as the ranking criterion. Due to lack of data for Peru, the electricity grid has not been included, but it is estimated that a large amount of transmission lines go through the roads. On the other hand, cities and mines have been considered as a potential points of demand. In cities, the existence of industrial hubs would allow the delivery of process heat in cogeneration with electricity if a heat network was built. Cities have been divided by their population, as explained in EC4, forming RC4a, RC4b, RC4c; meanwhile proximity to mines is RC4d. Each criteria is divided according to established thresholds into tiers, which award a specific score. The goal is setting a punctuation system to rank the locations from the most favourable to the least favourable. The method to establish the thresholds is explained in the section 4.1. Subsequently, the tiers have been created with assigned scores as shown in the figure 6.1:

RC1 - Annual DNI

Tier	DNI [kWh/m^2]	Score
1	3000-3149	100
2	2850-3000	95
3	2700-2850	90
4	2550-2700	85
5	2400-2550	80
6	2250-2400	70
7	2100-2250	60
8	1950-2100	50
9	1800-1950	40

RC2 - Proximity to water

Tier	Distance (km)	Score
1	0 - 3	100
2	3 - 5	80
3	5 - 7	70
4	7 - 9	60
5	More than 9 km	0

RC3 - Proximity to roads

Tier	Distance (km)	Score
1	0 - 5	100
2	5 - 10	80
3	10 - 15	60
4	15 - 20	40
5	More than 20 km	0

RC4a - Proximity to Lima

Tier	Distance (km)	Score
1	17 - 25	100
2	25 - 35	70
3	35 - 45	60
4	45 - 60	40
5	More than 60 km	0

RC4b - Proximity to cities over 250k

Tier	Distance (km)	Score
1	6 - 10	100
2	10 - 15	80
3	15 - 20	70
4	20 - 25	50
5	25 - 30	40
6	More than 30 km	0

RC4c - Proximity to cities over 100k

Tier	Distance (km)	Score
1	4 - 8	100
2	8 - 12	80
3	12 - 16	40
4	More than 16 km	0

RC4d - Proximity to mines

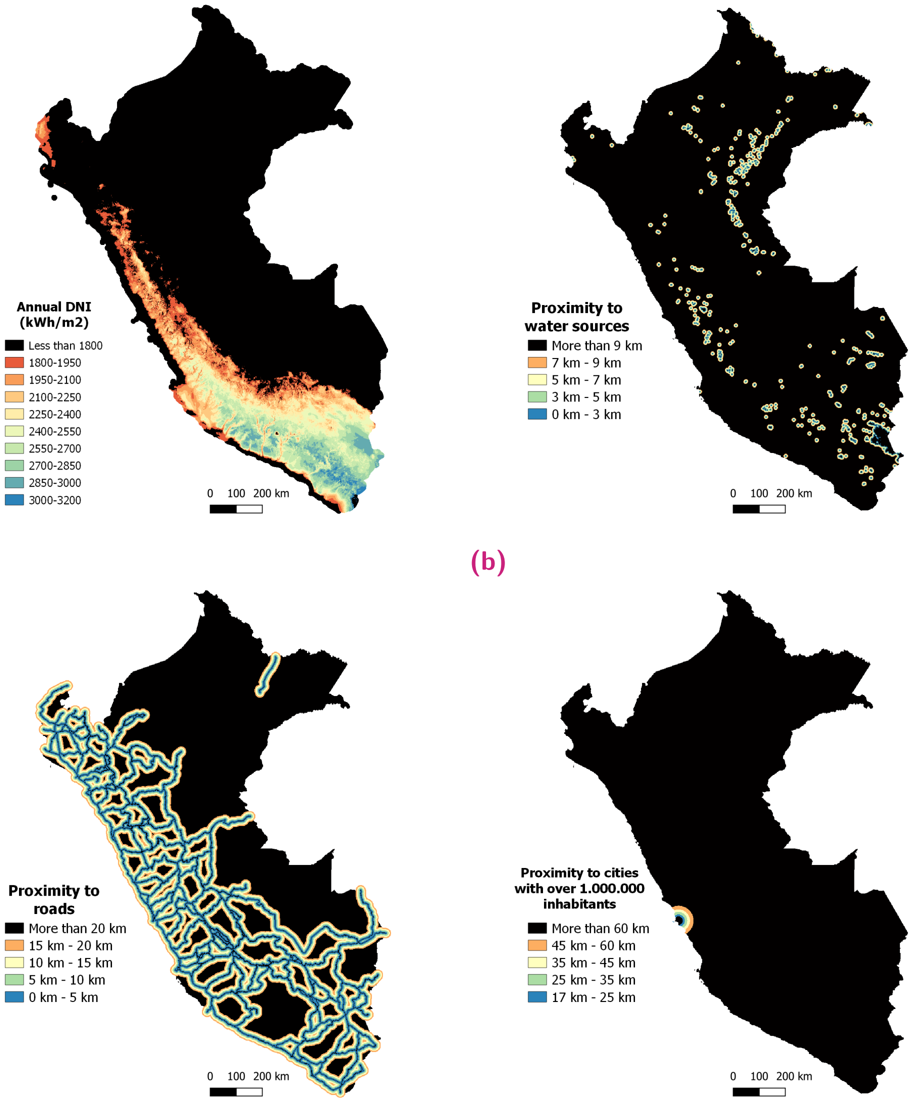
Tier	Distance (km)	Score
1	0 - 5	100
2	5 - 10	80
3	10 - 15	40
4	More than 15 km	0

Tab. 6.1.: Tiers and scores for each ranking criterion

For **RC1**, the dataset file of annual DNI is the same than the one used for EC5. For **RC2**, the information is taken from an ArcGis file, which is converted in a raster extension readable for QGIS. The raster has 9 values corresponding to different water elements, from which only value 1 has been selected. Filtering only the lakes, a raster layer water availability information has been imported to GRASS (see Figure

A.7 in the Appendix). For **RC3**, a vector file formed by lines representing the roads of the national road network *Red Vial Nacional* is added (see Figure A.8 in the Appendix). The vector is imported to GRASS and then rasterized and buffered in the different established tiers. For the layers corresponding **RC4a**, **RC4b** and **RC4c**, city classification in groups 1, 2 and 3 created in the first part of the analysis is used. Lastly, a vector file with mining cadaster information has been imported as a source information for **RC4d** (see Figure A.9 in the Appendix). For RC concerning proximity, the layers have been created with the buffer module of GRASS, creating one buffer level per tier.

The last step for creating the ranked layers for MCDM analysis is a raster reclassification in GRASS (*r.reclass*), using the scores assigned in the Figure 6.1. The resulting layers are shown in the Figure 6.5-6.6.



(a) (b)

(c) (d)

Fig. 6.5.: Maps with tiers for ranking criteria (II)

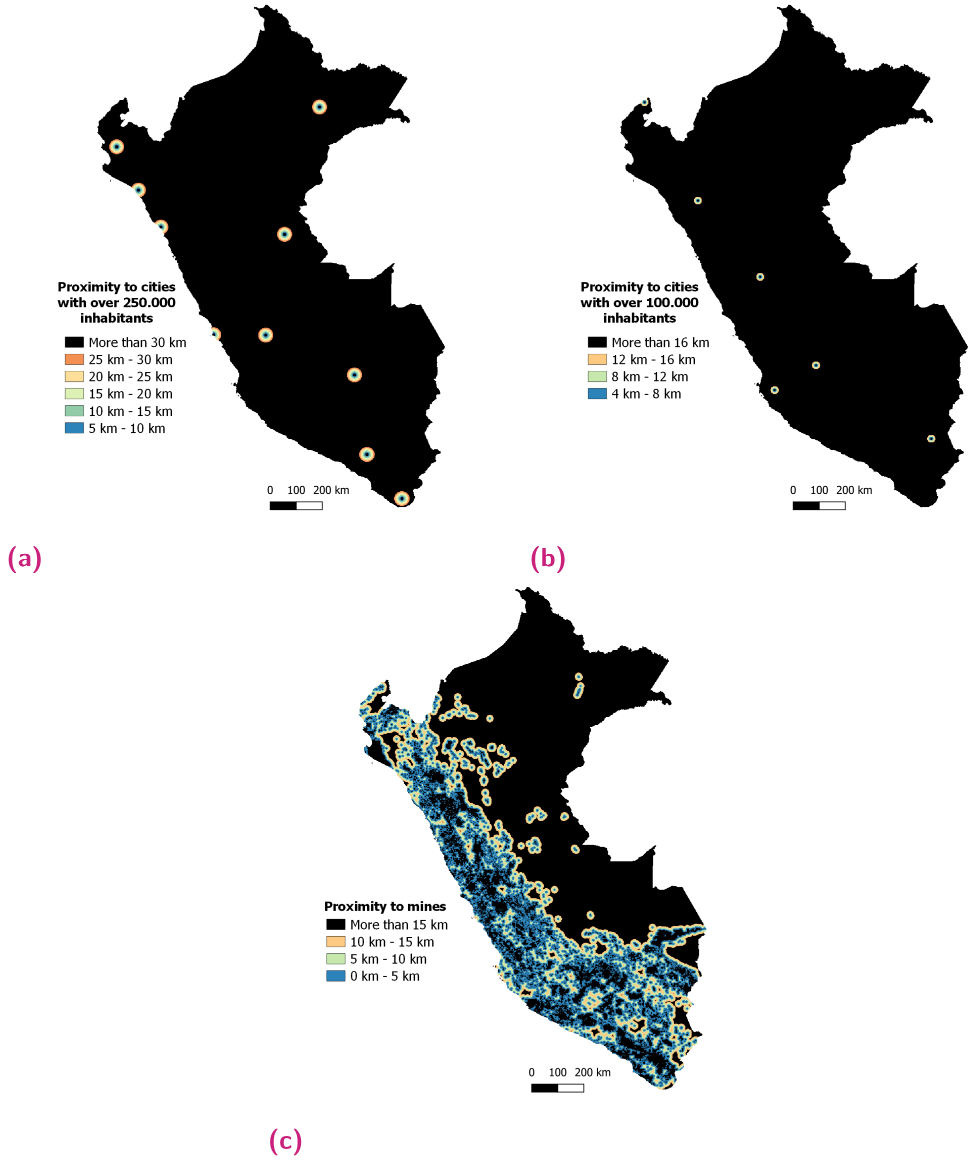


Fig. 6.6.: Maps with tiers for ranking criteria (II)

The last step is performing a comprehensive ranking considering the whole set of RC. The relative relevance of the different criteria is taken into account in this step, assigning different weights for each criterion according to Figure 4.3. As electricity generation in CSP installations is dominated by direct irradiation received, annual DNI (RC1) is the most determinant criterion and therefore is assigned a weight of 60%; meanwhile water availability is the second most important factor with a weight of 20%, and RC3 is given 10%. Lastly, RC4 has a total weight of 15%, which is divided in cities over 250.000 inhabitants with 9%, and cities below 250.000 and mines with 3% each. Each RC is multiplied by its corresponding weighting factor (for example, each score in RC1 is multiplied by 60, as the layer consists of integer values). The overall score is the addition of each ranking criterion total scores. As a last step, to verify if the result is contained within suitable areas calculated in the first part of the analysis, it has been multiplied by this layer with values 1. The described calculation has been processed through the GRASS module map algebra (*r.mapcalc*) using the diagram equation shown in the Figure 6.7:

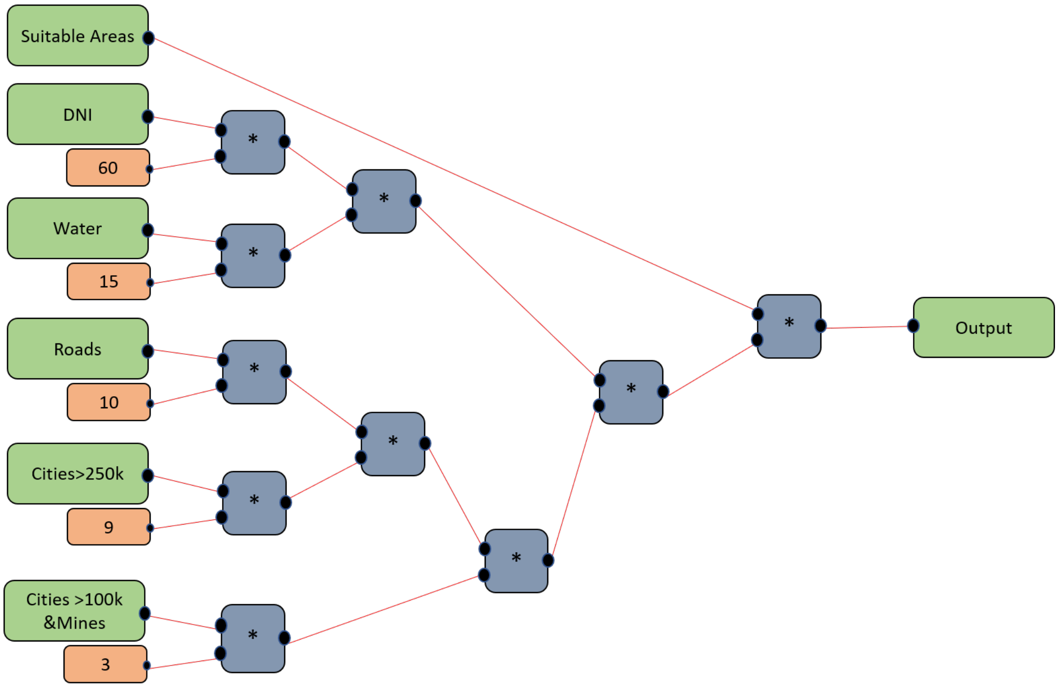


Fig. 6.7.: Algebraic equation to calculate ranked areas

The result is a raster map with values of the overall scores obtained for every point of the suitable areas maps calculated in the first part of the analysis. The ranked areas map is shown in the Figure 6.8. It is perceptible that areas located in the south of the country are more favourable than areas found in the northwest. The highest values are found in the scattered areas inland, which are located in the Andes mountain range. The larger suitable areas closer to the coast have lower ranking, except the sections located in Arequipa and Moquegua departments, with moderate to high scores. As the goal of the analysis was identifying the best locations for a CSP installation in the country, the 8 areas with the highest score have been identified and denominated hotspots. A hotspots is defined in the project with a highly favourable zone for the implementation of a large-scale CSP facility in Peru. The Figure 6.8 shows the ranking of suitable areas in a heat map and the location of the hotspots:

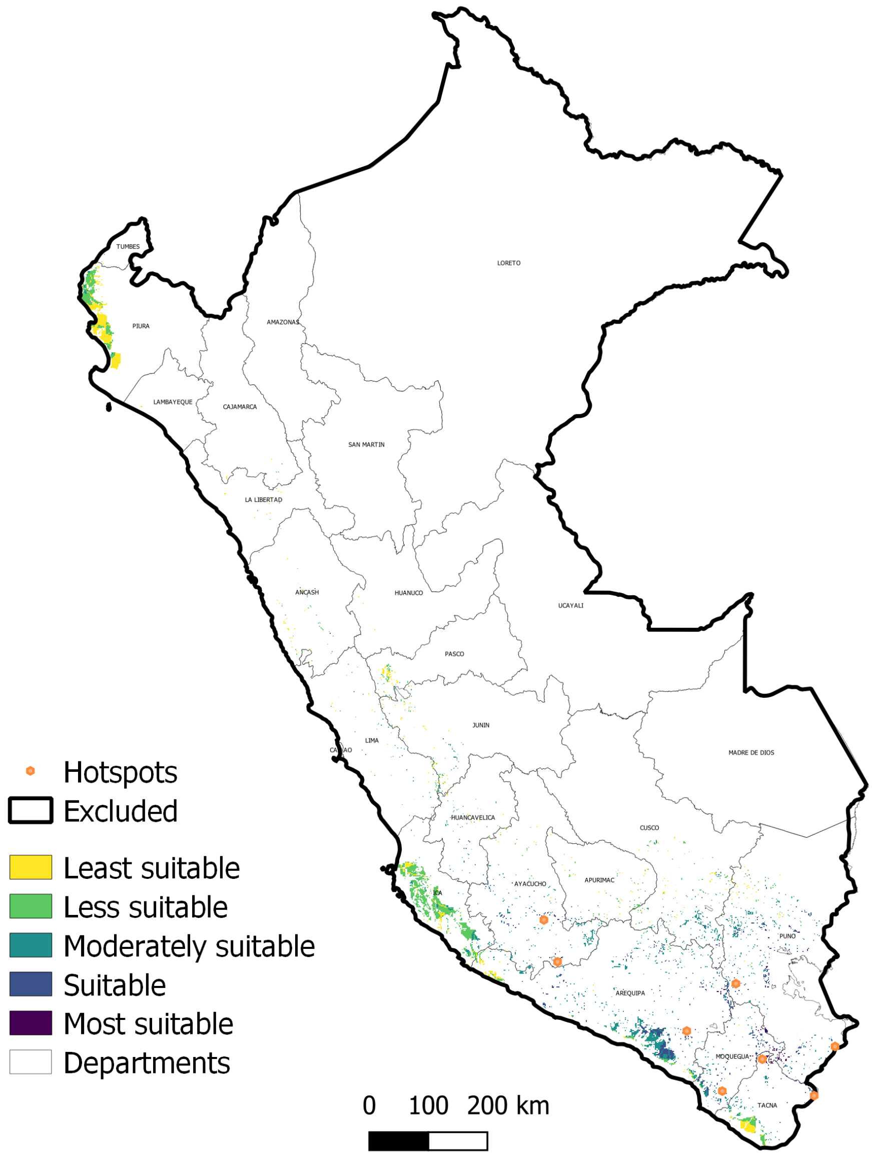
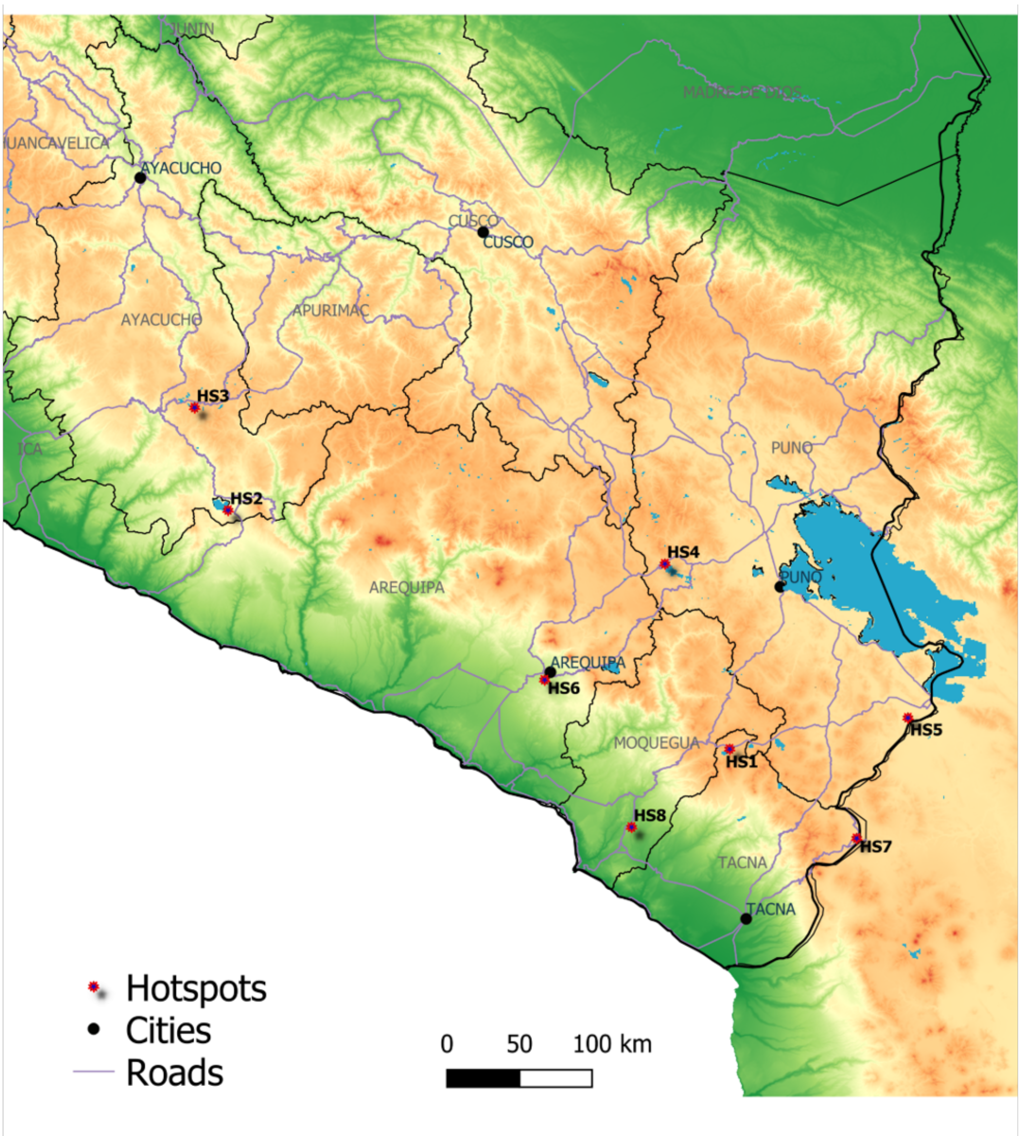


Fig. 6.8.: Overview of CSP suitability on all regions of Peru

The most favourable points are represented in dark blue in the map, in a scale which turns into yellow for the least favourable points. The map is showing the departmental limits, in order to locate the suitable areas better. According to the map, it is possible to conclude that the departments with the best conditions for the installation of large-scale CSP plants are Arequipa, Moquegua, Tacna, Puno and Ayacucho; as they contain at least one hotspot in their territory. Furthermore, there is a moderate potential for CSP technology in the departments of Ica, Junin, Pasco and Piura. To finish the analysis, the research takes a closer look into the identified hotspots. Therefore, the map is zoomed in the southern part of Peru.

6.3 Analysis of hotspots

The last part of the analysis aims to get an insight on the found hotspots. The Figure 6.9 presents a representation with lakes, national roads and nearby cities in a larger scale map of Southern Peru, as the eight hotspots are found in that area. Additionally, the elevation is considered in this part of the analysis (see Chapter 9).



#	Coord X	Coord Y	District	Province	Department	Rank	DNI (kWh/m2y)	Altitude (m)
1	-70,3616	-16,9019	CANDARAVE	CANDARAVE	TACNA	8500	**2931**	4465
2	-73,6489	-15,3381	PUYUSCA	PARINACOCHAS	AYACUCHO	8200	**2822**	3296
3	-70,7853	-15,6888	PUQUIO	LUCANAS	AYACUCHO	7900	**2611**	4442
4	-73,8680	-14,6658	SANTA LUCIA	LAMPA	PUNO	7900	**2634**	4266
5	-69,1928	-16,6973	KELLUYO	CHUCUITO	PUNO	7820	**2774**	3833
6	-71,5743	-16,4488	JACOBO HUNTER	AREQUIPA	AREQUIPA	7600	**2709**	2171
7	-69,5289	-17,4865	PALCA	TACNA	TACNA	7300	**3021**	4166
8	-71,0045	-17,4135	MOQUEGUA	MARISCAL NIETO	MOQUEGUA	6700	**2785**	1358

Fig. 6.9.: Identification of hotspots

The table in the bottom of the Figure 6.9 shows information about geographical coordinates, political divisions, solar radiation and altitude. It is ranked according to the scores obtained. As it was expected, the majority of the hotspots are located near small lakes. All the hotspots presented are also in the vicinity of a national road. On the other hand, it is interesting to notice that the majority of the hotspots are located in points with high altitude: HS1, H3, HS5 and HS7 are located above 4000 metres; meanwhile HS2 and HS4 pass the barrier of 3000 metres above the sea level. It is predictable that the cost of accessibility to implement infrastructure at this altitude can be a challenge. However, altitude has not been studied either as exclusion criteria or ranking criteria, as the infrastructure exists at highlands in Peru and many cities of the country are placed above 2000 metres; so apparently no limit on altitude should be established (see further explanation in Chapter 9). Only HS6 and HS8 are placed in areas below 3000 meters, but still the altitude is considerable.

The hotspot with the highest radiation is found in Palca (Tacna), near the border with Bolivia and Chile; with 3021 kWh/m_2 which could be used to electricity generation. Curiously, this zone is ranked 7th in the list. The highest score and apparently, the best location for a large-scale CSP installation in Peru is in the district of Candrave, also in the department of Tacna. The only hotspot which is in the vicinity of a large city is HS6, in the district Jacobo Hunter belonging to the metropolitan area of Arequipa, the second biggest city in Peru. It is also located near the copper mine Cerro Verde, the largest and most electricity consuming mine of Peru. As it close to a large city, a good nearby infrastructure is expected and the altitude is lower than the other hotspots, therefore it is estimated it would not increase the cost. For these reasons, HS6 will be the selected location to analyze the techno-economic feasibility of a large-scale CSP installation. With one of the lowest annual DNI among the hotspots, it would give room for even higher performances in other hotspots if the altitude and remoteness barriers are solved.

7 Techno-economic feasibility analysis

For the techno-economic analysis, the hotspot identified with the number 6 has been used. A 50MW CSP installation has been modelled, with the technology of solar tower and a thermal storage with molten salt as a heat transfer fluid.

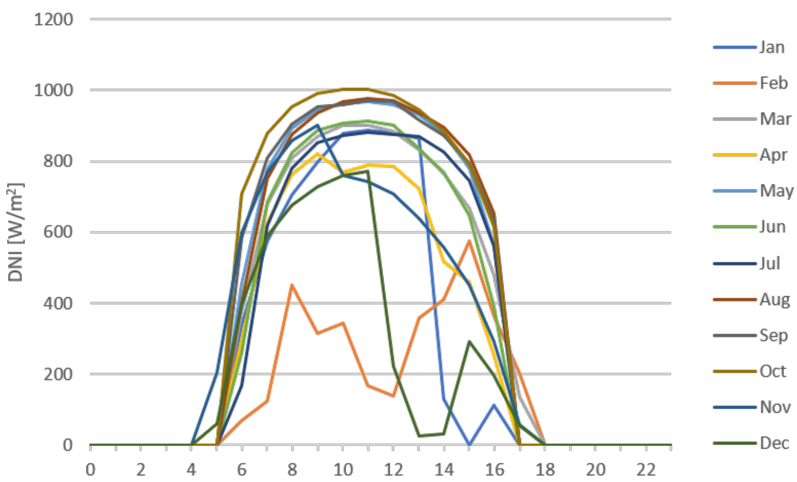
7.1 Technical feasibility

In the chapter 5, one of the main barriers for non-conventional renewable sources in Peru was concluded to be the intermittent availability of the resource for electricity generation. Therefore, the value of a potential CSP facility would be the possibility to produce a firm power independently of the moment of the day and the weather. When evaluating the technical feasibility of the solar tower molten salt storage system, this characteristic will be looked carefully.

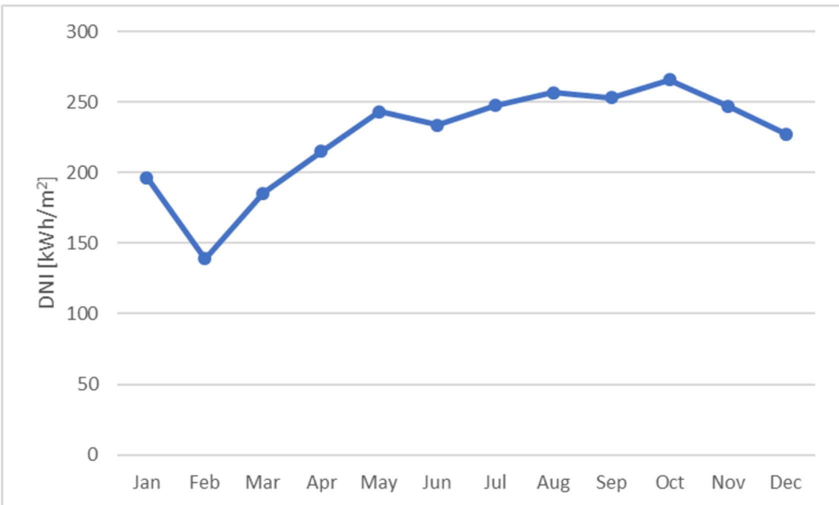
In the first part of the analysis, the distribution of the DNI is considered. The location of the plant is set to be in the district of Jacobo Hunter, on the vicinity of the city of Arequipa, presenting an annual DNI of 2709 kWh/m^2. The Figure 7.1 shows an aerial view of the location of the plant, provided by Google Earth:

Fig. 7.1.: Location of the CSP facility

The total amount of DNI received on the site is distributed hourly using the TMY file provided by NREL for a meteorological station nearby (coordinates -71.58, -16.47 and altitude 2483 meters). The total DNI value for that station is 2819 kWh/m^2, which is similar to the annual DNI of the hotspot. To use this value, the hourly DNI of the NREL dataset is distributed for a total value of 2709 kWh/m^2 using the Equation 4.1. The results are shown in the Figure 7.2. In the first chart (7.2a), incident DNI has been plotted hourly for the central day of each month to validate the daily distribution. The values are expressed in W/m^2. In the second chart (7.2b), the seasonality of the DNI is assessed showing the total received direct irradiance for each month, in kWh/m^2.



(a) Hourly DNI values for the 15th day of each month



(b) Monthly DNI values according to the generated hourly model

Fig. 7.2.: Temporal distribution of DNI in the study site

The values of the Figure 7.2a follow a normal distribution as it is expected for solar radiation. However, the series for months like February or December follow a different path. To understand that, it is necessary to consider the study uses a TMY, so factors as clouds or other meteorological effects can impact a specific day received radiation. What is possible to conclude from both charts is that monthly DNI is quite constant along the year, having similar total monthly irradiance. The minimum of February is explained by the fact that this month has only 28 days. The uniformity of the monthly radiation can become an advantage, as the more uniform the radiation is, the more advantage can be taken of the storage. If there was a striking difference between winter and summer months, it would happen the case in which if storage is optimized for summer would be clearly underused in winter; meanwhile if optimized in winter, it would be saturated in summer.

With the distributed DNI, the model is built according to the method explained in the section 4.4.2. The system consists of a heliostat field, controlled by the variable Solar Multiple (SM) and a molten salt thermal energy storage, which is controlled by the variable Hours of Thermal Storage (HTS). The hypothesis for the technical feasibility analysis is that the 50MW solar tower molten salt CSP facility can produce a base load. This entails keeping the production during most of the hours during the day, as it happens with combined cycle thermal plants or hydropower stations. The basic idea to achieve a constant power delivery is to design a heliostat field which can harvest more thermal energy from the sun than needed to run the power cycle, and this surplus of energy is stored in the hot molten salt tank and used to run the power cycle when the solar resource is not available, at night on in adverse weather conditions. To quantify the objective, the capacity factor (CF) of the plant is the parameter used. Natural gas based combined cycle plants can operate in the ranges above 80% of capacity factor in a full year. The technical feasibility analysis studies if these CF are reachable with the designed CSP installation, and in this case with which parameters of SM and HTS. The model has been simulated with a range of pair values for SM and HTS, and the results produced are recorded in the Figure 7.3:

	HTS												
SM	0	2	4	6	8	10	12	14	16	18	20	22	24
1,0	29%	29%	29%	29%	29%	29%	29%	29%	29%	29%	29%	29%	29%
1,5	38%	43%	44%	44%	44%	44%	44%	44%	44%	44%	44%	44%	44%
2,0	40%	48%	54%	57%	58%	58%	58%	58%	58%	58%	58%	58%	58%
2,5	41%	50%	57%	64%	69%	72%	73%	73%	73%	73%	73%	73%	73%
3,0	42%	51%	59%	66%	73%	79%	83%	84%	85%	85%	86%	86%	86%
3,5	43%	51%	59%	67%	75%	82%	88%	90%	91%	92%	92%	92%	93%
4,0	43%	52%	60%	68%	76%	83%	90%	93%	94%	94%	95%	95%	95%
4,5	44%	52%	60%	68%	76%	84%	91%	94%	95%	96%	96%	96%	97%
5,0	44%	53%	61%	69%	77%	85%	92%	95%	96%	97%	97%	97%	97%
5,5	44%	53%	61%	69%	77%	85%	93%	96%	97%	97%	97%	98%	98%
6,0	45%	53%	61%	69%	78%	86%	93%	96%	97%	98%	98%	98%	98%

Fig. 7.3.: Two variable analysis of CSP plant to find capacity factor

The calculations are provided from this step with steps of 0,5 for each increase of SM in a range from 1 to 6; and steps of 2 hours for thermal storage ranging from no storage to 1 day thermal storage. According to the results, it is possible to reach capacity factors over 80%, when the system presents a SM of at least 3, and 10 hours of storage. For all configurations above those values, the plant factor will be higher than 80%, reaching values of up to 98% hours at full load. If the system is given a certain storage capacity and it is plotted with the variation of SM (size of the solar field), it is noticeable that capacity factor has a maximum, which cannot be exceeded regardless the area of the solar field (see Figure 7.4). Therefore, it is possible to establish a maximum solar multiple depending on the size of the thermal storage.

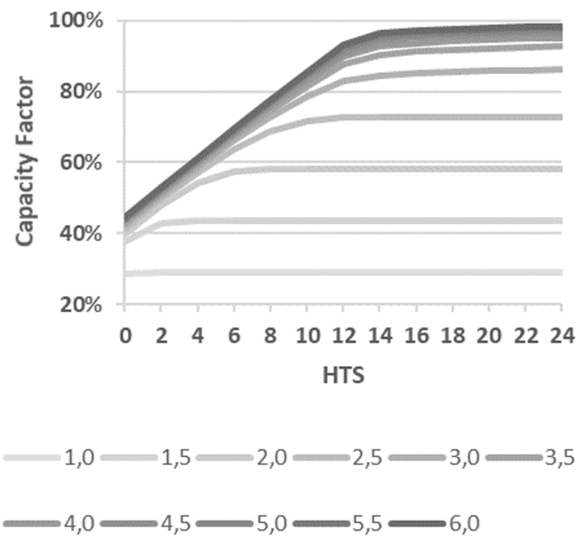


Fig. 7.4.: Capacity Factor for different SM configurations

The technical potential analysis concludes that is is possible to build a solar tower molten salt storage plant with a firm power of 50MW, presenting a Capacity Factor over 80% with the configurations shown in the Table 7.1:

SM	HTS
3	12h
4	14h
5	14h
6	14h

Tab. 7.1.: Pairs of integer values for a technically feasible CSP installation (CP>80%)

The output of the annual operation model is a yearly electricity production in MWh/year from the CSP plant, using solely the heliostat field and the thermal storage. No back-up has been considered.

7.2 Economic feasibility

After confirming that a CSP installation is both geographically and technically feasible in Peru, the decisive point of the analysis draws on the economic feasibility, as it is the barrier that most renewable energy projects are confronted with. To assess the economic feasibility of the designed 50MW solar tower molten salt project, the Levelized Cost of the Electricity (LCOE) has been taken as the decisive factor. The study of literature showed an average LCOE of 250 USD/MWh for CSP technology, which makes it difficult to compete with traditional fossil fuel based technologies ranging from 48 to 150 USD/MWh (IRENA, 2018), when energy investment companies make a decision to build a new power plant.

LCOE calculation has taken into account the electricity generation estimated in the operation model, with a 0,5% degradation factor per year; and the costs of the installation which are directly linked with the control parameters **SM** and **HTS** (see Table 4.5). The financial parameters established are a lifetime of 30 years, inflation rate of 2,48% and discount rate of 7%. As there is an important infrastructural work, the construction of the plant takes 3 years until it can become operational; however, the capital investment is payed the first year. The explanation for the choice of these values is found in the chapter 4. Using the same method than for the CF, a two variable analysis of LCOE has been performed, to optimize the parameters SM and HTS, searching for the minimum value of LCOE. The results are presented in the Figure 7.5 (see next page).

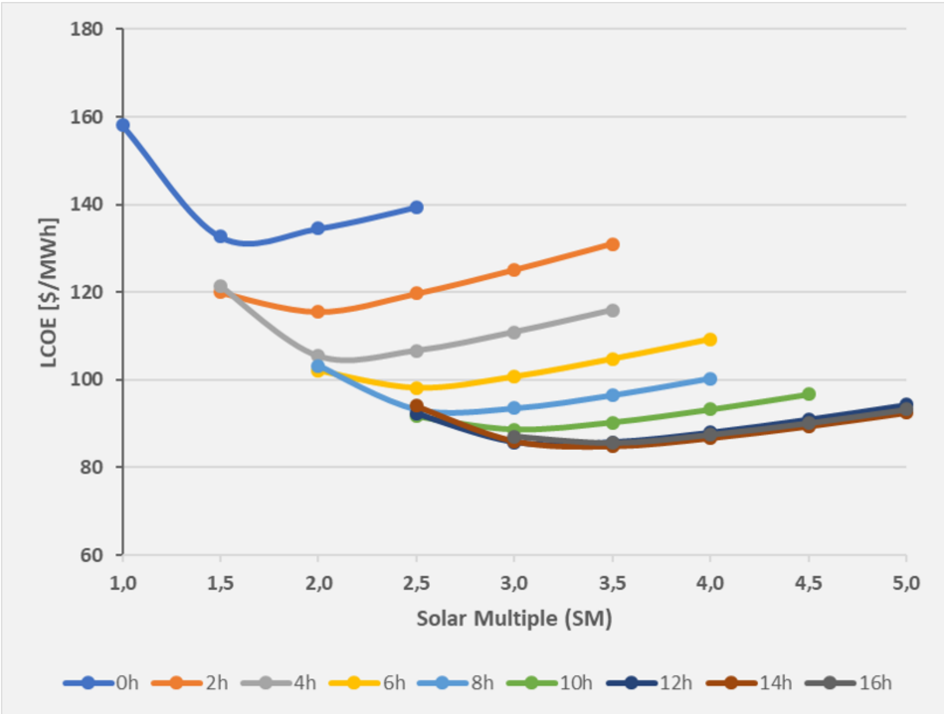
It is remarkable that keeping a constant thermal storage capacity and plotting against SM, the LCOE reaches a minimum value and subsequently rises its value. Therefore, there is a SM optimization for each value of thermal storage hours. The whole range of value has a minimum LCOE of **84,7 USD/MWh**, which is found for the configuration Solar Multiple 3,5, and 14 hours of thermal storage. As the Capacity Factor for this configuration is 90%, the configuration is validated. The technical parameters for the 50MW solar tower plant are for the optimal design:

Item	Value	Unit
Firm Capacity	50	MW
Area heliostat field	721.688	m^2
Number heliostats	5000	
Total Area Plant	901688	m^2
	0,9	km^2
Volume tanks	8713	m^3
Storage Capacity	188	MWh

Tab. 7.2.: Technical design parameters of the 50 MW solar tower molten salt plant

	HTS												
SM	0	2	4	6	8	10	12	14	16	18	20	22	24
1,0	158,1	162,9	167,6	172,4	177,1	181,8	186,6	191,3	196,0	200,7	205,5	210,2	214,9
1,5	132,7	120,0	121,5	124,6	127,8	131,0	134,1	137,3	140,4	143,6	146,8	149,9	153,1
2,0	134,5	115,6	105,4	102,1	103,2	105,5	107,9	110,3	112,6	115,0	117,4	119,8	122,1
2,5	139,4	119,7	106,6	98,1	93,3	91,6	92,3	94,1	95,9	97,8	99,7	101,6	103,5
3,0	145,6	125,1	110,9	100,7	93,5	88,6	85,8	85,9	87,1	88,3	89,6	91,0	92,4
3,5	152,5	131,0	115,9	104,8	96,5	90,2	85,8	**84,7**	85,6	86,6	87,7	88,9	90,2
4,0	159,7	137,1	121,2	109,3	100,3	93,2	88,0	86,6	87,5	88,5	89,6	90,8	92,0
4,5	167,2	143,4	126,7	114,1	104,4	96,7	90,9	89,4	90,1	91,1	92,3	93,5	94,7
5,0	174,8	149,8	132,3	119,1	108,7	100,5	94,3	92,5	93,2	94,3	95,4	96,6	97,8
5,5	182,5	156,3	138,0	124,1	113,2	104,5	97,8	95,9	96,6	97,7	98,8	99,9	101,1
6,0	190,3	162,8	143,7	129,1	117,7	108,5	101,5	99,4	100,1	101,1	102,3	103,4	104,7

(a)



(b)

Fig. 7.5.: Two variable analysis of LCOE for the designed CSP plant

The Figure 7.5 shows that for the most basic design, with solar field scaled to generate electricity at full capacity during the maximum radiation time and no thermal storage, the cost of electricity is 158 USD/MWh, lower than the average cost for CSP plants. For the optimized case, the LCOE of 84,7 USD/MWh is in the range of fossil fuel electricity generation, therefore it could compete with these technologies. The reasons for the low LCOE compared with the average in the literature can lay in several factors:

- The plant is located in a site with a high DNI of 2709 kWh/m^2, which is the most decisive factor for the performance of the plant. Compared with the locations of the majority of commercial plants, USA and Spain direct irradiance are nearly double.

- The economic parameters have been selected to represent the state of the art of the technology, representing the cost reduction in the last year. The cost parameters of existing projects are likely to be higher.

Finally, the study takes a closer look into the techno-economic outputs of the optimal design, to draw additional economic conclusions. The techno-economic results for this plant are presented in the Table 7.3:

Item	Value	Unit
Net Capital Cost	302.289.111	USD
CAPEX per capacity	6.046	USD/kW
Yearly O&M	4.685.476	USD
Fuel costs	0	USD
Electricity generation	395850	MWh/year
Lifetime	30	years

Tab. 7.3.: Economic outputs of the economic feasibility analysis

With the obtained financial results, it is possible to estimate a Net Present Value of the Investment if a price is established. If the price per MWh is equal to the LCOE, the NPV is close to 0. For any electricity price higher than LCOE, the NPV will be positive and therefore the investment profitable. For example, for a price of 90 USD/Mwh, the NPV of the project is 21 million USD. The investment is paid back on the 11th year after the beginning of the construction. If only counted since the beginning of the operation, the return of the investment is produced already in the 8th year, which is an acceptable value; considering it is a large investment with high capital cost.

The conclusion is that CSP technologies can be considered as an option in Peru for new electricity generation projects. The country presents privileged conditions, which allow that already at the current state of the technology, a solar tower plant with storage can compete with other technologies for generation of electricity. To complete the analysis, the results are checked with a sensitivity analysis, which allow the direct comparison with the alternatives which are recurrently chosen for base-load plants in Peru; and in a second part, sensitivity analysis is also used to check the robustness of the analysis as many inputs in the model are assumed and can suffer important variations when the project is implemented.

8 Sensitivity analyses

The last part of the analysis is a series of sensitivity analyses with the aim of checking the robustness of the results, and establish several scenarios which can entail an improvement or downfall for the project. Yet in the first part, the results obtained in the Chapter 7 are compared with the possible alternatives.

8.1 Comparative analysis with traditional alternatives

The new electricity capacity installed in Peru during the last years, is predominantly made by thermal generation. Therefore, in this section the LCOE is estimated for natural gas combined cycle power plant, and diesel reciprocating engine; using the same financial parameters; to estimate the position of the designed solar thermal power plant compared with other fossil fuel alternatives.

8.1.1 Diesel reciprocating engine

The natural gas of Camisea field only supplies the centre of the country, especially the area of Chilca, where modern natural gas plants are installed. In Southern Peru, thermal generation is often covered with diesel reciprocating engines in areas with large energy demand, as it can be the case of a mine. To estimate the LCOE, the parameters shown in the Figure 8.1 are used. Data are provided by (LAZARD, 2017) and (Volker Quaschning, 2015) for emissions, for the same discount rate, plant factor and capacity of 50MW like the studied plant.

Item	Value	Unit
CAPEX per capacity	500	USD/kW
Fixed O&M	10	USD/kW
Variable O&M	10	USD/MWh
Fuel costs	173	USD/MWh
Electricity generation	395850	MWh/year
Lifetime	20	years
Emissions	0,27	$kgCO_2/kWh$

Tab. 8.1.: Economic parameters for diesel reciprocating engine

The LCOE resulting is **157,95 USD/MWh**, which is in the level of the most basic CSP plant with SM equal to 1 and no storage. Moreover, the CO_2 emissions rise to 1636074 tonnes during the lifetime of the plant, which is 10 years less than for CSP plant. Therefore, a power tower CSP plant would be more feasible than diesel reciprocating engine for the generation of large amounts of electricity in areas which are remote to the grid. To this extent, it would be a further step to investigate if there are large mining projects near the hotspots which were identified in secluded areas.

8.1.2 Natural gas combined cycle

However, the most used solution is natural gas cogeneration, especially after the beginning of the exploitation of Camisea gas. Most of them are located in the central part of the country, close to the large demand present in the city of Lima but they also supply distant areas in the country. For example, the largest mine of Peru, Cerro Verde, in the south of Arequipa and very close to the projected plant, constructed the gas-fired station Recka in the central part of Peru. This entails a large cost of transmission and it can present shortage of capacity on the grid. The financial parameters to estimate the LCOE of a natural gas in Peru are also provided by (LAZARD, 2017), with the exception of the fuel cost. Due to the fact that Peru is a large producer of natural gas, the fuel is considered cheaper than an average gas plant, therefore the cost value is provided by official sources (Promigas, 2018), and the emission factor is given by (Volker Quaschning, 2015)

Item	Value	Unit
CAPEX per capacity	1100	USD/kW
Fixed O&M	11,7	USD/kW
Variable O&M	3,50	USD/MWh
Fuel costs	33,50	USD/MWh
Electricity generation	395850	MWh/year
Lifetime	20	years
Emissions	0,20	$kgCO_2/kWh$

Tab. 8.2.: Economic parameters for diesel reciprocating engine

The LCOE resulting is **51,95 USD/MWh**, therefore it is a more cost-effective technology than the modelled solar tower. The CO_2 emissions accounts 1142072 tonnes during the lifetime of the plant, which is also 10 years less than for CSP plant. But it is necessary to consider that due to the high governmental support natural gas is exempt of special taxation in Peru like other fossil fuels. This is a result of the campaign of the government and the industry to understand natural gas as a clean source, because it emits less and it is more efficient. A sensitivity analysis has been performed on the level of taxation that could be implemented on natural gas in the future. The Figure 8.1 shows the results:

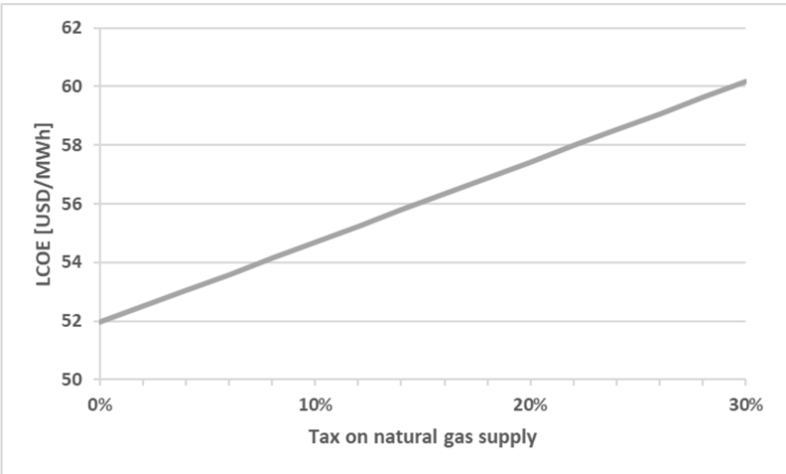


Fig. 8.1.: Sensitivity analysis on the natural gas tax

Even though with a tax of 30%, the LCOE would rise above 60 USD/MWh; it would be lower than the LCOE for the solar thermal station designed. Further cost reductions would be necessary for the solar thermal plant to be economically comparable with a large-scale natural gas combined-cycle power plant.

8.2 Sensitivity analysis of the solar tower molten salt plant

The parameters used for the estimation of the LCOE are subject to a number of assumptions, and a deeper analysis as for the implementation of the CSP plant might introduce fluctuations in the parameters. Therefore, a sensitivity analysis has been performed, in the most relevant inputs for the final result.

8.2.1 Capital investment

The graph on the Figure 8.2, shows the different items which contribute to the capital investment for the optimized plant, in order to give an impression of the relative importance of each cost.

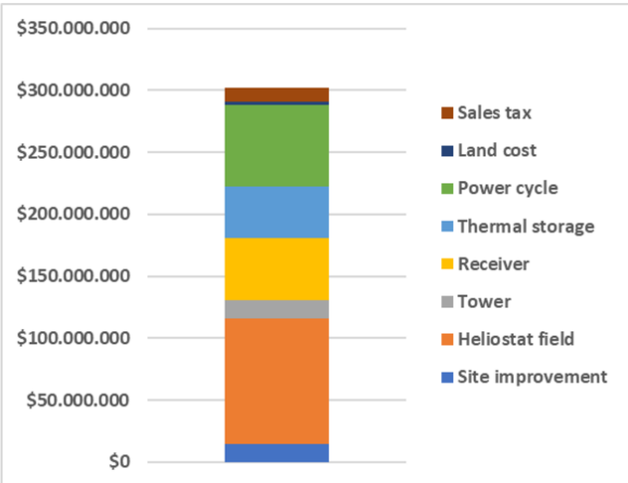


Fig. 8.2.: Components of the capital cost

The most decisive item is the heliostat field with a cost over 100 million USD. Future reductions in the cost production of the heliostats would make a significant impact on the price. Other important factors are the solar receiver and the thermal storage tanks. On the other hand, the cost of land or the tower are relatively irrelevant compared with the magnitude of the other costs. The overall capital investment cost is expressed in relation to the nominal capacity of the plant, giving a cost of 6046 USD/kW installed, which is in the range of costs expressed in the IRENA report (IRENA, 2018). The results of the sensitivity analysis for capital investment are shown in the Figure 8.3:

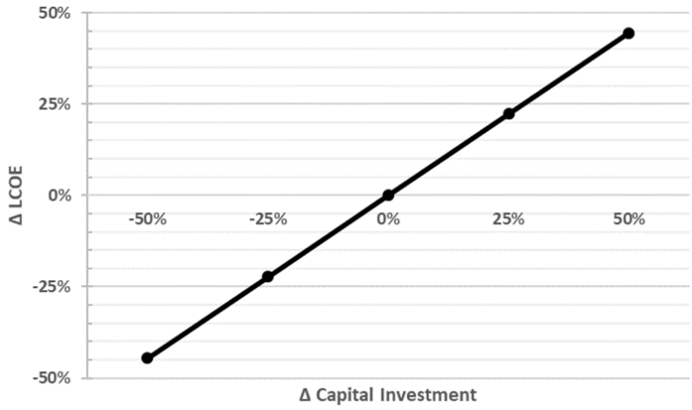


Fig. 8.3.: Sensitivity analysis on capital investment

The graph shows a striking impact of the capital cost per capacity on the LCOE. The relation is near 1:1. If capital cost per kilowatt is reduced in 25%, the LCOE follows with a decrease of nearly 25%. This impact suggest a good future for the technology when the costs are favoured by the learning curves effect. With a reduction of approximately 40% of CAPEX, the LCOE would approach to the combined cycle natural gas plants.

8.2.2 Direct Normal Irradiation

The annual DNI incident in the area has been pointed as the most important geographical criterion for the feasibility of a CSP plant. A sensitivity analysis has been performed for the optimized plant of SM 3,5 and 14 hours of thermal storage, see Figure 8.4:

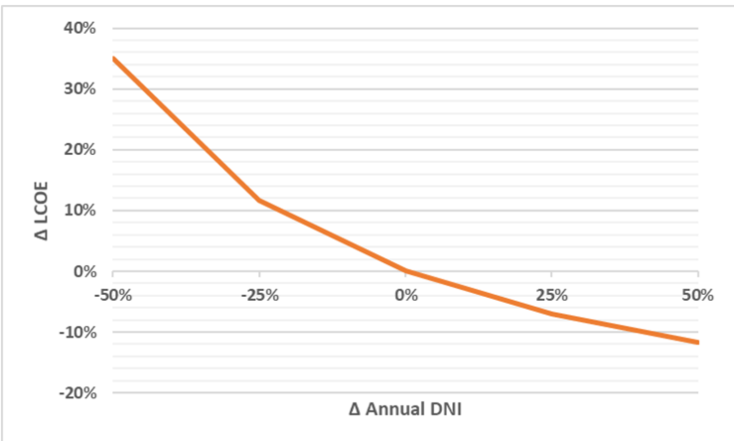


Fig. 8.4.: Sensitivity analysis on annual DNI

The chart shows that LCOE rises sharply when the annual DNI decreases below 25%, but it is relatively stable within the window of 25% upwards or downwards, with fluctuations on LCOE below 10%. If the DNI increases above 25% the decrease on LCOE continues steadily. The conclusion is that the dimensioning of the plant is robust in terms of annual DNI, as it is a parameter that typically fluctuates through the years. However, as the result of the analysis demonstrate, these fluctuations would not make a big impact on the LCOE of the plant.

It is important to highlight that the sensitivity analysis on Direct Normal Irradiance cannot be transferred to a plant in another location, for instance to estimate the LCOE in another hotspot of those identified in the Chapter 6, as the distribution of the radiation is different along the year and thus the optimization of Solar Multiple and Thermal Storage pairs would differ.

8.2.3 Discount rate

The discount rate is a decisive factor in an investment, because it contains information concerning the expected profit of the investment and it used to compare different investment in private companies. The real discount factor of 7% used in the analysis has been recommended by an expert in the Peruvian electricity sector, as part of a range between 7 to 10%. Therefore, a sensitivity analysis is carried out to uncover the impact of the discount rate.

Fig. 8.5.: Sensitivity analysis on real discount rate

The results, as shown in the Figure 8.5, display a considerable impact of the discount rate in the final LCOE result. Only a decrease of 1 point in the LCOE reduces the LCOE in 10%. Therefore, within the range of discount rates given, the difference between selecting 7 or 10% is an increase of more than 30% in the LCOE, a factor that has to be considered when stating that CSP is a economically feasible technology for Peru.

On the other hand, a discount rate of 3% returns a LCOE of 54 USD/MWh, which is comparable with the option of combined cycle with natural gas. This discount rate would not be acceptable for a large private investor, yet public investment fund could support the initiative with this discount rate to introduce the technology in the country and produce the expected learning effects to reduce costs for future plants and therefore, expand the market for CSP technologies in Peru.

8.2.4 Degradation rate

Lastly, the influence of the degradation rate is studied. As the first plant of its kind in the country, the plant could be subjected to a higher degradation rate than the conventional because not much expertise in the technology is acquired at the moment. Therefore, a sensitivity analysis is performed in the degradation rate.

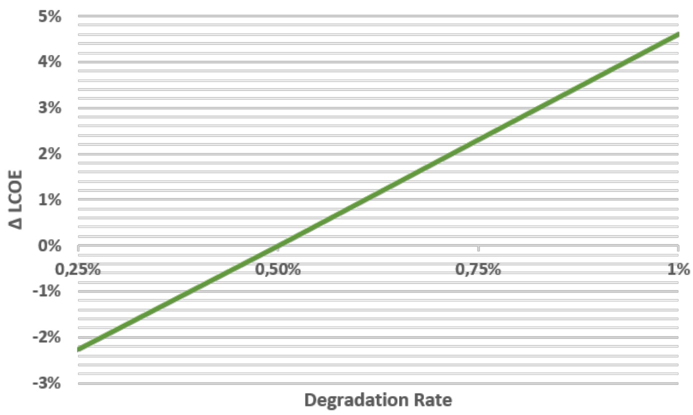


Fig. 8.6.: Sensitivity analysis on degradation rate

The graph in Figure 8.6 shows a linear correlation between the degradation rate and LCOE, as it diminishes the production per year especially in the second half of the project lifetime. However, at the studied ranges below 1% the impact of the degradation rate is below 5% of the LCOE. Therefore, the analysis is considered robust in terms of degradation rate.

To draw a conclusion on the sensitivity analysis, the 50MW solar tower plant with molten salt storage is a favourable option compared with a diesel reciprocating engine, therefore in areas without supply of natural gas could be considered as the first option for a new electricity generation project. Compared with natural gas fired combined cycles the LCOE is higher even though they stay in the same dimensional scale. Additionally, the sensitivity analyses show that the CSP plant can become more competitive if taxation on natural gas for generation is implemented in Peru, the capital investment costs of CSP decrease or a lower discount rate is selected. The analysis is robust to fluctuations in the annual value of DNI for the selected location and the degradation rate of the plant. Compared with the alternatives of fossil fuel power plants, a CSP based installation would save more than 1 million tones of CO_2 emissions during its lifetime.

9 Discussion

The following chapter discuss the process of analysis that has been carried out to answer the research question. The discussion has been divided in four sections. Firstly, data used in the research are validated, the second part discuss the methodology used to solve the problem and the third part discuss the obtained results and explain the reasons to be considered valid. Finally, the fourth section describes possible implications of the research and future studies to continue with the topic.

9.1 Data validation

Data used in the project have their origin in a wide range of sources: interviews with experts in the field, official documentation, international statistics and databases and state of the art software.

For the analysis of the current situation in Peru, two interviews were conducted with university professors specialized in Energy and Electricity. The answers given were following the same discourse line, identifying the problems that renewable energy technologies face in the country. Their conclusions are compatible with the reviewed literature in Peru, which consisted in technical documentation produced by the state institutions (OSINERGMIN and MINEM) and press notes. However, it was detected large difficulties to find relevant data in terms of investments and costs, especially when it comes to the electricity market. The governmental web pages include a "transparency portal" to display internal information to the public, even though this tool has not been used for time constraints. For the cost of natural gas, important differences were found among documents, but this fact was attributed to the declaration zero effect and the specific business plans of different countries. Therefore, it is concluded that more information concerning electricity generation investments should be public; to raise awareness of different alternatives and the real societal cost of the decisions taken at a high level.

During the geographical potential analysis, a wide range of datasets have been explored in the format of GIS files, especially .tiff and .shapefiles. A part of the data is provided by ministries of Peru, concerning administrative limits, urban areas and infrastructure. The validity of the data is accepted as the origin of the maps was an official source. However, data for urban areas or electricity transmission grid (SEIN) was missed, as they are not produced or easily available for the public. The rest of the datasets are obtained from international specialized databases, providing geographical information for topography, land use, water availability and protected areas, which are validated as they are supported by reputed international institutions. One of the most relevant dataset obtained was the annual DNI map by the Global Solar Atlas. This a project promoted by the World Bank organization which intents to provide a sound ground information for the development of energy solar projects around the world. The Atlas dates from 2016, therefore it is relatively new. The methodology to predict annual DNI data is through satellite-based analysis and field measures. In comparison with the other available source, the Solar Atlas of Peru, elaborated by the public institutions of Peru in 2003; the Global Solar Atlas shows higher resolutions plus higher values of DNI than the rather conservative study of 2003. As most of the existing analysis of solar potential in Peru use the 2003 solar atlas, the analysis performed constitutes one of the first attempt to apply the information of the Global Solar Atlas in Peru, which adds value to the research. When compared with the information extracted by the meteorological stations found in the NRSDB, the Global Atlas map shows compatibility of results. For the analysed hotspot, the annual DNI value disagreed in less than 4% with the NRSDB information for a Typical Meteorological Year. Considering the station is located in a range of less than 5 kilometers to the plant, the results given by the Global Solar Atlas are considered validated.

The techno-economic analysis includes several assumptions in terms of data collection. As there is not a representative plant with CSP technologies in Peru at the moment, general information for this kind of plants have been provided for the research through the worldwide used NREL tool System Advisor Model (SAM). When opening a project with the selected category, the software loads a set of default data, corresponding to the state of the art of the technology in a worldwide basis. The data inputs are compared with the analysis parameters used by the professor Eunice Villicaña from UTEP to calculate the potential of CSP in Peru, and the data are considered compatible. However, the overall cost of the installation is considerably cheaper than the previous analysis. This is attributed to the state of the art technology presented by SAM, which uses current data which are periodically updated. The parameters have been additionally contrasted with international reports on the cost of renewable technologies (IRENA, 2018) and (LAZARD, 2017), with data converging to similar values. Finally, it is important to highlight that input data of a CSP installation heavily depend on the local conditions, therefore when the decision of implementing the plant is firm, a more exhaustive techno-economic analysis should be performed, using data for the specific location.

9.2 Discussion of methods

The choice of method as an important impact on the result. Different methods were considered when making the decision upon the methodology to find the three levels of potential for CSP technologies in Peru. A geographical analysis was disregarded on a first stage of the project, but adversities were encountered when designing the CSP installations on locations chosen to fulfill a demand. At first, a plant was planned to provide the mine of Cerro Verde, but the slope of the surrounding land discouraged the project. In a second attempt, the idea was to established a CSP cogeneration plant to supply electricity for the operation of the mine Tia Maria and energy for desalination to use desalinated water in the mine. The project was located in the coast of Arequipa region, but the values of DNI were low in the first kilometers of land from the coast, and only become higher when placed in an elevation of approximately 1000 meters, where it would be expensive to pump the water. Discarding these two ideas in the first steps of the project was a decisive factor to conduct a geographical feasibility analysis, in order to lead the location of the plant in a suitable area. For the actual analysis, scientific papers researching solar geographical potential were consulted, and it was found that a majority of them use a GIS-based multicriteria decision making method. The geographic analysis carried out in Tanzania (Aly, Jensen, et al., 2017) was used as a base for the construction of the methodology, and it proved a successful method to obtain the desired results. The first step consisted in creating a suitable area layer, by excluding areas which are not suitable according to a set of criteria. The method for establishing land cover suitable for CSP, the calculation of the expansion area for urban units was taken by the research paper in Tanzania. The second part of the analysis consisted in a ranking of suitable areas according to a range of criteria. In this case, the use of only water bodies for the RC2 was a decision made in order to prevent water supply problems, which are present in many municipalities of the south of the country. Additionally, a lack of information regarding electrical infrastructure was resolved assigning a higher weight to road infrastructure to cover RC3 Accessibility. It can be noted that in many cases grid lines follow roads. National road network has been used, but not all national roads are properly paid, so it would mean problems to transport the material. Some departmental or local roads could have been considered. The GIS-methodology consisting in using GRASS tool to convert vector information in raster and reclassify the raster presented a challenge when the information was not limited to the surface of Peru, as it was necessary to cut the layers or combine them with a raster representing the limits of Peru. The superposition of maps with different raster resolution caused the project to present an output with worse resolution than the input maps. In the maps for DNI, land use or topography, the pixel scale was a grid with the range from 300x300 meters to 900x900. The final layer, has a resolution between 1500 to 2000 square meters per pixel. The impact on the techno-economical feasibility analysis is that for areas marked by one pixel, only areas smaller than 2 km^2 should be considered.

The second part of the analysis corresponds to the techno-economic feasibility study. A 50MW capacity plant consisting in the technology of solar tower with a thermal storage containing molten salt was projected. To model the technical operation several methods were considered, given the complexity of the system and the large amount of parameters involved. The software SAM provides an optimization tool for a solar tower CSP plant. However, it was not used to calculate the LCOE in order to control all steps of the process to be able to analyze the integrity of the analysis. The method used by the professor Eunice Villicaña for the estimation of LCOE for CSP installation in Peru was closely studied but the monthly operation method makes it unsuitable for the analysis when a thermal storage is includes, which fluctuates its charge status daily. In conclusion, an hourly based analysis was performed using the average efficiencies given in professor's Villicaña's method. Solar field efficiencies are fluctuating depending on the position of the sun, the tracking system of the heliostat, the atmosphere at the instant moment among a wide range of factors. However, average efficiencies are used as the hourly calculation of the efficiencies was out of the scope of the research, which is to find an estimation of LCOE for CSP solar tower plant. A second important assumption consists in the consideration that all incident DNI is converted by the system in thermal energy and transferred to the molten salts, when normally the plant requires a minimum radiation to start the heat production. This simplification has the objective to match the annual DNI obtained in the geographical analysis with the electrical output of the model. The last important simplification in the model is the fact that the impact of the temperature of the salts is disregarded. Molten salts needs a minimum temperature to avoid fusion, and the temperature of the salts has an important effect on the radiation losses as well as the instant efficiency of the power plant, which is considered constant. The economic analysis contains a set of assumptions. Taxation on sales has been disregarded, as no clear regulation of CSP generation exists. Engineering and other indirect costs, as well as loan coast are considered to be included in the capital investment. The consideration of this factors would be relevant when a definitive economic feasibility plan is adopted previous to the implementation of the plant.

The strength of the tailored method use that has been carried out is that the researcher controls in every step the validity of the partial outputs and reaches an acceptable estimations, which allow to draw the first conclusions on the suitability of CSP technology in Peru. The disadvantages are the large number of assumptions and simplification which have been performed, as a consequence of lack of relevant data or the time and complexity limitation that has been established to be able to produce a comprehensive analysis of the three categories of potential for CSP.

9.3 Discussion of results and validation

The research question asked *Is Concentrated Solar Power (CSP) with thermal storage a techno-economically feasible option for Peru?*, and the results apparently suggest a positive response to the question. However, to confirm the statement is important to validate the achieved results.

The geographic potential analysis shows that there are are a number of areas which are suitable for the installation of CSP plants, even though the total area is smaller than it could have been expected with the DNI map. The main reason is the topography of most of the areas with a high value of DNI, as they are located in sites with altitude, and in many cases the slope of the terrain excludes the area to be considered feasible for CSP. Anyway, the results of the hotspot analysis, shows that 4 out of 8 selected hotspots are located to more than 4000 meters altitude, in flat areas. The validity of these results would have to be confirmed by a specific study, as a high level of uncertainty emerges when the plant is decided to install at such a high level. However, the altitude has not been considered as exclusion criterion or ranking criterion, because there is not specific limitation that altitude represents and it is more linked to the normal absence of proper infrastructure at high altitudes. In case a large city is place at altitude, the infrastructure can be present and thus the single factor of altitude cannot constitute a limitation for the feasibility of the plant. For that reason, the HS6 near the city of Arequipa has been selected as the most reliable hotspot and the techno-economic analysis has been performed for that location. To validate the result of DNI obtained for the analyzed hotspot, it is compared with DNI values of other CSP projects in the world (Figure 9.1).

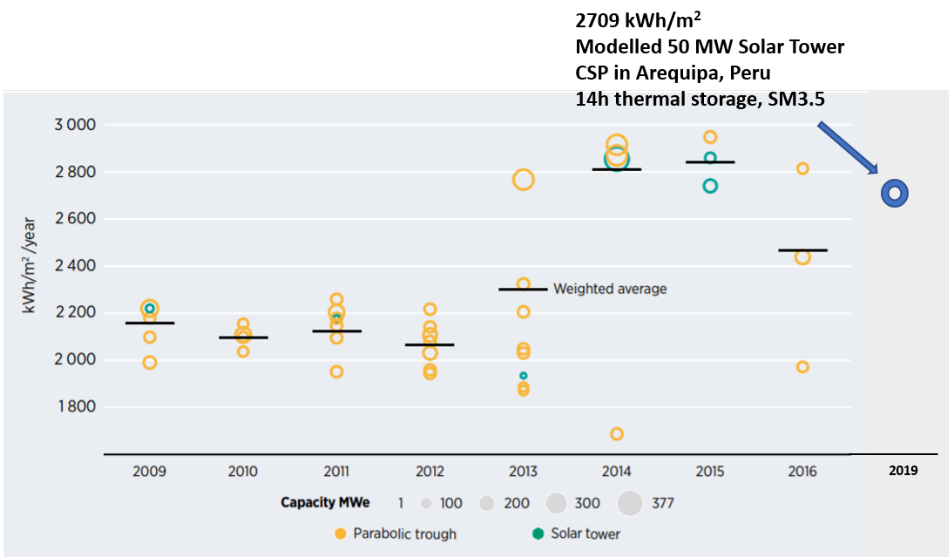


Fig. 9.1.: DNI of operational CSP plants (2009-2016). Adapted from (IRENA, 2018)

The Figure shows the annual DNI design points of CSP projects from 2009 to 2016. As the first commercial plants were built in Spain and USA, the values of DNI until 2013 keep below 2400 kWh/m^2 per year. However, with the world expansion of the technology in the last years, values of DNI have risen up to 3000 kWh/m^2. The projected DNI parameter of 2709 kWh/m^2 is in the range of the values used, so it can be validated.

Finally, the result of the techno-economic feasibility assessment for the 50 MW solar tower CSP plant has been compared with other commercial CSP projects worldwide. The LCOE has been plotted in the graph of the publication *Renewable Power Generation Costs in 2017* by IRENA. As shown in the Figure 9.2 the achieved LCOE is below the values for the cost of electricity in any project before 2018. Even though the value has been placed in 2019, as the construction of the plant takes 3 yeas the project could start operation not before 2022. The achieved LCOE is comparable then with the new commisioned power plant in United Arab States that is shown in the right corner of the Figure.

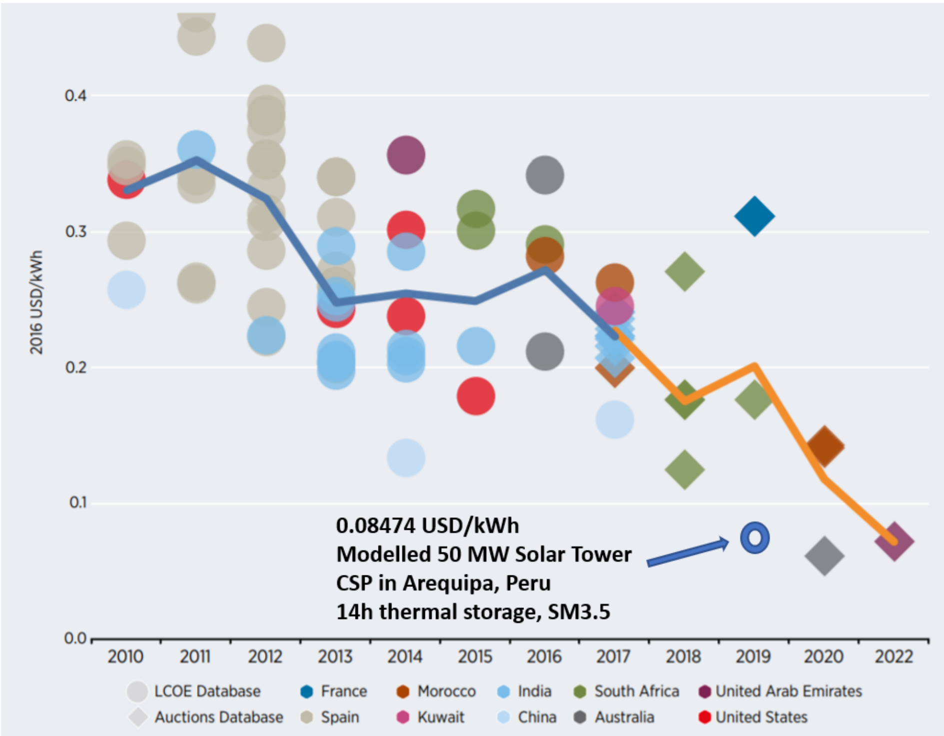


Fig. 9.2.: LCOE or tariff price of operational CSP plants (2010-2022). Adapted from (IRENA, 2018)

Subsequently, a selection of commercial CSP solar tower plants has been plotted in a table to compare the technical and financial parameters with the parameters calculated in the analysis. The information regarding worldwide projects has been found in the CSP Database (SolarPACES, 2019). The Table 9.1 shows power tower

CSP plants worldwide ordered by the start of operations. The Heat Transfer Fluid in the majority of the plants is the molten salt, as the design plant is using. The project is among the plants with higher storage capacity, as it is constructed to behave as a base load station. In this group is found the station Gemasolar in Spain, which was the first of its type to research the possibilities for a distributed generation. Regarding the capital investment cost (USD/kW), the plant of design is in the range of values presented. Note that the two plants of Chile present similar values for investment (4545 and 7692). To compare the annual electricity generation (MWh) it is necessary to analyze with plants with the same capacity. The designed plant, doubles the year generation of the other two plants with 50 MW capacity: Khi Solar One in South Africa and Supcon Solar in China. This is achieved thanks to the large thermal storage capacity installed. Concerning the most relevant value, LCOE of the plant is lower than any of the LCOE presented for plants currently active. It is comparable for the cost presented by plants to be commisioned during the next year. The plant Copiapó in the Atacama desert presents a LCOE of 63 USD/MWh; in analogy with the calculated cost. Thus, the result is considered validated.

Project	Country, Start	HTF	MW	HTS	USD/kW	MWh	USD/MW
Gemasolar Thermosolar Plant	Spain, 2011	Molten salt	19,9	15	13166	80000	-
Ivanpah Solar Electric	USA, 2014	Water	392		5612	1079232	-
Khi Solar One	South Africa, 2016	Water/Steam	50	2	10000	180000	-
Supcon Solar Project	China, 2018	Molten salt	50	7	2200	146000	169
Ashalim Plot B	Israel, 2017	Water/Steam	121		-		215
Atacama-1	Chile, 2018	Molten salt	110	17.5	4545		-
Redstone Power Plant	South Africa, 2018	Molten salt	100	12	7150	480000	124
Huanghe Tower CSP	China, 2017	Water/Steam	135	3.7		628448	169
Copiapó	Chile, 2019	Molten salt	260	14	7692	1800000	63
MINOS	Greece, 2020	Molten salt	52	5			316
Aurora Solar Project	Australia, 2020	Molten Salt	150	8	3043	500000	56
Modelled in "Arequipa"	Peru	Molten Salt	50	14	6046	395850	84,74

Tab. 9.1.: Comparing commercial CSP projects to the modelled CSP plant in Peru

Lastly, the results are compared with the analysis presented by the professor Eunice Villicaña in the 4th Global Energy Forum in Peru, shown in the Figure 9.3:

Data	Tacna	Ica	Moquegua
DNI [W/m2]	677	650	694
Tem [°C]	21	22	15
GWh/año	368	376	342
FP	35%	36%	32%
LCOE_ min [$MWh]	$ 144.00	$ 141.00	$ 155.00
LCOE_max [$MWh]	$ 224.00	$ 218.00	$ 241.00
DNI [W/m2]	677	650	694

Fig. 9.3.: Summary of LCOE estimation for CSP technology in Peru, from (Ortiz, 2018a)

In words of the author, the input data for DNI and economical parameters adopted were conservative, to obtain a reliable value of LCOE. Moreover, the plants are modelled for the DNI of the three cities, not considering areas out of the city which might present a higher radiation. Additionally, the DNI values are based in the Solar Atlas Peru 2003, not the most recent one by the World Bank. The plant was modelled without thermal storage but to harvest the maxium DNI possible; and the result of annual electricity generation are similar to the results found in the analysis. The range of LCOE given in the Figure, from 144 to 241 USD/MWh are higher than the calculated in the project. During the interview with Eunice, a last statement was:

> In the case of CSP technologies, to become feasible, companies and developers in Peru are asking for a LCOE of 80 USD/MWh

The calculated LCOE of 84,74 USD/MWh make the project, according to this statement attractive for investors in Peru. Regarding the comparison with the previous LCOE study, the results are once more considered valid as being in the range of less than double of the analysis shown in the Figure 9.3, considering that the analysis of this report has looked for the state of the art conditions.

9.4 Future research

As one of the first studies about Concentrating Solar Power feasibility of Peru, the results of this thesis can be used for more specific analysis with the objective of the implementation of the first CSP plant in Peru in a period of 5 years. To expand the knowledge generated in the analysis, the 7 hotspots identified can be analysed to verify if they can become the site for a new CSP plant, with special interest in the hotspots with higher DNI or the situated on high altitude in order to verify the actual impact of the location for a real operation of a plant.

In a more worldwide view, the methodologies used in the project have emerged in the last 2 years and continue being updated. The Global Solar Atlas was created in 2016 as a base for new solar generation projects. The combination of GIS analysis with Multicriteria Decision making and techno-economic simulation using tools like System Advisor Model, can constitute a comprehensive methodology to study the Concentrating Solar Potential in many other regions of the world, including in a national scale. Governments and private investors should conduct analysis to verify the possibilities to use a technology which does not present emissions, does not have a fuel cost and can ensure a uniform dispatch.

10 Conclusions

In the light of the current world transformation to fight climate change, the eyes were turned towards a developing country like Peru and its energy transition. Despite being a country with a large incident solar radiation, the number of solar generating plants is reduced. The existence of large reserves of natural gas has lead the government to support this path, and the technologies which aim to compete against the gas have to present an important characteristic: firm power generation. Among the renewable energy technologies, Concentrating Solar Power is possibly which can adjust better to these conditions, but Peru has never implemented the technology nor has plans for it. For that reason, this report aims to answer the following research question: **Is Concentrated Solar Power (CSP) with thermal storage a techno-economically feasible option for Peru?**

To fit in CSP technologies in Peru, an analysis on the current configuration of the sector was necessary to decide the type of technology that could best adapt to the needs. Hence, the first subquestion was *How is electricity currently generated in Peru?* The analysis shows a sector which is highly dominated by natural gas generation but presents downfalls. The excess of supply and low fuel cost declaration are sinking the marginal cost and creating a distortion in the market. Moreover, electricity generation is heavily concentrated in the centre of the country, causing congestion in the transmission. With this panorama, a large-scale solar tower plant with thermal storage can be sighted as an appropriate solution to diversify the generation and avoid the dependence on the fuel cost.

After deciding the specific technology to implement, to answer the research question, the three categories of potential for a determined technology were analyzed: geographic potential, technological potential and economic potential. The second subquestion: *Where are the most suitable locations in Peru to build large-scale concentrating solar power installations?*, dealt with the geographic potential. A GIS-based analysis was carried out with the objective to identify which areas are most suitable for the installation of the considered CSP plant. Firstly, a map was generated with the areas that fulfill the requirements for CSP: high Direct Solar Irradiation, flat terrain, and availability of the land as it cannot be occupied by urban areas, economic activities or protected zones. The result showed that the CSP potential of Peru is concentrated in the south of the country, with larger areas near the coast. To find the most suitable locations, the suitable areas were ranked in base of established criteria of high radiation and proximity to water sources, infrastructure and demand. Eight hotspots were identified in the departments of Tacna, Ayacucho, Arequipa, Puno and Moquegua. All of them present high values of radiation, predicting an important CSP potential in Peru.

The last and decisive subquestion was titled *What is the techno-economical feasibility for CSP-based electricity generation in Peru?* To answer the question, a simulation of the intended CSP plant was carried out for one of the locations found in the geographic analysis. In the vicinity of the city of Arequipa, a 50 MW solar tower plant with thermal storage by molten salt was modelled, establishing two parameters to optimize the techno-economic performance: the size of the solar field to concentrate the radiation and the capacity of the thermal storage. The best configuration was found for a plant with Solar Multiple 3.5 (oversize respect the needed area to run the 50 MW power cycle), and thermal storage with capacity to produce electricity for 14 hours in absence of radiation. The plant with these parameters present a Capacity Factor of 90%, verifying the technical feasibility condition that needs to be competitive with natural gas with a uniform availability. In economic terms, the plant was simulated for a 30 years lifetime with a discount rate of 7%, presenting a competitive LCOE of 84,74 USD/MWh, comparable with the threshold of feasibility for CSP projects that the expert interviewed set in 80 USD/MWh . Even though the cost of electricity generation is higher than natural gas combined cycle plants, the result was better than predicted by previous studies and comparable with commercial projects existing in other countries. The high level of solar radiation in the south allow to keep a LCOE even below the average.

As suitable potential was found for all the three categories, it can be concluded that Concentrating Solar Power technology can be a feasible option for new electricity generation projects in Peru and should be considered by investing groups and developers. Moreover, the progress of the years will improve the feasibility of CSP plants, as it is expected a decrease in the capital costs, and the introduction of taxation on natural gas supply to comply with the climate agreements; factors that are expected to tip the scales towards a technology with no CO_2 emissions and uniform production.

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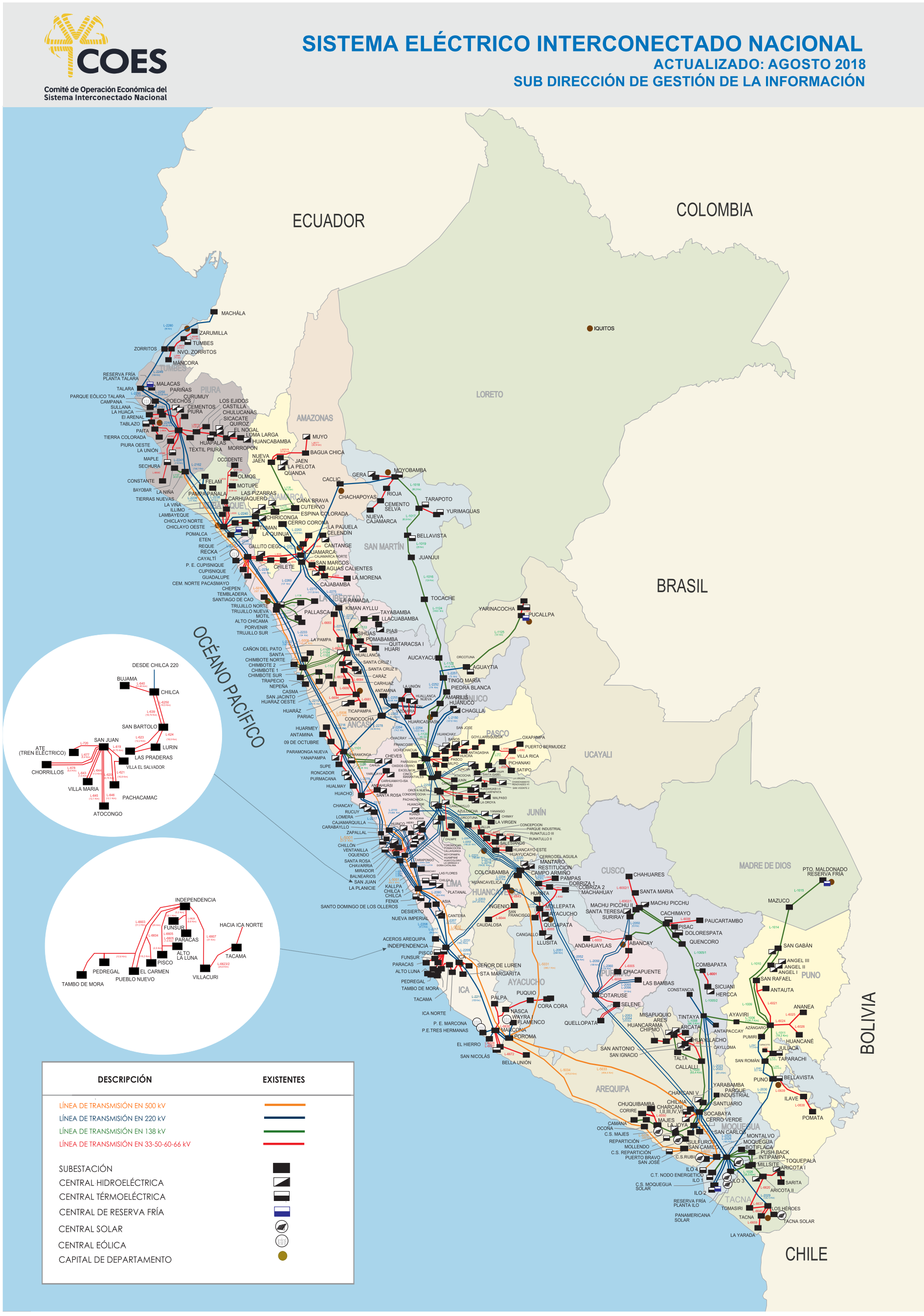
A

Collection of maps

A.1 Map of SEIN. August 2018



Source:(COES, 2018)

A.2 Solar map of Peru

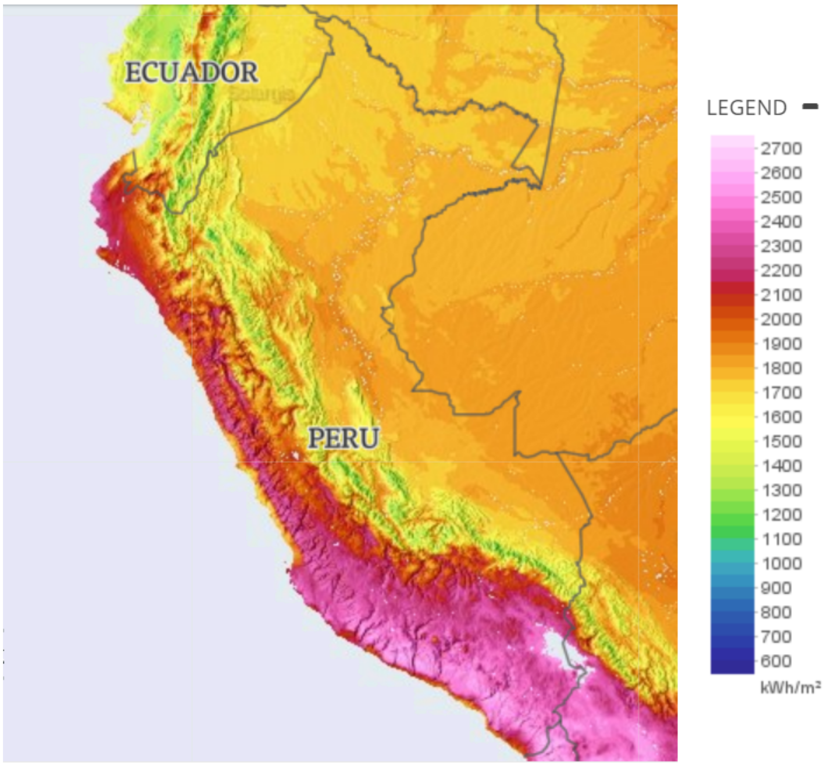
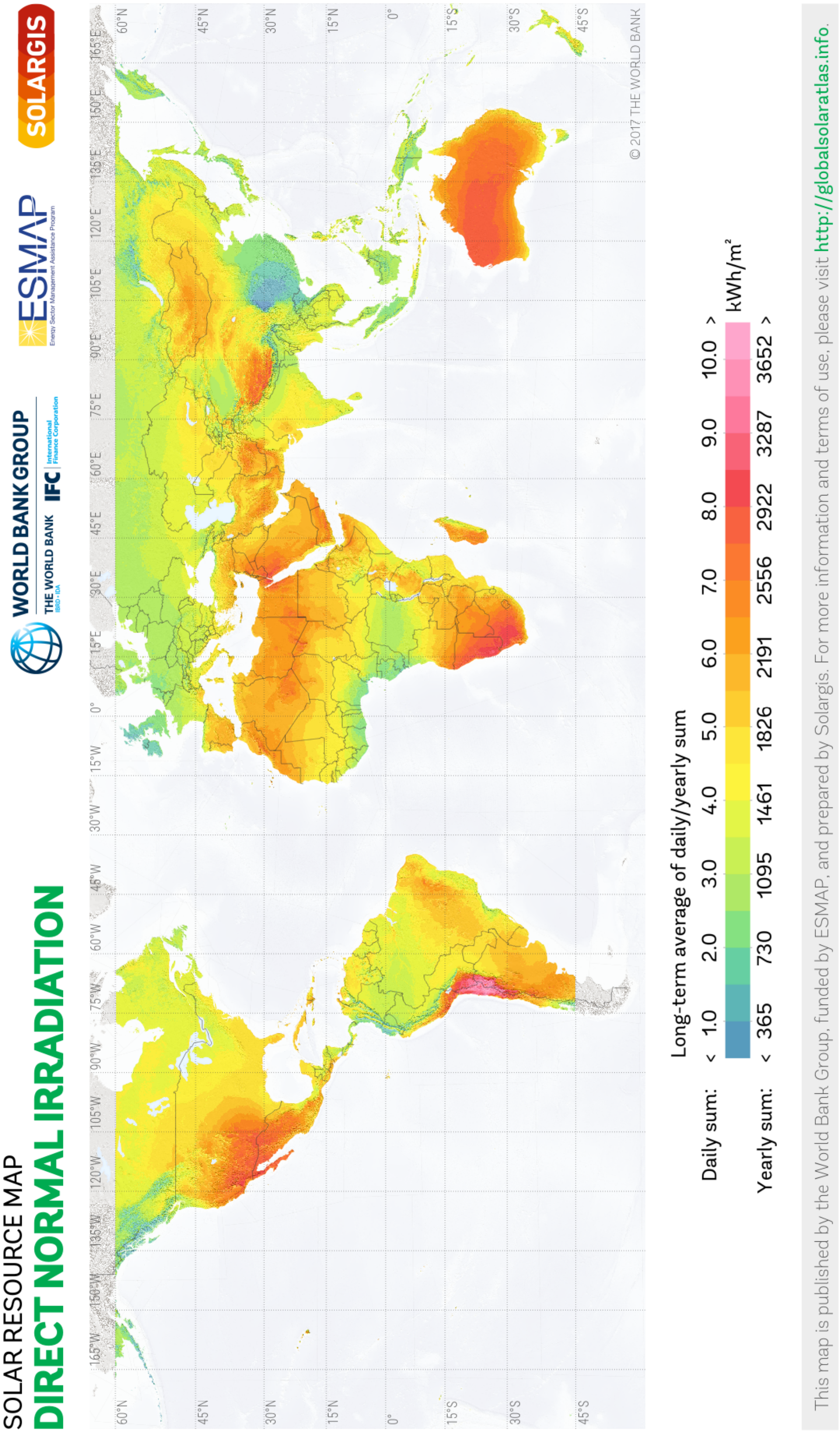


Fig. A.1.: Global Horizontal Irradiation in Peru, (World Bank Group, 2018)

A.3 Direct Normal Irradiation world map



Source: (World Bank Group, 2018)

A.4 Input maps for geographical potential analysis

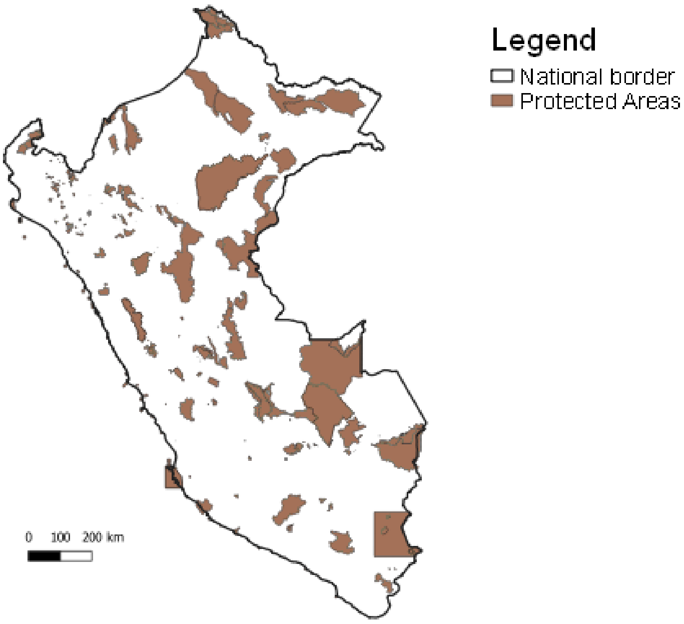


Fig. A.2.: Protected Areas in Peru

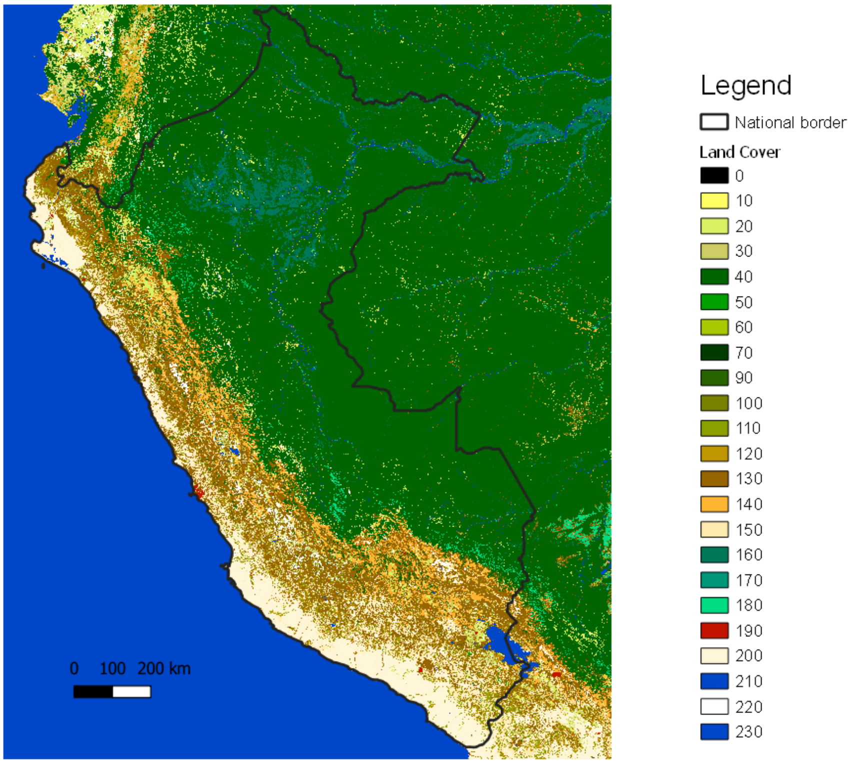
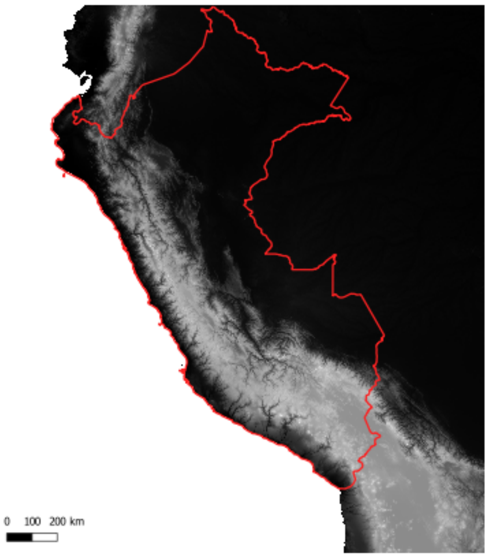
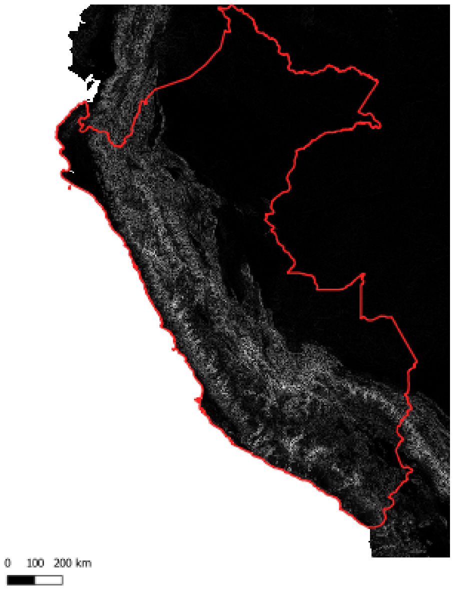


Fig. A.3.: Use of land in Peru



(a) DEM of Peru



(b) Slopes map of Peru

Fig. A.4.: Conversion from DEM to slope map with GRASS. Information is presented in a greyscale, 0 corresponds to black and it turns into whiter for the higher values

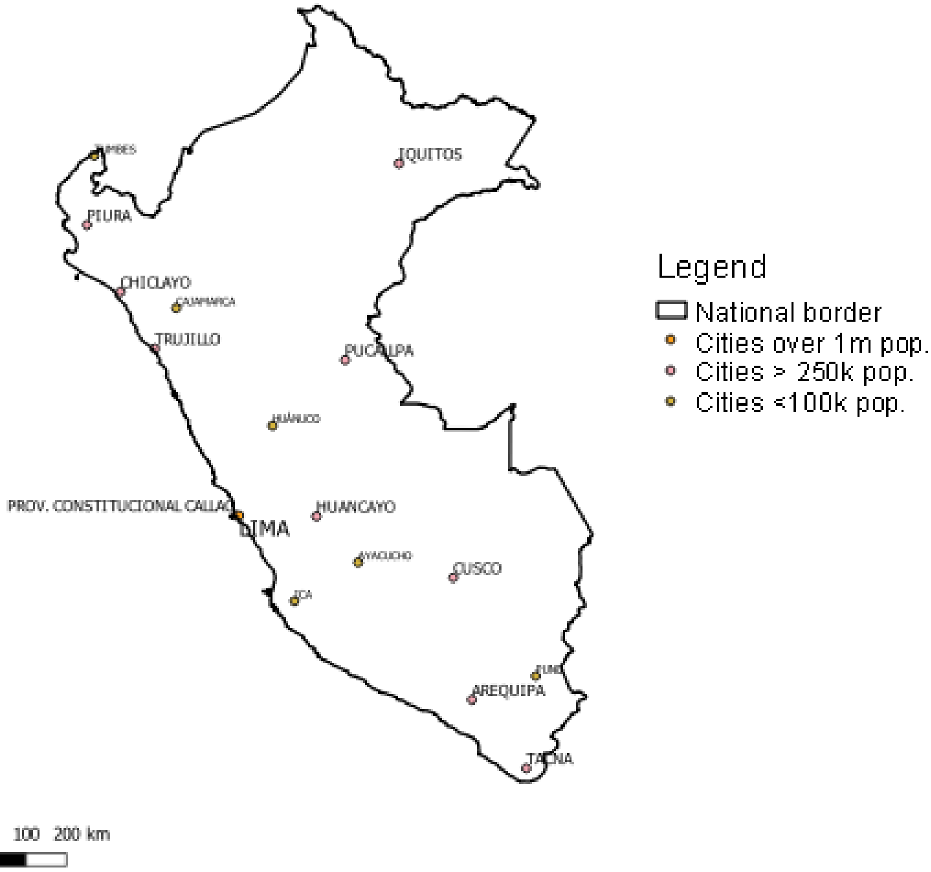


Fig. A.5.: Map of cities over 100.000 inhabitants in Peru

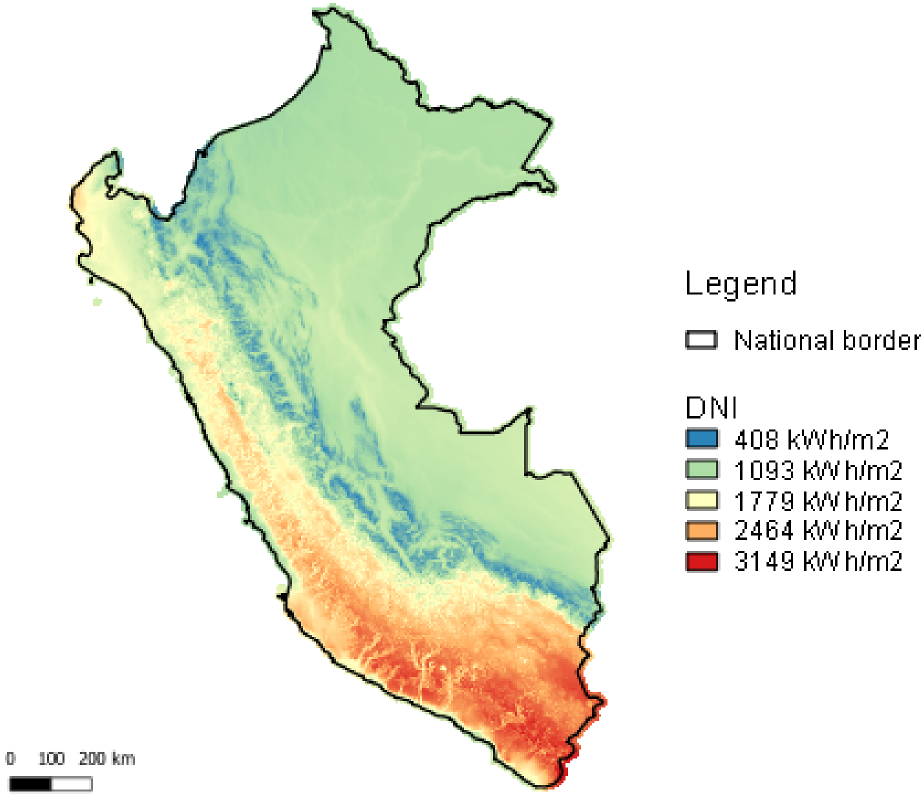


Fig. A.6.: Annual Direct Normal Irrandiance in Peru[kWh/m_2]

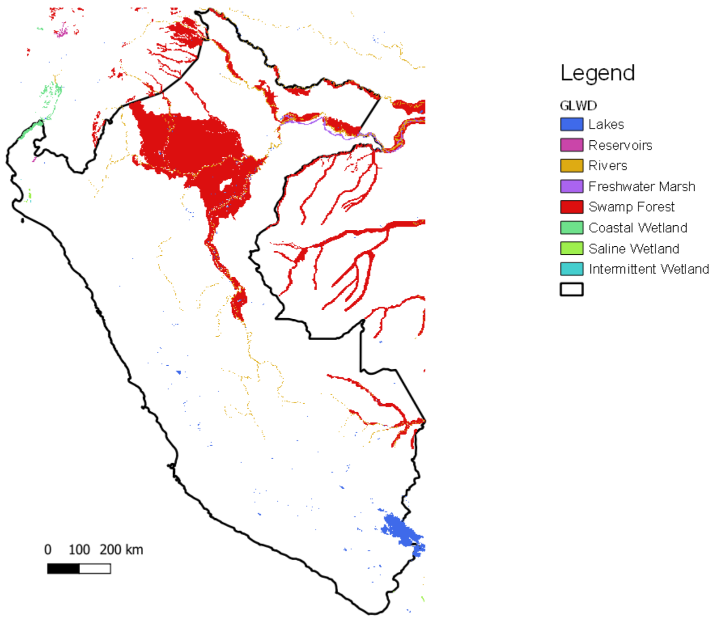


Fig. A.7.: Water resources in Peru

Fig. A.8.: National road network of Peru

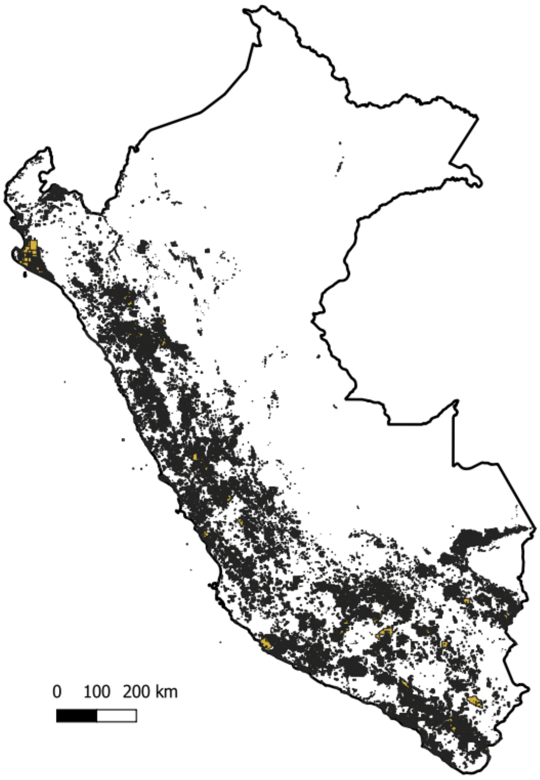


Fig. A.9.: Mining concessions map of Peru

B Calculation of Levelized Cost of Electricity

The calculation of LCOE has the following inputs:

Firm Power	**50**	MW
Investment	**302289111**	$
O&M	**4685476**	$
Production	**395850**	MWh/year
Real Discount rate	**7%**	
Inflation	**2,48%**	
Nominal Discount rate	**9,6536%**	
Annual degradation	**0,5%**	
Lifetime	**30**	years

The LCOE is calculated with the division of the column *Discounted production*, which has been discounted with the real discount rate, and the column *Discounted payments*, discounted by the nominal rate:

Year	Prod [MWh/y]	Investment	O&M	Disc payments	Disc production
0	0	$ 302.289.111	$ -	$ 302.289.111	0
1	0		$ -	$ -	0
2	0		$ -	$ -	0
3	395850		$ 4.685.476	$ 3.553.735	323132
4	393871		$ 4.685.476	$ 3.240.874	300482
5	391902		$ 4.685.476	$ 2.955.557	279421
6	389942		$ 4.685.476	$ 2.695.358	259835
7	387993		$ 4.685.476	$ 2.458.066	241622
8	386053		$ 4.685.476	$ 2.241.664	224686
9	384122		$ 4.685.476	$ 2.044.314	208937
10	382202		$ 4.685.476	$ 1.864.339	194292
11	380291		$ 4.685.476	$ 1.700.207	180673
12	378389		$ 4.685.476	$ 1.550.526	168009
13	376497		$ 4.685.476	$ 1.414.022	156233
14	374615		$ 4.685.476	$ 1.289.535	145282
15	372742		$ 4.685.476	$ 1.176.008	135099
16	370878		$ 4.685.476	$ 1.072.476	125629
17	369024		$ 4.685.476	$ 978.058	116823
18	367179		$ 4.685.476	$ 891.952	108635
19	365343		$ 4.685.476	$ 813.427	101020
20	363516		$ 4.685.476	$ 741.815	93939
21	361698		$ 4.685.476	$ 676.508	87355
22	359890		$ 4.685.476	$ 616.950	81232
23	358090		$ 4.685.476	$ 562.636	75538
24	356300		$ 4.685.476	$ 513.103	70243
25	354518		$ 4.685.476	$ 467.931	65320
26	352746		$ 4.685.476	$ 426.735	60741
27	350982		$ 4.685.476	$ 389.167	56484
28	349227		$ 4.685.476	$ 354.905	52525
29	347481		$ 4.685.476	$ 323.661	48843
30	345744		$ 4.685.476	$ 295.166	45419
				$ 339.597.806	4007451
				LCOE	84,74