Generating Electricity from Agricultural Residue Biomass in Bolivia; A GIS and Techno-economic Analysis

by

Ana Teresa Morato Lopez

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science
in
Engineering Management

Department of Mechanical Engineering
University of Alberta

Abstract

Agricultural residues, a renewable source of energy, are widely available in Bolivia. Using agricultural residues to generate electricity on a large scale could decrease dependence on fossil fuels and provide a secure energy supply. Although the country depends on natural gas to generate electricity, the share of renewable energies in the power portfolio is expected to increase from 36% in 2015 to 78% in 2025. A significant portion will be covered by hydro, followed by solar and wind. However, there are currently no initiatives that consider using biomass to generate electricity on a large scale. The present study is focused on electricity generation in Bolivia using agricultural residues. Most of the time, agricultural residues are left on fields for soil conservation or simply burned, thereby increasing air pollution. Through a biomass quantification process, this study estimated biomass availability to be 3.8 M dry t/yr. The biomass logistics involve collecting and baling the dispersed agricultural residues and moving the bales to biomass collection points (BCPs) for truck pick-up and further delivery to the energy conversion facility. A framework was developed in a GIS environment for locating BCPs considering biomass yield variation and proximity to road networks. The framework was applied to Bolivia, and 107 BCPs were sited to collect altogether 1.5 M dry t/yr. In order to assess the suitability of sites for bioenergy facilities, social, environmental, and economic factors were considered in GIS-based models. Since biomass transportation is a key parameter, mostly due to associated emissions and costs, a network analysis was conducted to optimally locate bioenergy facilities such that the weighted transportation distance was minimized. The conversion technology considered was combustion (grate-firing and fluidized bed). The levelized cost of electricity (LCOE), considered as an economic indicator, includes only the feedstock cost, capital cost, and operating and maintenance cost so that it can be compared with existing studies and technologies. The LCOE was estimated for a wide range of plant sizes (10-600 MW). The lowest LCOE was estimated at 111 $/MWh for fluidized bed technology at an optimal power plant size of 300 MW. The energy cost during the first year of generating electricity was estimated at 71.6 $/MWh, well above than the actual energy cost of 19.5 $/MWh, which is low because of the natural gas subsidy. If policies change in favor of renewable energies and the fossil fuel subsidy is removed, biomass becomes competitive. The results and analysis of this study are expected to provide information for, and increase the attention of, policy makers about a potential source that has not yet been well exploited.

Preface

This thesis is an original work by Teresa Morato under the supervision of Dr. Amit Kumar.

Chapter 2 of this thesis was submitted to the journal *Renewable and Sustainable Energy Reviews* as "Assessment of energy production potential from agricultural residues in Bolivia" by Teresa Morato, Mahdi Vaezi, and Amit Kumar.

Chapter 3 of this thesis will be submitted to the journal *Renewable and Sustainable Energy Reviews* as "Developing a framework to optimally locate biomass collection points to improve the biomass-based energy facilities location procedure – a case for a South American country: Bolivia" by Teresa Morato, Mahdi Vaezi, and Amit Kumar.

Chapter 4 of this thesis will be submitted to the journal *Renewable Energy* as "Assessment of energy production potential from agricultural residues in Bolivia" by Teresa Morato, Mahdi Vaezi, and Amit Kumar.

In these three chapters, I was responsible for data collection, model development, and manuscript composition. Mahdi Vaezi reviewed the models, assessed the results, and edited the manuscript. Amit Kumar was the supervisory author and contributed to concept formulation, results analysis, and manuscript edits.

Dedication

This is dedicated to my beloved homeland. I admire your humble love of nature as a living being. Keep protecting your rich land and clean air.

Acknowledgements

Firstly, I would like to express my sincere gratitude to my supervisor, Dr. Amit Kumar, for his instructions, recommendations, and encouragement throughout this work. He has demonstrated his hard passion and dedication on research studies, which became an inspiration to me. It has been a pleasure to work on this project with him and to be guided by his knowledge. I would also like to thank Dr. Mahdi Vaezi for his continuous feedback and orientation throughout this work. Astrid Blodgett is also thanked for her work on editing this thesis.

I am deeply thankful to Dr. Rafiq Ahmad and Dr. Rajender Gupta, members of my examination committee, for reviewing my thesis and providing constructive comments.

I am grateful to the Ministry of Education, Bolivia and the University of Alberta, Canada for the financial support to conduct this research.

I would like to acknowledge the National Institute of Statistics (Instituto Nacional de Estadística, INE) for providing data and clarification on the Agricultural Census, 2013. I would also like to acknowledge GeoBolivia for providing geographic information and constant support. I acknowledge the National Electricity Company (Empresa Nacional de Electricidad, ENDE), the National Load Dispatch Committee (Comité Nacional de Despacho de Carga, CNDC), Guabirá Energía, Hidroeléctrica Boliviana, and transportation companies that provided information, but the results and recommendations are solely mine and my colleagues'.

I would like to thank my family for their love, support, and patience. My deep appreciation to my parents for giving me the best life lesson, their example; to my brothers for their care and support; and to my sister for delighting my life.

I would also like to thank the Sustainable Energy Research Group for their support. I express sincere thanks to Prashant Patel, Anil Katta, and Elvis Ibadin for their wonderful friendship. I thank my Latin friends, especially Marissa Castro and Angie Mena, for their continuous encouragement.

Foremost, I deeply thank God for his blessings and giving me the opportunity to undertake this research study.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AE	Electricity Authority (La Autoridad de Electricidad)
AHP	Analytic hierarchy process
BP	British Petroleum
BCB	Central Bank of Bolivia (Banco Central de Bolivia)
BCPs	Biomass collection points
BFB	Bubbling fluidized bed
CERs	Certified emission reductions
CFB	Circulating fluidized bed
CNDC	National Load Dispatch Committee (Comité Nacional de Despacho de Carga)
CO_2	Carbon dioxide
COP	Conference of the Parties
CPI	Consumer price index
GHG	Greenhouse gas
GIS	Geographic information system
GWh	Gigawatt hours
IEO	International Energy Outlook
INE	National Institute of Statistics (Instituto Nacional de Estadística)
INRA	National Institute of Agrarian Reform (Instituto Nacional de Reforma Agraria)
IRENA	International Renewable Energy Agency
IRR	Internal rate of return

LCOE	Levelized cost of electricity
LMDC	Like-minded developing countries
MCP	Thousand cubic feet
Mt	Million tonne
MW	Megawatt
NG	Natural gas
OECD	The Organization for Economic Co-operation and Development
O&M	Operation and maintenance
PCCI	Power capital cost index
RPR	Residue-to-product ratio
t	tonnes
VAT	Value added tax
yr	Year

Chapter 1: Introduction

1.1 Background

The world is going through an energy transition in order to address energy security and global warming issues. Efforts have been made worldwide to decrease anthropogenic greenhouse gas emissions (GHG), the main contributors to global warming, in order to keep the average near-surface temperature below 2°C relative to pre-industrial levels [1]. However, worldwide energy consumption is expected to increase 28% between 2015 and 2040 [2] due to urbanization needs, population growth, and expansion of electricity access, mostly in developing countries [1, 2]. In order to mitigate global warming effects by replacing fossil fuels, and meet energy demand, the share of renewable energy has to increase at a fast rate. Several developing countries are interested in introducing renewable energy in order to exploit their energy potential, reduce GHG emissions, decrease their global warming vulnerability, and ensure a sustainable source of energy; therefore, studies on promoting the use of renewable energy sources are crucial [2].

Bolivia, a developing country with a low GHG emissions contribution (e.g., the energy sector contributes 0.027% to global emissions) [3, 4], plans to change its power portfolio by increasing the share of renewable energy sources [5]. According to the government plan, the goal for 2025 is to expand electricity access to the entire Bolivian population and to increase the installed capacity from 1,600 MW in 2015 to 13,600 MW by 2025 [6]. National consumption is expected to increase by only 3,000 MW, and the rest will be exported to neighboring countries [7]. Most of this installed capacity target is expected to be supplied by large hydro power plants (74%); however, hydro power plants require geographic modifications, such as clearing forest areas, deviating river channels, and altering river levels, which may impact nearby communities and ecosystems [8, 9]. The second source of supply of electricity are natural gas-based power plants (22% in 2025) [6], which are currently the main electricity generators (73% in 2015) [6]. Natural gas, however, is a non-renewable source with a reserves-to-production ratio (the ratio between the volume of natural gas that can be economically extracted and the production rate) of 14 years [10]. Although there are natural gas explorations, no new natural gas reservoirs have been approved. The lack of fossil fuels and the steady increase in energy demand could lead to an oil crisis. Therefore, there is a need to seek renewable energy sources in order to meet national targets and replace fossil fuels in a sustainable way.

Biomass, a carbon-neutral source of energy, can provide dispatchable, baseload electricity [11]. There is a wide variety of biomass, i.e., forest residues, agricultural residues, residues from food industry processing, waste from municipalities, energy crops, etc. In Bolivia, the sugar processing industry Guabira uses bagasse (a sugar processing by-product) to generate and inject 21 MW electricity into the grid [12, 13]. Other sugar industries use bagasse at small scales for their own consumption (e.g., San Buenaventura [6]). There are also two biomass projects under study based on energy crops in Cobija and Riveralta [6]. There are drawbacks in using energy crops, such as deforestation to clear farm areas, road construction to increase accessibility, and the time needed for the energy crop to be adapted in the environmental conditions. Nevertheless, there are no projects considering agricultural residues, a low-cost and unused source, to generate electricity at large scales.

While there is no data on either availability or application of agricultural residues in Bolivia, it is known that farmers leave residues in the fields for soil conservation. When residues are abundant, farmers burn them in open fields to prepare the land for the next crop; this offers no benefit. Using agricultural residues could decrease current dependence on fossil fuels and provide a sustainable source of energy. Research on biomass quantification is specific to the study region since the process depends on the type of biomass available, yield, spatial distribution, and current practice. No study has been conducted on biomass quantification in Bolivia. An assessment of the energy potential of sustainable agricultural residue biomass could help decision and policy makers in providing information on this renewable energy source. Bolivia produces a wide variety of agricultural products because of the different temperatures and humidity levels across the country. Santa Cruz, one of nine departments in Bolivia, has a strong agriculture sector and is a good candidate for the location of biomass-based energy conversion facilities.

Locating biomass-based facilities is a complex process that involves multi-criteria analysis. Biomass logistics play an important role in this process because it covers the collection of dispersed agricultural residues in fields and transportation to the biomass-based facility. Agricultural residues are compacted into bales and these bales are stored on one side of the field near a road, so that trucks can pick them up [14, 15]. However, this approach is not practical if not all fields have access to paved roads where large-haul trucks travel. Other studies on economic assessment have assumed a singular circular area from where biomass is collected at a constant yield. However, this is not accurate when biomass availability varies greatly. There is a need, then, to improve the biomass logistics in such a way that biomass bales can be moved to biomass collection points (BCPs), which are located at the roadside and can provide storage space for a time. BCPs collect different amounts of biomass depending on biomass availability in surrounding areas. No previous study has been conducted to locate BCPs in high biomass availability areas and near paved roads for truck pick-up, and further, to use the obtained information on BCPs (location and biomass weight collected) as an input for optimally locating biomass-based energy facilities.

Trucks collect biomass from BCPs and transport it to the facility. Since transportation not only has a cost but also releases GHGs to the environment, the facility should be located close to the fields. Economic, social, and environmental aspects also need to be considered in locating biomass-based facilities. For example, protected areas must be excluded from site consideration. Several studies [16-20] on locating optimal biomass-based energy facilities used geographic information systems (GIS) to perform exclusion, preference, and suitability analyses (in order to consider social, economic, and environmental factors). The suitability analysis can identify candidate sites for energy facilities. Candidate sites, biomass collection sites, and road networks are used in a network analysis to identify the optimal location of biomass-based energy facilities. No studies have been conducted on locating optimal sites for biomass-based energy conversion facilities in Bolivia. A proper network analysis considers Bolivia's actual road network, biomass availability, and its spatial distribution in order to minimize the weighted transportation distance. Reducing transportation distance and corresponding cost is reflected in the techno-economic assessment of using biomass to generate energy.

The capital cost of renewable energy technologies is sometimes the main barrier to renewable energy use. However, global warming concerns have created an increasing cycle of improving technologies, decreasing technology cost, and financing alternatives [11]. A techno-economic assessment on the feasibility of using agricultural residues to generate electricity is crucial to determine the optimal plant size and the cost of energy. Cost components were analyzed and compared with other studies. The cost analyses help to identify major cost components and may show possible ways for optimizing them. Although techno-economic assessments of using biomass for energy generation purposes has been widely studied [18, 21-24], no previous studies estimated the cost of generating energy using agricultural residues Bolivia.

1.2 Research objectives

The overall objective of this research is to study the use of biomass from agricultural residues to generate energy in Bolivia. The specific objectives of this research are as follows:

- To estimate the biomass availability from agricultural residues across the country,
- To create maps using geographic information systems (GIS) to display the biomass availability at municipal level and identify large residue-producing municipalities,
- To develop a framework for locating biomass collection points using GIS,
- To determine the optimal location of bioenergy facilities in Bolivia, considering social, environmental, and economic factors,
- To develop a techno-economic model to estimate the cost of electricity from biomass and optimal plant size,

1.3 Research approach

1.3.1 Biomass quantification

The biomass quantification process consists of estimating the volume of agricultural residues that is sustainably available to generate energy. Statistical information based on the annual agricultural production per municipality was collected from the National Institute of Statistics (Instituto Nacional de Estadistica, INE) [25]. The residue-to-product ratio (RTP) was used to estimate the volume of residues generated from the crop harvesting activity. Based on common practices and biomass properties, some portions were reduced to obtain the sustainable biomass availability amount for energy generation purposes. GIS was used to understand the spatial distribution of biomass availability and identify the main residue-producer municipalities.

1.3.2 Location of BCPs and biomass-based energy facilities

A framework was developed to locate BCPs. This process consists of an iterative process that gives preference to high biomass availability and a road network. The optimal facility site is located through several processes using geospatial data in a GIS environment. Geographical data was collected from the national geoportal service, GeoBolivia [26]. A multi-criteria analysis was conducted to identify the most suitable areas to locate a bioenergy facility. In the model, unsuitable areas were removed while other areas were given preference values, depending on their distance from preference factors (e.g., roads). The most suitable areas for biomass-based facilities were identified, and a network analysis was conducted to find the optimal facility location by minimizing the road transportation distance.

1.3.3 Techno-economic assessment

A techno-economic assessment of the use of agricultural residues to generate electricity in Bolivia was conducted. A techno-economic model was created to estimate the cost of electricity from agricultural residues. The combustion technologies considered were grate-firing and fluidized bed. The cost analysis was divided into biomass logistics cost and energy conversion cost (at the facility). Biomass logistics costs were estimated based on information available about current practice and capital cost was collected from a literature review, since this study is the first of its kind in the country. The model estimated the levelized cost of electricity (LCOE), an economic indicator, for a wide range of plant sizes and determined the optimal plant size, the one that corresponds to the minimum LCOE. The cost of electricity was estimated for the first year of generating electricity and compared with the current cost of natural gas-based thermoelectric power plants.

1.4 The scope and limitations of this study

This study is focused on power generation using agricultural residue biomass in Bolivia. The agricultural residues considered here are sugarcane, soybean, corn, rice, sorghum, and sunflower. Some important factors in the biomass quantification were gathered from a literature review of different regions rather than from the study area directly because no information is available. Most of the biomass considered here is generated in the Department of Santa Cruz, hence, the optimal site location analysis was focussed on this department. The accuracy in locating BCPs and biomass-based energy facilities was limited to the most updated geographical information available for the study area. The conversion technology considered was combustion. Costs in the techno-economic model were converted to US dollars and updated to the base year, 2017.

1.5 Organization of the thesis

Chapter 1, the current chapter, presents the research background, research objectives, research approach, scope and limitations, and organization of the thesis.

Chapter 2 covers the biomass quantification process in Bolivia. The factors used in the quantification process are defined and total energy potential is estimated. A map showing the spatial biomass distribution was created. The major residue producer municipalities were identified.

Chapter 3 describes the framework developed in a GIS environment to locate BCPs. The model was applied to the case study, Bolivia. In this chapter, we describe our approach to optimally locating energy facilities. The analysis included social, environmental, and economic factors.

Chapter 4 describes the techno-economic assessment of using agricultural residues for energy generation. The cost components were analyzed and estimated for a base case scenario. An economic model was created to estimate the cost of energy. A sensitivity analysis was conducted to assess the effects of cost components, energy conversion, and economic model parameters on the energy cost.

Chapter 5 provides conclusions and recommendations for future work.

References

[1] International Energy Agency (IEA). World Energy Outlook 2017. 2017. https://www.iea.org/Textbase/npsum/weo2017SUM.pdf. (Accessed 09.06.18).

[2] Energy Information Administration (EIA). International Energy Outlook 2017. 2017. https://www.eia.gov/outlooks/ieo/pdf/0484(2017).pdf. (Accessed 09.06.18).

[3] Ministerio de relaciones exteriores. Posición Boliviana en las Negociaciones Internacionales de la Convención Macro de Naciones Unidas sobre Cambio Climático (CMNUCC). 2016. http://www.embolivia.org.br/UserFiles/File/PDFs/emb_climatico.PDF. (Accessed 15.05.18).

[4] The dialogue - Leadership for the Americas. Can Latin America transition to low carbon energy? 2016. http://www.thedialogue.org/wp-content/uploads/2016/10/WCEE-Presentation_10.17.16-1.pdf. (Accessed 05.06.18).

[5] Empresa Nacional de Electricidad (ENDE). Memoria anual 2016. 2017. http://www.ende.bo/public/memorias/memoria-2016-ende-corporacion.pdf. (Accessed 15.04.18).

[6] Empresa Nacional de Electricidad (ENDE). Memoria anual, 2015. 2016. http://www.ende.bo/public/memorias/memoria-2015-10-final.pdf. (Accessed 15.10.16).

[7] Fernandez M. Estimacion del potencial de introduction de energias renovables Energetica. 2010;11:1-5.

[8] Solón. El caso del Chepete y El Bala. Fundación Solón. 2017. https://fundacionsolon.org/2017/05/10/el-caso-del-chepete-y-el-bala/. (Accessed 15.05.18).

[9] Telma M. Hidroeléctrica Rositas: el proyecto que rechazan las comunidades y que amenaza a un área protegida en Bolivia Mongabay Latam. 2017. https://es.mongabay.com/2017/07/hidroelectrica-rositas-proyecto-rechazan-las-comunidades-amenaza-area-protegida-bolivia/. (Accessed 05.05.18).

[10] British Petroleum (BP). Statistical Review of World Energy. 2016. https://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2016/bp-statistical-review-of-world-energy-2016-full-report.pdf. (Accessed 04.05.17).

[11] International Renewable Energy Agency (IRENA). Renewable power generation costs in 2014. 2015. https://www.irena.org/documentdownloads/publications/irena_re_power_costs_2014_report.pdf. (Accessed 10.06.18).

[12] Campos M. Guabirá prevé generar 45MW de energía. El Dia. 2013. https://www.eldia.com.bo/index.php?cat=357&pla=3&id_articulo=117356. (Accessed 10.09.16).

[13] Guabirá. Guabirá energía S.A. 2014. http://www.guabira.com/guabira/guabira-energia-sa.html. (Accessed 09.04.18).

[14] Sharma B, Ingalls RG, Jones CL, Huhnke RL, Khanchi A. Scenario optimization modeling approach for design and management of biomass-to-biorefinery supply chain system. Bioresource Technology. 2013;150:163-71.

[15] Sokhansanj S, Fenton J. Cost benefit of biomass supply and pre-processing. BIOCAP Canada 2006. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.546.5141&rep=rep1&type=pdf. (Accessed 20.04.18).

[16] Ullah M. Techno-economic assessment of utilization of food processing waste for production of energy and chemicals [Thesis]. University of Alberta; 2017.

[17] Sultana A, Kumar A. Optimal siting and size of bioenergy facilities using geographic information system. Applied Energy. 2012;94:192-201.

[18] Khan MMU, Vaezi M, Kumar A. Optimal siting of solid waste-to-value-added facilities through a GIS-based assessment. Sci Total Environ. 2018;610:1065-75.

[19] Viana H, Cohen WB, Lopes D, Aranha J. Assessment of forest biomass for use as energy. GIS-based analysis of geographical availability and locations of wood-fired power plants in Portugal. Applied Energy. 2010;87:2551-60.

[20] Voivontas D, Assimacopoulos D, Koukios E. Assessment of biomass potential for power production: a GIS based method. Biomass and bioenergy. 2001;20:101-12.

[21] Sultana A, Kumar A, Harfield D. Development of agri-pellet production cost and optimum size. Bioresource Technology. 2010;101:5609-21.

[22] Kumar A, Cameron JB, Flynn PC. Biomass power cost and optimum plant size in western Canada. Biomass and Bioenergy. 2003;24:445-64.

[23] Thakur A. Power Generation from Forest Residues [Thesis]. University of Alberta; 2011.

[24] Dassanayake GD. Utilization of Triticale Straw for Power Generation [Thesis]. University of Alberta; 2012.

[25] Instituto Nacional de Estadistica (INE). Primer censo agropecuario. 2013. http://sice.ine.gob.bo/censofichacna/. (Accessed 03.06.18).

[26] Vicepresidencia del Estado Plurinacional de Bolivia. Información Geográfica de Bolivia, GeoBolivia. http://geo.gob.bo/portal/. (Accessed 04.05.17).

Chapter 2: Assessment of energy production potential from agricultural residues in Bolivia[1]

2.1 Introduction

Bolivia, a South American country, has been installing renewable energy plants including wind and solar since 2014 [1]. There are three reasons for using renewables in the country: to satisfy local energy demand, increase energy independency, and export excess energy [2]. According to the Patriotic Agenda 2025 [3, 4], the government target is to universalize electricity access [5-8], which was only 71% in 2007. Bolivia imports 18% of its total energy consumption [1]; the major imported fuel is diesel (6.1x10^9 Btu in 2014 or 77% of the imported energy [1]). However, a government policy was proposed to substitute imported and national fossil fuels with renewable resources to decrease dependency on imported fuels [9]. There is a high energy demand from neighboring countries, which is 8,000 MW, 500 MW, and 500 MW from Brazil, Argentina, and Paraguay, respectively [10]. The government's plan is to ensure national energy security and export the excess to neighboring countries [9]. The aim is to export 8,930 MW by 2030 [11]. Therefore, Bolivia requires a significant increase in energy production. Bolivia's national target is to increase power generation to 13,387 MW by 2030 [11] with the contribution of renewable energies to cover 79% [8, 11]. A considerable portion of this goal will be met using hydro, while 535 MW (4% of the target) will come from other renewable resources.

---

[1] Paper submitted as Morato T., Vaezi M., Kumar A., to the journal *Renewable and Sustainable Energy Reviews*, 2018

Biomass feedstock (e.g., agricultural residues), an alternative source of energy, if used towards clean energy production, will not only provide farmers an additional source of income, but also contribute towards meeting the national and regional energy demands discussed above. In 1997, a 1 MW biomass conversion plant using nut shells and wood residues was built in Beni, but it is not yet operational due to issues regarding the conversion process and lack of maintenance management [5]. Guabira, a sugar producing plant in Santa Cruz, has the biggest biomass facility in Bolivia using bagasse[2] to supply 21 MW to the grid [12, 13]. There are three more biomass projects in the country under study. One is San Buenaventura, a new sugar production plant located in the north of La Paz that produces 1.9 MW of power for on-site consumption. Its goal is to inject 10 MW to the grid [14]. The other two, Cobija and Riveralta, each with 20 MW capacity [14], located in Pando and Beni, respectively, are at various stages of studying and planning. Figure 2-1 shows the location of the biomass-based power plant in operation and the three projects under study stage across the country. As shown in the figure, they are located in different departments (the primary subdivisions of Bolivia).

---

[2] Bagasse is an industrial residue collected after extracting sugarcane juice, a byproduct of sugar production.

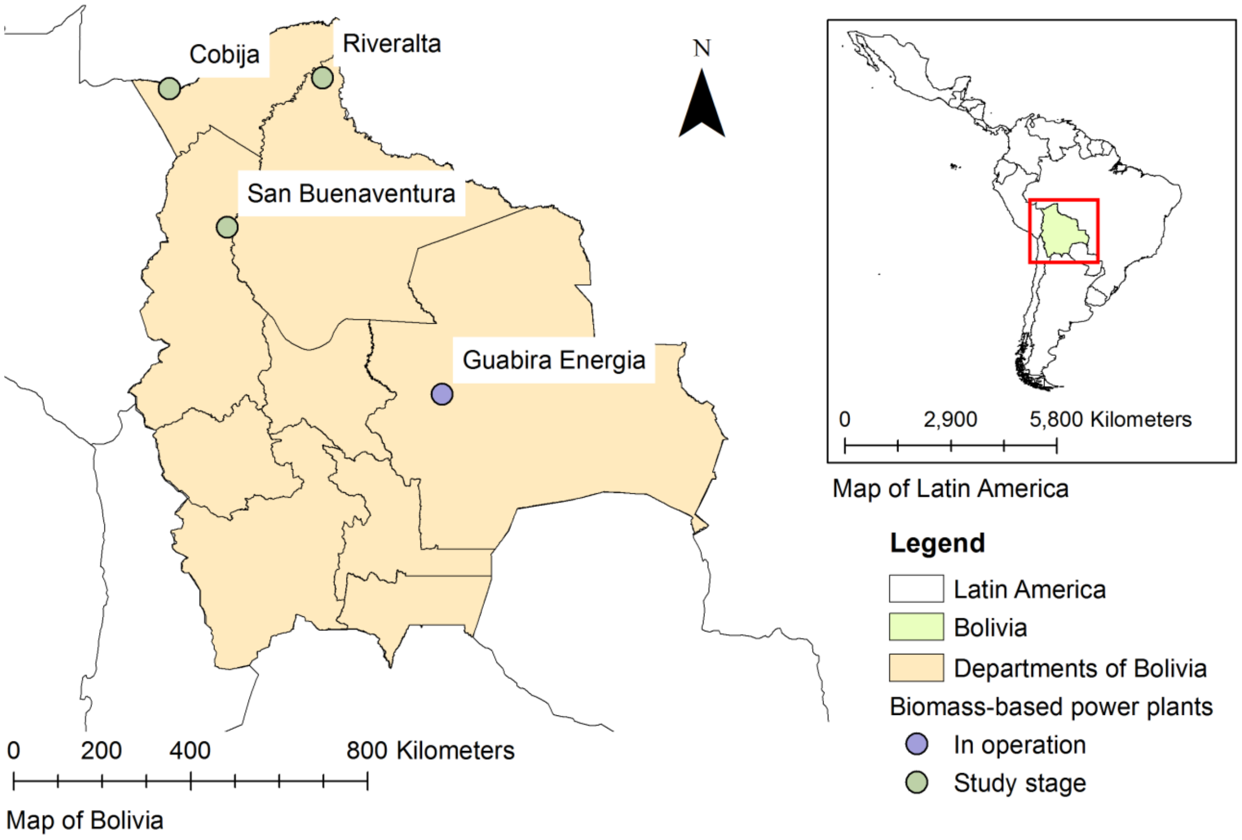


Figure 2-1: Location of biomass-based power plants across Bolivia

The renewable energy plan elaborated by the Ministry of Hydrocarbons and Energy [5] states that it is important to conduct research for inventory and the characterization of biomass types by geographic region in order to identify energy potential zones. Similarly, feasibility studies for biomass-based energy facilities are necessary [5]. However, there is no information on the quantification of agricultural residues produced in the country nor any record on the final disposition of these residues. Depending on the region, residues can be burned on land, used in small industries (e.g., rice husk for brick production), burned as fuel for cooking in households, landfilled, or left on the farm for soil conservation. Burning is the most common solution when agricultural residues are in excess and block the next crop growth. This activity reduces labor time and cost; however, it negatively affects the nearby communities, soil properties, and the environment [15].

It is necessary to conduct an extensive study on the identification/quantification of the biomass potentially available to generate energy (i.e., electricity) to meet the goals set in Bolivia's Patriotic Agenda 2025 [4]. This research project aims to assess the sustainable biomass availability in Bolivia for energy purposes. To achieve this overall objective, the following specific objectives have been set:

- To identify major crop residues and estimate the quantity of residues produced in each municipality using statistical information on crop production and the residue-to-product ratios obtained from the literature;
- To estimate the sustainable dry biomass available for energy generation purposes in each municipality considering several factors including soil conservation, machinery capacity, animal feeding, losses, and moisture content;
- To determine the potential energy per municipality to be generated from agricultural residues;
- To develop spatial distribution maps of agricultural residues throughout the country and identify large residue-producing municipalities.

2.2 Method

2.2.1 The study area

The Plurinational State of Bolivia is located in the central part of South America, without a coastline and surrounded by Brazil, Paraguay, Argentina, Chile, and Peru. The nation’s total land is 1,098,581 km^2 and the population was 10,969,649 as of July 2016 [16]. Bolivia has three different physiographic regions. The southwest is characterized by highlands (the highest elevation is 6,542 meters above sea level), the central region has slopes and valleys, and the eastern region is a flat lowland area (the lowest elevation is 90 meters above sea level) [16, 17]. The climate varies with the extremes in altitude. For instance, the western side is generally cold and semi-arid, the central region has a temperate climate, and the eastern region is humid and tropical [16, 17]. Because of the geographic and climate contrast, Bolivia has an extensive biodiversity. The Bolivian territory is organized in nine departments, as shown in Figure 2-2, and subdivided into 112 provinces and 339 municipalities [17].

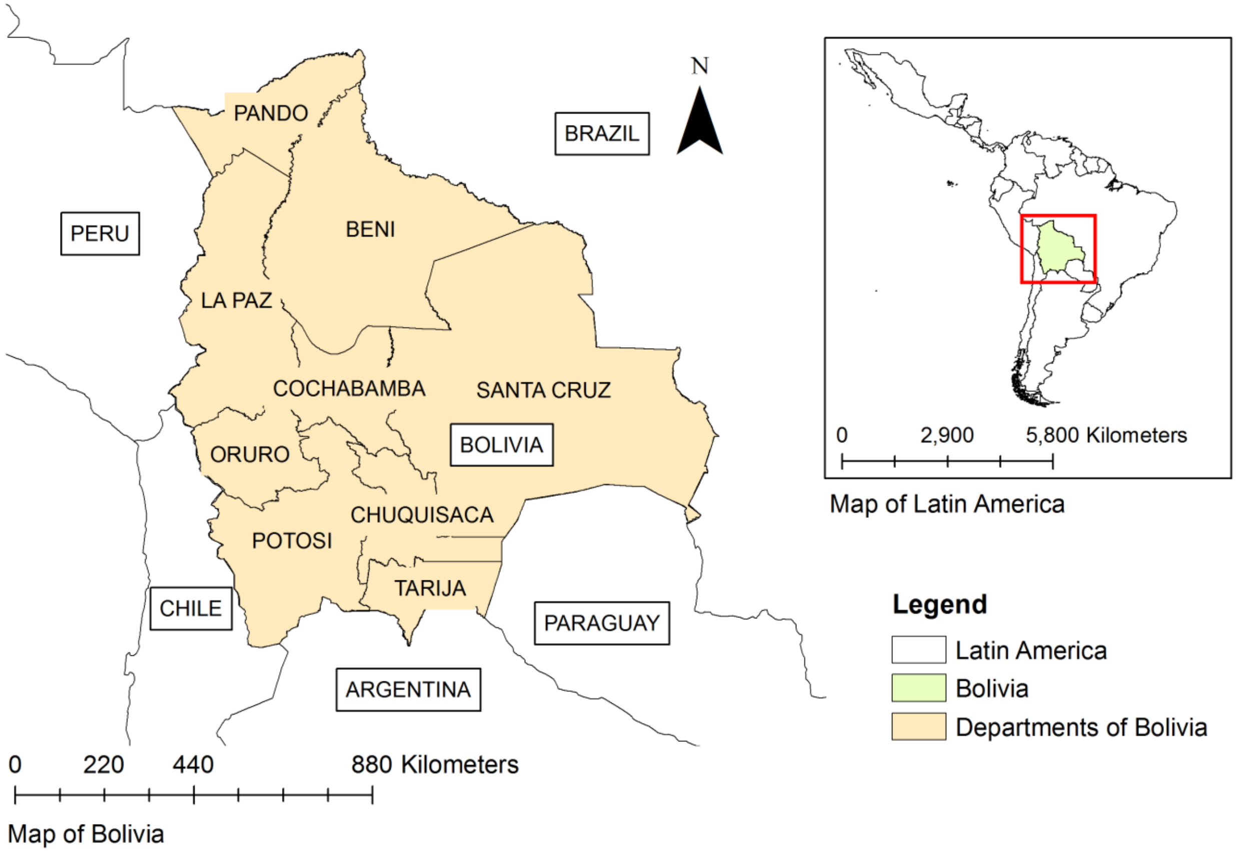


Figure 2-2: Map of the study area

2.2.2 Data collection

To the best of our knowledge, there are no data on biomass availability based on agricultural residues for energy production purposes in Bolivia. Accordingly, the first stage in this study was data collection on crop production. The data from National Institute of Statistics in Bolivia (Instituto Nacional de Estadística, INE) [18], which conducted the first agricultural census in 2013, was used in this stage.

2.2.3 Identification of potential agricultural residues

Figure 2-3 shows the percentage contributions to total crop production from 32 major crops in Bolivia. The contribution from sugarcane is the highest (51%), followed by soybean (16%) and corn (5%) [19].

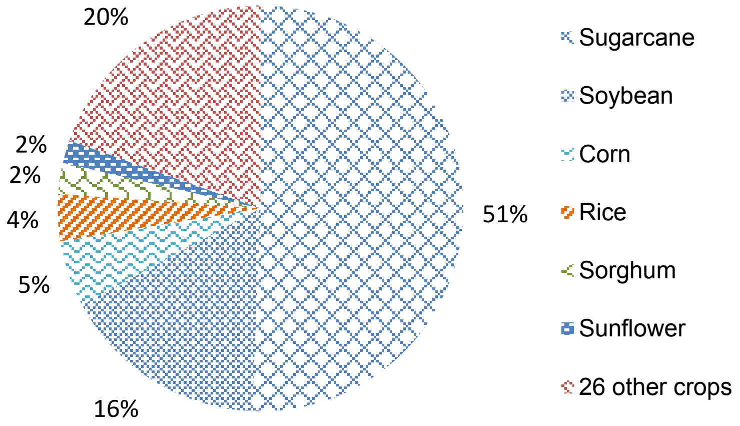


Figure 2-3: National crop production, adapted from INE 2013

The six crops listed in Figure 2-3 are mostly produced in the department of Santa Cruz, which is located in the eastern part of the country. Figure 2-4 shows the location of Santa Cruz in Bolivia along with the location of 56 municipalities in Santa Cruz, whose corresponding municipality names are listed below the figure. Concentrated crop production is logistically and economically preferred when locating a biomass facility. The production of the other 26 crops is distributed across the country, and their annual production is less than the six major crops. Therefore, six major crop residues were selected to conduct the present research: sugarcane (top and leaves), soybean (stalk, leaves and husk), corn (stalk and husk), rice (husk), sorghum (stalk, husk and leaves), and sunflower (stalk).

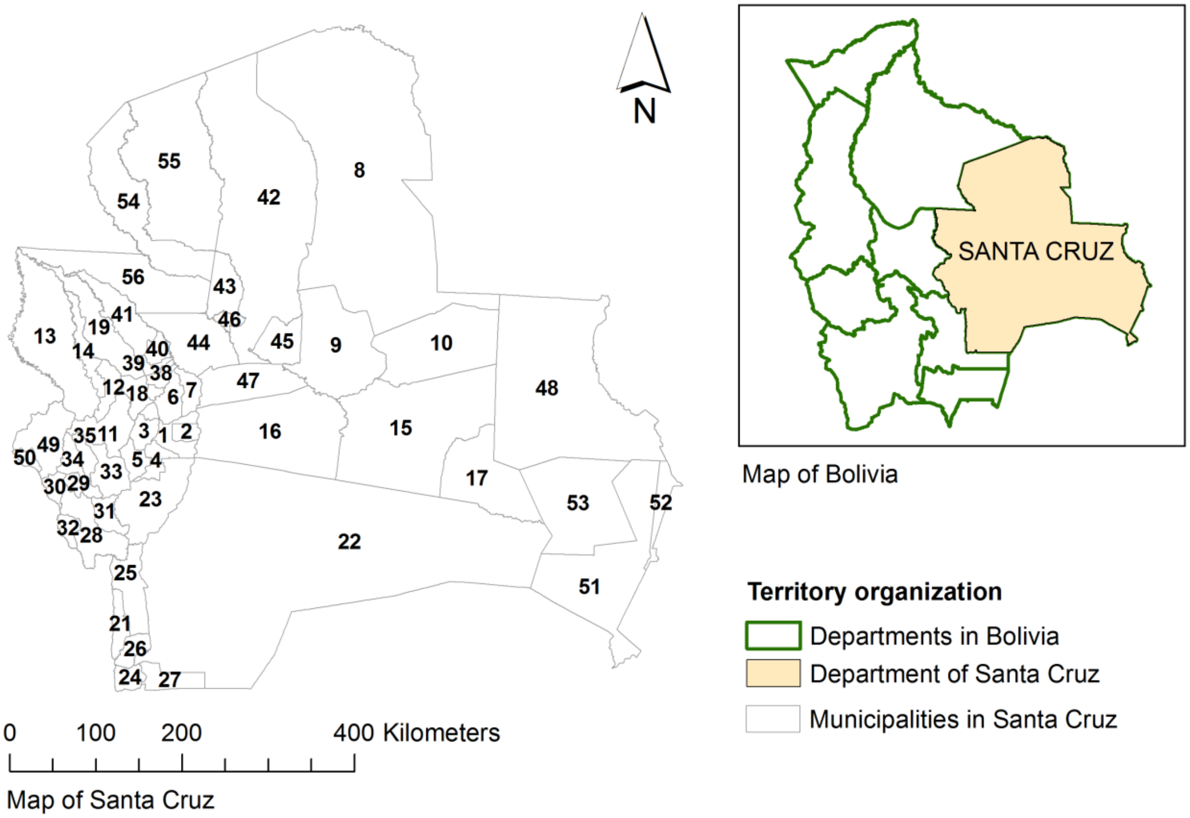


Figure 2-4: Santa Cruz Department and its municipalities

1 Santa Cruz de la Sierra
2 Cotoca
3 Porongo

4 La Guardia
5 El Torno
6 Warnes
7 Okinawa Uno
8 San Ignacio de Velasco
9 San Miguel de Velasco
10 San Rafael
11 Buena Vista
12 San Carlos
13 Yapacaní
14 San Juan de Yapacaní
15 San José de Chiquitos
16 Pailón

20 Colpa Bélgica
21 Lagunillas
22 Charagua

23 Cabezas
24 Cuevo
25 Gutiérrez
26 Camiri
27 Boyuibe
28 Vallegrande
29 Trigal
30 Moro
31 Postrer Valle
32 Pucará
33 Samaipata
34 Pampa Grande
35 Mairana

39 Mineros
40 Fernández Alonso
41 San Pedro

42 Concepción
43 San Javier
44 San Julián
45 San Antonio de Lomerío
46 San Ramon
47 Cuatro Cañadas
48 San Matías
49 Comarapa
50 Saipina
51 Puerto Suárez
52 Puerto Quijarro
53 Carmen Rivero Tórrez
54 Ascensión de Guarayos

17 Roboré
18 Portachuelo
19 Santa Rosa del Sara
36 Quirusillas
37 Montero
38 Gral, Saavedra
55 Urubichá
56 El Puente

2.2.4 Parameters for quantifying biomass availability

The method for quantifying biomass availability for energy purposes is shown in Figure 2-5. Statistical information on crop production per municipality and the residue-to-product ratios were used to estimate the quantity of agricultural residues produced through crop harvesting activities. Several factors were then considered in a similar way as in previous studies [20, 21] to estimate the sustainable biomass availability.

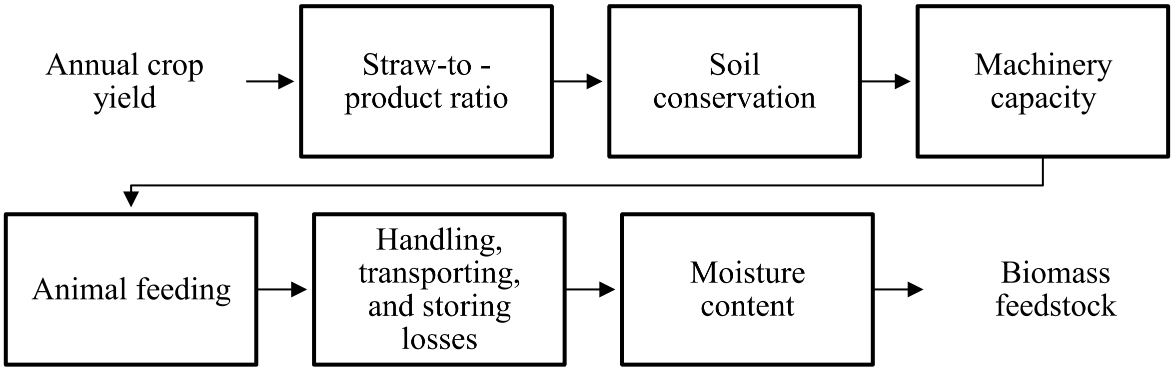


Figure 2-5: Parameters considered in biomass quantification

2.2.4.1 Annual crop yield

Crop yield is the ratio between the annual crop production and the physical crop area. The data provided by the INE [22] reported crop production and cropland for summer and winter separately. There are two factors to consider in the crop yield calculation. One is crop rotation, which means crops planted in the same land change seasonally. The other factor is the use of the same cropland for two or three consecutive crops in a year. For this study, a two-crop rotation per year was considered, one in summer and the other in winter. Total annual crop production (the sum of summer and winter production) was calculated. The crop area was considered to be the maximum of the summer and winter areas. Equation 2-1 estimates the crop yield per year:

$$y_{crop} = \frac{Q_s + Q_w}{max[A_s, A_w]} \tag{2-1}$$

where y_{crop} is crop yield, Q_s and Q_w are crop production in summer and winter, and A_s and A_w are croplands in summer and winter.

2.2.4.2 Residue-to-product ratio

The residue-to-product ratio (RPR) is also called the straw-to-grain ratio for grain crops or the straw-to-stalk ratio when the stalk is the main product, e.g., for sugarcane. In this study, the term residue-to-product ratio is used for both types of crop products. The ratio is defined as the relation between the mass of the residues left over and the mass of the crop harvested. Each crop comes with a specific ratio that depends on local environmental conditions, crop yield, and harvesting technology. Since there are no data reported on the residue-to-product ratio for crops in Bolivia, ratios from previous studies were averaged and used for this study (see Table 2-1).

Table 2-1: Residue-to-product ratio

rg hu	**Sunflower**		
Ref	RPR	Region	Ref
[30]	3	Ontario	[23]
[31]	5	Texas	[24]
[28]	2.7	EU	[25]
[24]	2.2	India	[26]
[27]	1	US	[27]
	1.7	Buenos Aires	[28]
	1.9	Pueyrredon	[29]
Present study for Bolivia			
1.4	2.5		

Sugarcane			Soybean			Corn			Rice				
RPR	Region	Ref	RPR	Region	Ref	RPR	Region	Ref	RPR	Region	Ref	RPR	Region
0.22	Brazil	[32]	0.92	NY & Fla	[35]	1.42	Brazil	[32]	1.49	Brazil	[32]	1.13	_
0.18	Brazil	[37]	2.05	Brazil	[32]	0.98	Nebraska	[33]	1.4	Texas	[24]	1.7	Ethiopia
0.2	Texas	[24]	2.5	_	[36]	1	Canada	[20]	1.5	US	[27]	2.56	Buenos Aires
0.23	US	[27]	1.75	US	[34]	1.4	Buenos Aires	[28]	1.7	EU	[25]	1.07	Texas
0.3	Kenya	[38]	1.5	Buenos Aires	[28]	1.07	Texas	[24]				1.5	US
			1.5	Ontario	[23]	1	US	[27]					
			2	Argentina	[29]	1	US	[34]					
			0.85	Texas	[24]	1	Ontario	[23]					
			1	US	[27]	1.4	Pueyrredon	[29]					
	0.22			1.6			1.2			1.5			

Table 2-1 lists the RPR for sugarcane, soybean, corn, rice, sorghum, and sunflower. While the ratio remains almost constant for sugarcane, ratios for soybean and corn are lower in most North America regions than in southern areas. This could be attributed to both environmental conditions and technologies. The RPR remains almost constant in four different regions for rice and varies noticeably for sorghum. Sunflower has the highest RPR of all the crops. The values adopted in this study are given in the last row of Table 2-1.

The gross residues yield y_{res} is calculated using Equation 2-2:

$$y_{res} = RPR \cdot y_{crop} \tag{2-2}$$

2.2.4.3 Soil conservation

Soil organic matter (SOM) is important for providing nutrients to plants and maintaining the physical properties of the soil. Removing an excessive quantity of residues over the long term can lead to soil erosion and compaction [39]. Therefore, some of the residues must be left on the land. The amount left depends on crop yield, soil quality, and harvesting process. According to several studies [20, 21, 23, 40, 41], the minimum amount of agricultural residues left on the land for soil conservation is 0.75 t/ha. . Other sources recommend that 30% of the residues be left on the land [33, 34, 42]. This study considers 0.75 t/ha/yr as the residue left on the land for the sustainable soil conservation.

2.2.4.4 Machinery capacity

Depending on the land slope and technical characteristics of the machinery used for harvesting, a portion, e.g., the bottom of the stalk, cannot be removed because of technical limitations [20]. The percentage of residues left on the land because of machinery capacity is approximately 25% for soybean, corn, rice, sorghum, and sunflower [20]. This factor is not considered for sugarcane since the cane (stalk) is the product used for sugar production; therefore, the portion left by the machinery does not affect the quantity of sugarcane residues.

The amount left on land for soil conservation and the amount left due to machinery capacity are compared, and the maximum value is subtracted from the gross residue yield as shown in Equation 2-3:

$$y_{rem} = y_{res} - max|q_{soil}, q_{mach}| \tag{2-3}$$

where q_{soil} is the quantity of residues left for soil conservation (0.75 t/ha/yr), q_{mach} is the quantity left for machinery limitations ($q_{mach} = 0.25 \cdot y_{res}$), and y_{rem} is the amount of residues removed.

2.2.4.5 Animal feeding

A portion of agricultural residues is generally used for animal feeding. Since there is no information available on this use of residues in Bolivia, information from the literature [43] has been used here instead, assuming the same animal feeding requirement. A regression analysis between the straw for animal feeding and the number of animals (cattle and sheep) in 10 Canadian provinces was developed, and the proportional relationship equation was used to estimate the required residue for animal feeding based on the number of animals in each department in Bolivia, according to INE (2013) [18] (Table 2-2).

Table 2-2: Animal feeding by department in Bolivia

Department	**Number of cattle** (‘000)	**Number of sheep** (‘000)	**Residue left for animal feeding** [t/yr]	**Residue left for animal feeding per cropland area** [t/ha/yr]
Santa Cruz	2,540,461	165,531	822,313	0.37

Department	Number of cattle ('000)	Number of sheep ('000)	Residue left for animal feeding [t/yr]	Residue left for animal feeding per cropland area [t/ha/yr]
Oruro	76,187	1,442,699	30,873	0.29
Beni	3,737,494	12,428	1,210,254	23.33
Pando	79,605	3,645	25,792	1.61
Chuquisaca	695,845	879,704	229,097	1.27
La Paz	597,679	3,301,879	207,726	0.81
Cochabamba	442,719	1,475,302	149,696	0.71
Potosi	211,980	1,635,109	75,670	0.47
Tarija	459,464	371,598	150,372	1.79
Bolivia	**8,841,434**	**9,287,895**	**2,902,794**	

Animal feeding in this study considers only cattle and sheep, and the amount of residue for cattle is significantly higher than for sheep (320kg/yr/cattle and 4.3kg/yr/sheep). Beni has the most cattle among the department and also high cattle feeding demand; the residue requirement is likewise high for this department and not viable for energy purposes in this department.

2.2.4.6 Losses

A portion of the estimated yield has to be subtracted because of losses during collection, transportation, and storage. An earlier study [44] considered a 10% loss for decomposition in storage and handling. Liu [40] considered an 18% loss: 3% for handling straw in the field, 5% for loading and transporting bales, and 10% for storing. A reduction of 18% due to losses is considered here.

2.2.4.7 Moisture content

The straw moisture content depends on crop type and climate condition. The moisture content affects conversion technology selection and the process design. Table 2-3 gives different moisture content values for each crop residue assessed here.

Table 2-3: Moisture content in crop residues

Sugarcane		**Soybean**		**Corn**		**Rice**		**Sorghum**		**Sunflower**	
MC%	**Ref**	**MC%**	**Ref**	**MC%**	**Ref**	**MC%**	**Ref**	**MC%**	**Ref**	**MC%**	**Ref**
35	[37]	21.6	[29]	27	[32]	20	Brazil	16.2	[45]	22.9	[29]
35	[46]	16	[36]	15.5	[20]	25	UE	17	[47]		
		17	[32]	26.2	[29]						
		20	[48]	30	[25]						
				20	[49]						
Present study for Bolivia											
35		20		23		20		16.5		23%	

2.2.5 Potential energy

2.2.5.1 Low heating value (LHV)

After the biomass availability on a dry basis is calculated, it is multiplied by the corresponding low heating value to estimate the maximum potential energy from the residues by municipality. Table 2-4 shows the low heating values for the six crops studied here. The values adopted for this study are in Table 2-5.

Table 2-4: Low heating value of agricultural residues [GJ/t]

Sugarcane		**Soybean**		**Corn**		**Rice**		**Sorghum**		**Sunflower**	
LHV [GJ/t]	**Ref**	**LHV** [GJ/t]	**Ref**	**LHV** [GJ/t]	**Ref**	**LHV** [GJ/t]	**Ref**	**LHV** [GJ/t]	**Ref**	**LHV** [GJ/t]	**Ref**
17.3	[37]	17.6	[29]	18.3	[33]	14	[24]	14	[24]	18.6	[24]
18.6	[24]	16.3	[24]	14	[24]	17.5	[25]	12.55	[27]	17.5	[25]
		18	[48]	17.8	[29]					17	[29]

Table 2-5 summarizes all the factors adopted in this research to estimate the biomass feedstock from the six major crops produced in Bolivia: sugarcane, soybean, corn, rice, sorghum, and sunflower.

Table 2-5: Values adopted in this study

Crop	**RPR**	**Soil conservation** [t/ha]	**Losses** [%]	**Moisture content** [%]	**HHV** [GJ/t]
Sugarcane	0.22	0.75	18	35	18
Soybean	1.6	0.75	18	20	17.3
Corn	1.2	0.75	18	22	16.5
Rice	1.5	0.75	18	20	15.5
Sorghum	1.4	0.75	18	16.5	13
Sunflower	2.5	0.75	18	23	17.5

2.2.5.2 Development of biomass intensity maps in ArcGIS

The software ArcGIS 10.4 [50] was used in this study to create spatial distribution maps based on the total biomass availability in t/yr, the biomass yield in t/ha/yr, the characterizations of the six crop residues, and identify the location of main municipalities in generating agricultural residues across Bolivia.

2.3 Results and discussion

2.3.1 Biomass quantification

A biomass quantification of agricultural residues from sugarcane, soybean, corn, rice, sorghum and sunflower was conducted for Bolivia. From the total generation of agricultural residues (i.e., 9.1 Mt/yr), the sustainable residue biomass available for energy purposes becomes 3.8 dry Mt/yr after removing biomass for soil conservation, animal feeding, machinery capacity, losses, and water due to moisture content. The overall biomass breakdown assessment is presented in

Table 2-6 for Bolivia, for Santa Cruz (one of nine departments, and the one where most of the biomass availability is concentrated), and for the other eight departments together.

Table 2-6: Availability of agricultural residue from different crops in Bolivia

		Country: Bolivia	**Department: Santa Cruz**	**Other 8 Departments**
Agricultural crop production [t/yr]	Sugarcane	8,088,316	7,601,300	487,015.65
	Soybean	2,628,109	2,616,498	11,611.11
	Corn	845,982	641,146	204,835.33
	Rice	392,523	331,456	61,067.19
	Sorghum	598,272	594,824	3,447.40
	Sunflower	291,432	291,116	315.35
	Total	12,844,633	12,076,341	768,292
Generation of crop residues [t/yr]	Sugarcane	1,779,430	1,672,286	107,143.44
	Soybean	4,204,974	4,186,396	18,577.78
	Corn	1,015,178	769,376	245,802.40

		Country: Bolivia	Department: Santa Cruz	Other 8 Departments
	Rice	588,785	497,184	91,600.78
	Sorghum	837,580	832,754	4,826.35
	Sunflower	728,575	727,786	788.37
	Total	9,154,521	8,685,782	468,739
Biomass availability assessment [t/yr]	Removed for soil conservation	2,128,202	1,950,440	177762
	Removed for animal feeding	931,356	746,794	184562
	Handling looses	1,097,093	1,077,939	19155
	Water in biomass due to moisture content	1,203,472	1,176,096	27376
Availability	Dry biomass availability [t/yr]	3,794,398	3,734,513	59,884
	Percent availability	100%	98.4%	1.6%

Because 98% of the country's biomass is generated in the department of Santa Cruz, the rest of the paper discusses only the results obtained for this department.

Figures 2-6 and 2-7 compare the agricultural crop production and the available residue biomass quantified, showing that the correcting factors applied can influence an initial perception based only on agricultural production information. As observed in the graphs, although the production of sugarcane is greater than other crops, the residues generated from this crop represent only 22% of the total stalk production. Soybean, the second major crop, is the main energy potential source.

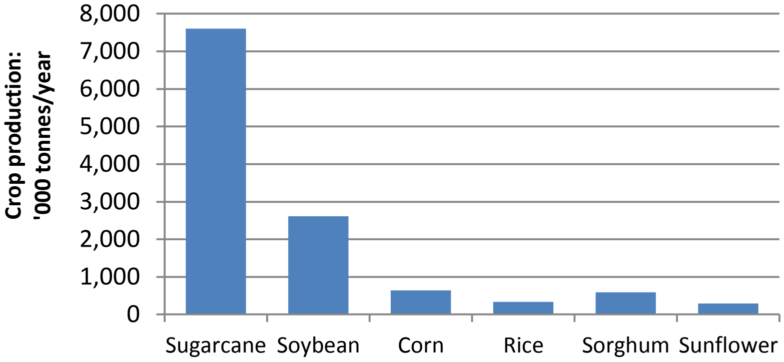


Figure 2-6: Crop production in Santa Cruz

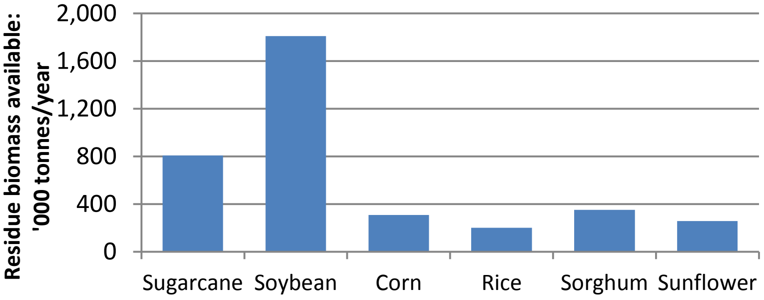


Figure 2-7: Residue biomass availability in Santa Cruz

The contribution of soybean residues is 49% of the total biomass availability, followed by sugarcane at 22%. The contribution of corn, sorghum, and sunflower is around 8% each, and the smallest biomass contribution is 5%, coming from rice.

2.3.2 Spatial biomass distribution in Bolivia

The spatial distribution of residue biomass available [t/yr] and biomass yield [t/ha/yr] is depicted in Figures 2-8 and 2-9, respectively, for the whole country and enlarged for the department of Santa Cruz. As shown in these figures, the availability is mostly noticeable in Santa Cruz and negligible in other departments.

The technology used for cultivating and harvesting crops varies greatly throughout the country. In some regions, farmers do not have efficient machines. This situation is reflected in low biomass yield values. Since biomass yield is the ratio between generated residues and harvesting area, a low yield is not logistically convenient because the available residues are spatially scattered in larger areas than high yield farms, and it increases the biomass collection cost. For example, Portachuelo, the eighteenth municipality in the list in Figure 2-4, generates a considerable biomass amount (see Figure 2-8); however, the biomass yield is low (see Figure 2-9). Accordingly, the two parameters, biomass availability [t/yr] and biomass yield [t/ha/yr], are plotted in Figures 2-8 and 2-9. Since the biomass quantification has been conducted at the municipality level and the exact geographic location of agricultural areas was not considered in this study, the larger residue-producing municipalities are those that generate greater biomass amounts at the municipality level, as shown in Figures 2-8.

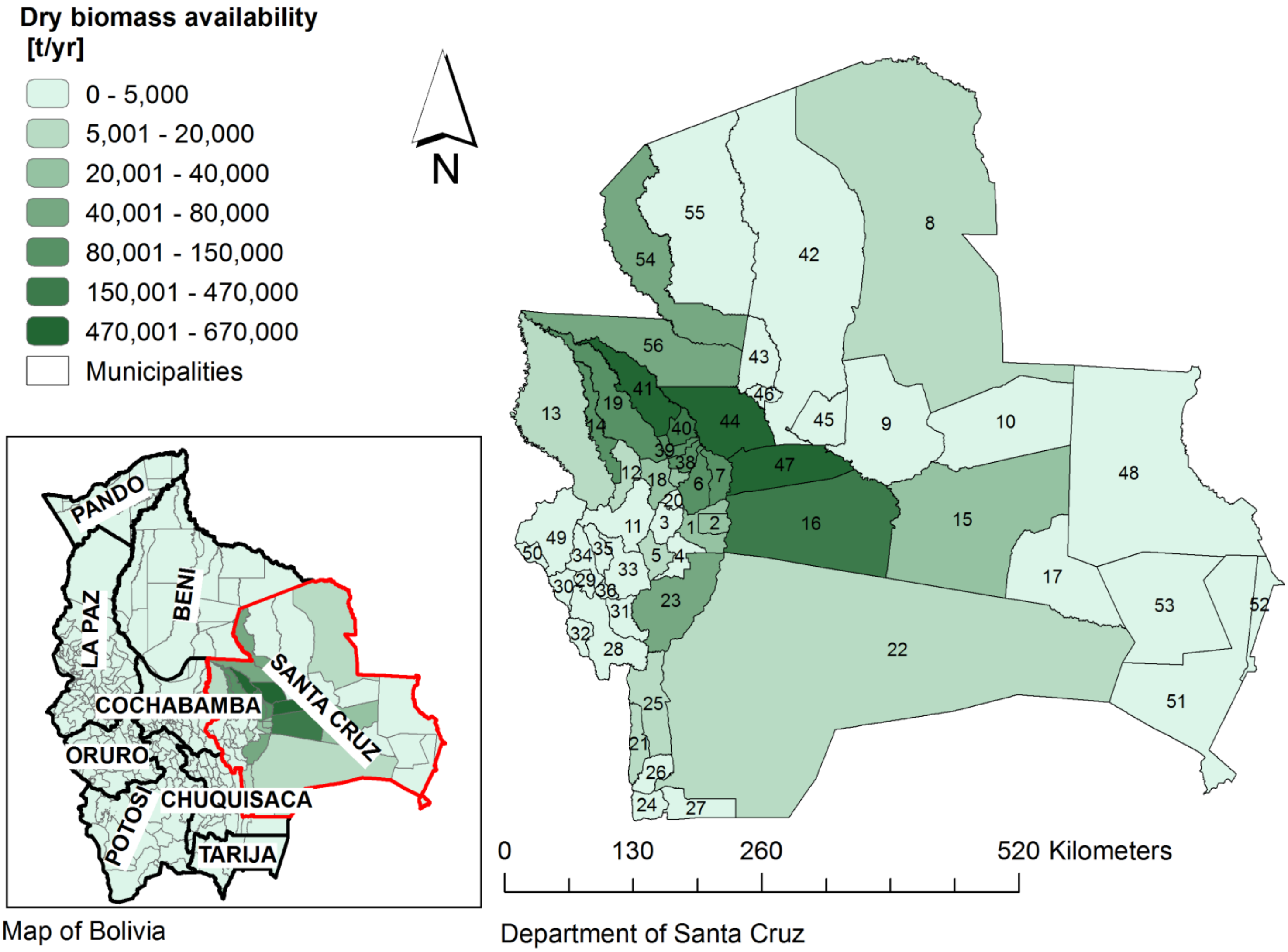


Figure 2-8: Dry biomass availability [t/yr]. Numbers in the map of Santa Cruz are taken from Figure 2-4.

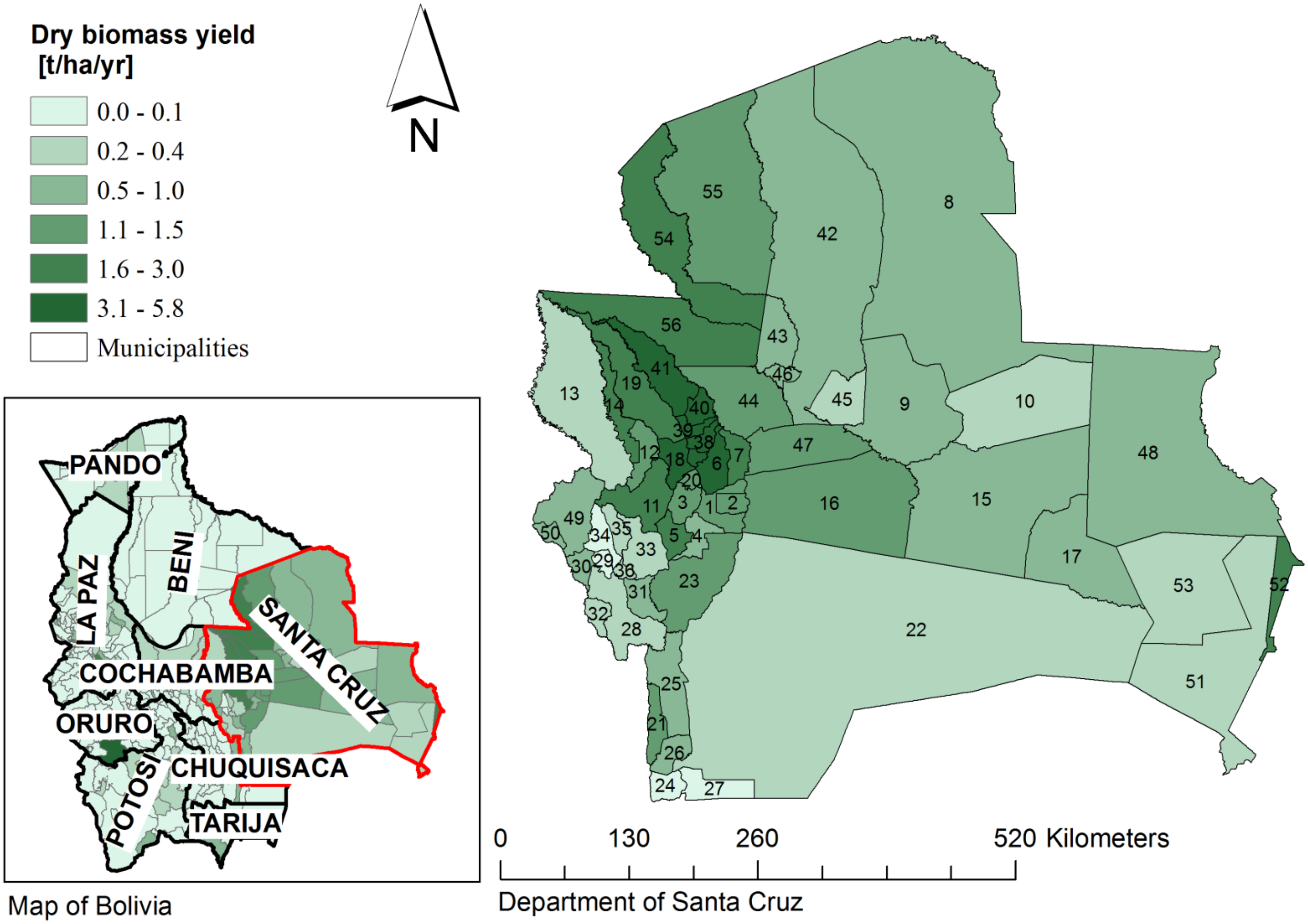
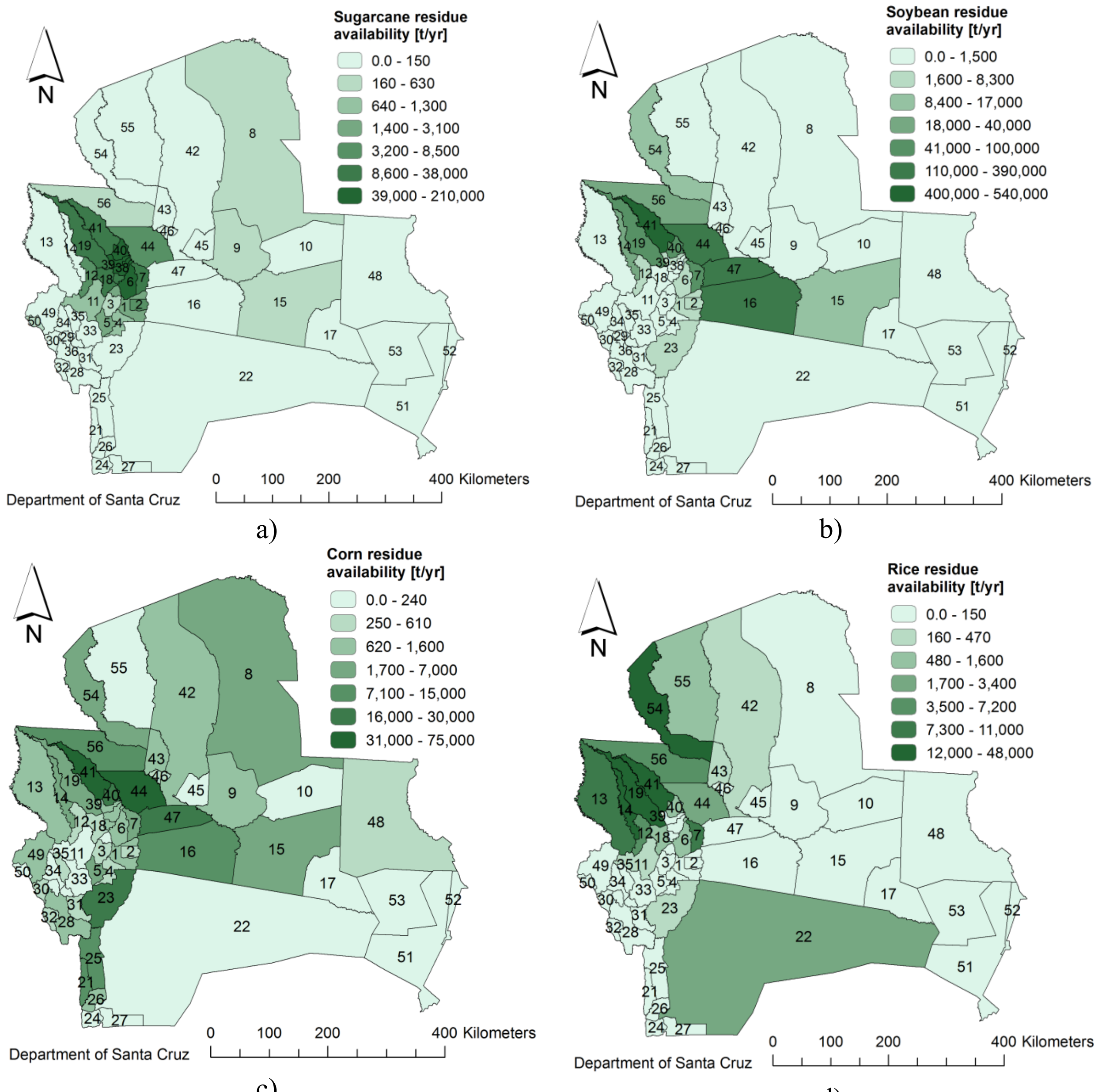


Figure 2-9: Dry biomass yield [t/ha/yr]. Municipality numbers are taken from Figure 2-4.

The spatial distribution and characterization based on crop residue type are shown in Figure 2-10. The residues from soybean and sugarcane are the two major biomass sources and contribute 71% of the total sustainable biomass availability for energy purposes. The fact that the large residue generation of these two crops is concentrated in a few municipalities and they are adjacent to each other (as shown in Figure 2-10 [a] and [b]) is an advantage for a biomass-based facility.

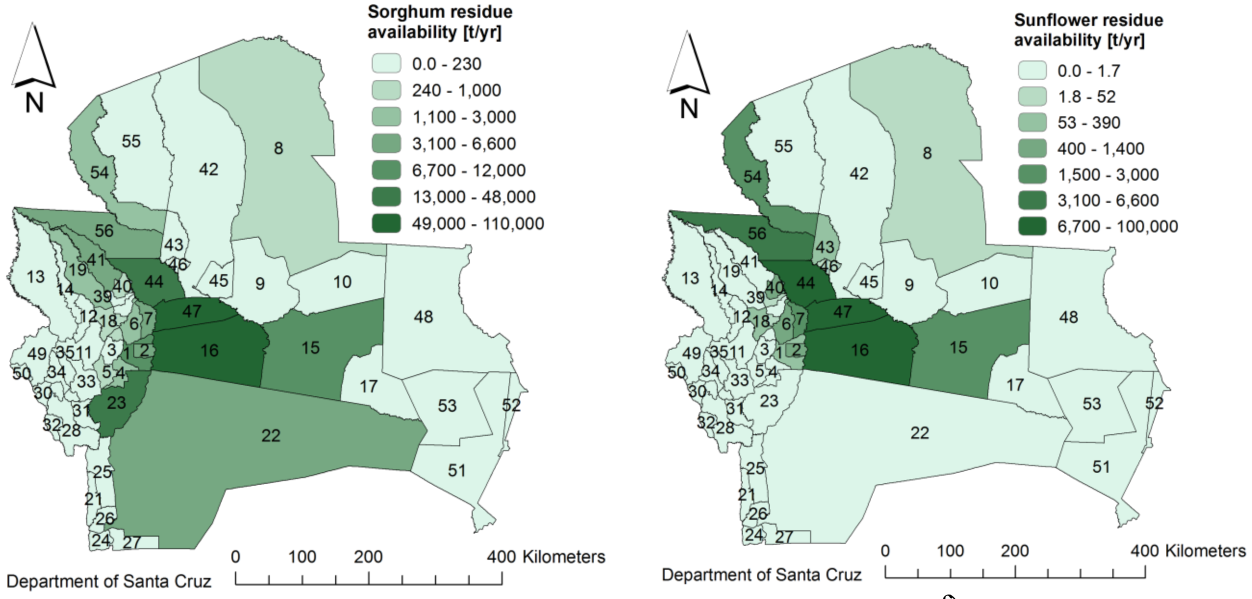


a)

b)

c)

d)



e)

f)

Figure 2-10: Biomass availability in the department of Santa Cruz by crop: a) sugarcane, b) soybean, c) corn, d) rice, e) sorghum, and f) sunflower. Numbers are taken from Figure 2-4.

The residues generated from the other four crops (corn, rice, sorghum, and sunflower) are dispersed throughout the department (shown in Figure 2-10 [c - f]); however, a portion of these residues is also produced in the same municipalities where sugarcane and soybean are mainly generated, thereby increasing the biomass availability in these regions.

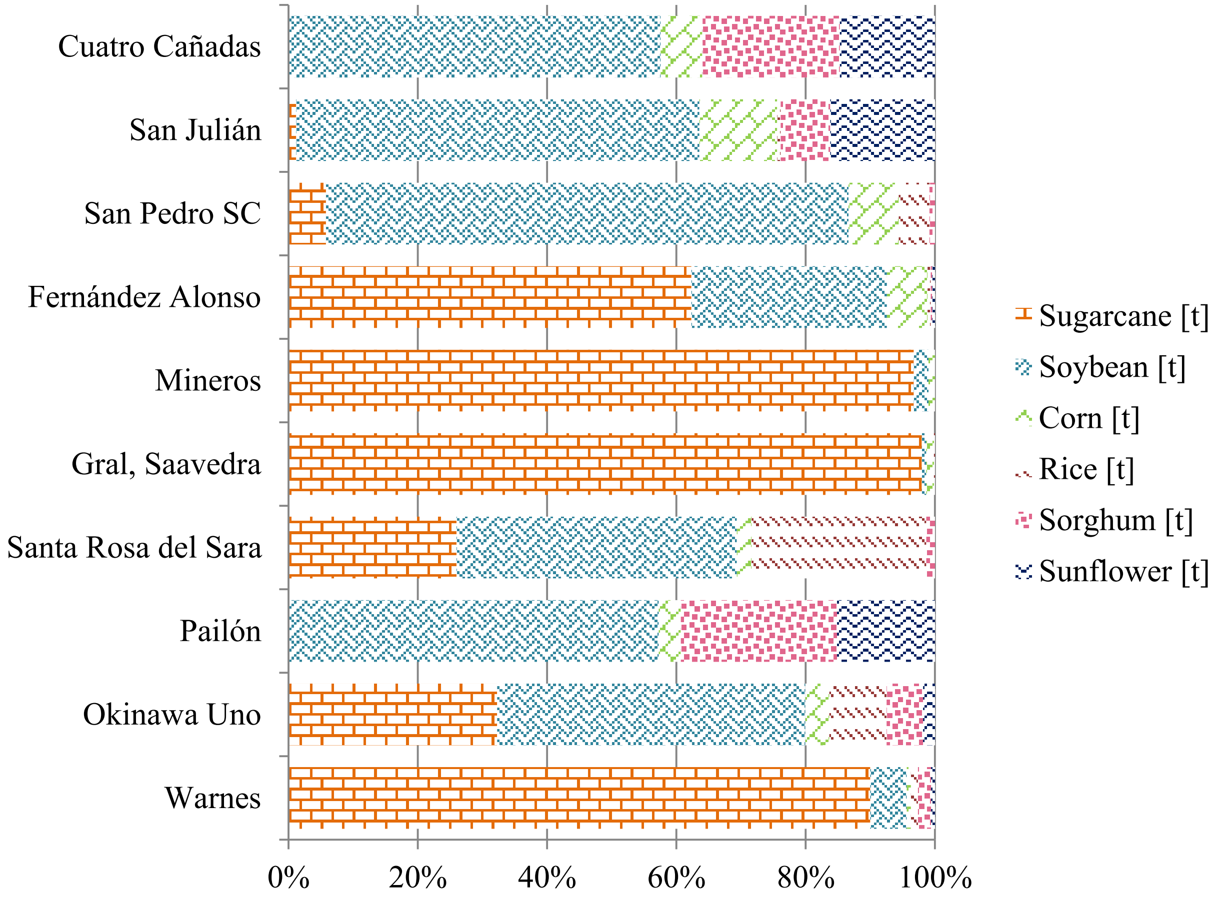


Figure 2-11: Biomass composition in the main residue-producing municipalities

Figure 2-11 shows the composition of biomass residue in the ten main municipalities that contribute the largest generation of agricultural residue in the country. The municipalities generating large sugarcane residues are Fernandez Alonso (0.21 Mt/yr), Mineros (0.13 Mt/yr) and Gral. Saavedra (0.13 Mt/yr), and the municipalities generating large soybean residues are San Pedro (0.54 Mt/yr), San Julian (0.39 Mt/yr) and Cuatro Cañadas (0.27 MT/yr). The geographic location of the ten main residue-producing municipalities is enlarged in Figure 2-12.

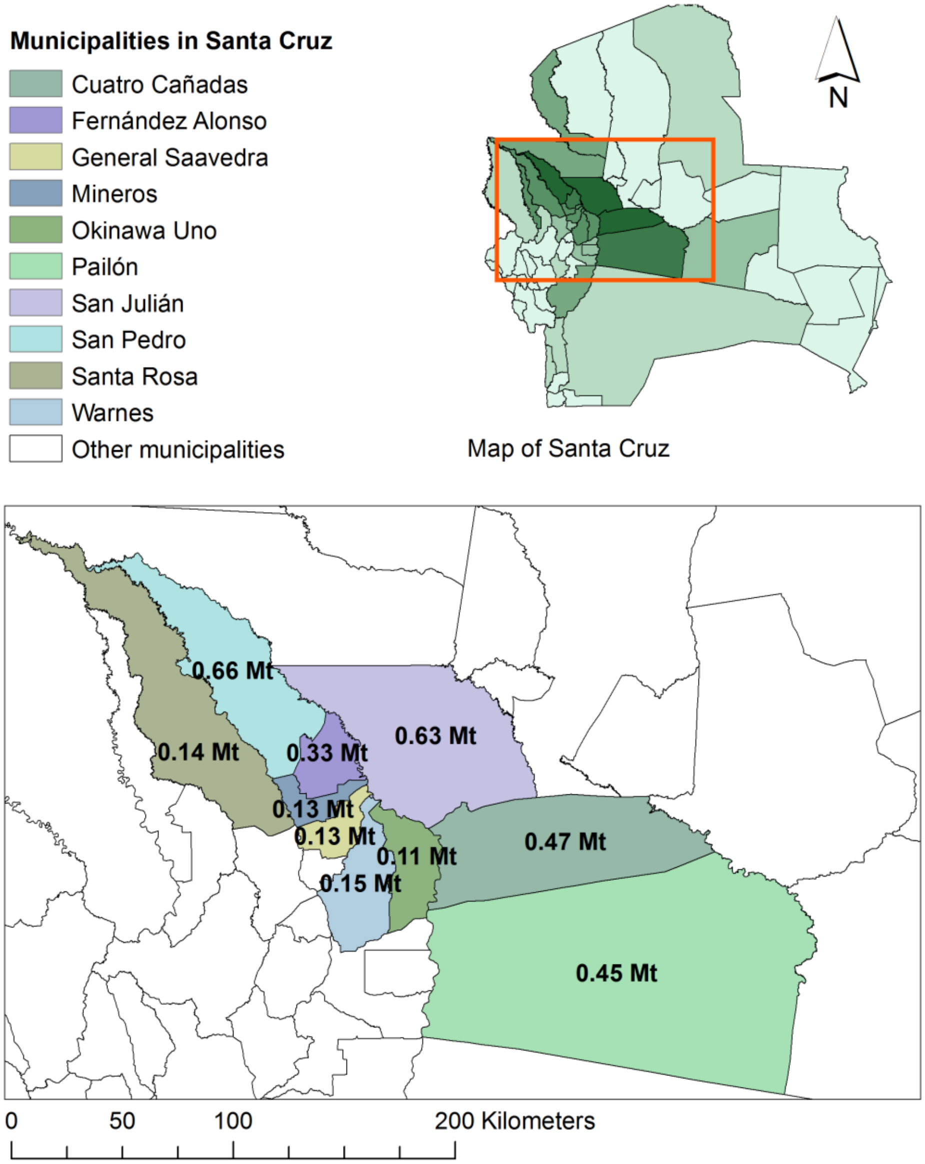


Figure 2-12: Location of the ten main municipalities that generate large agricultural residues for energy purposes

2.3.3 Potential energy in the department of Santa Cruz

To calculate the power and energy potential per municipality, we are assuming that the biomass per municipality estimated here is collected (there are no barriers in accessibility, nor transportation distances) and there is one biomass-based facility per municipality. We also assume an efficiency of 30% in converting biomass into electricity [51-54] and a capacity factor of 0.72 (equivalent to 6307 operating hours per year) [8, 55]. The energy and power potentials are estimated for the ten municipalities identified earlier, both for the department of Santa Cruz and for Bolivia. Under these conditions, the energy and power potentials are listed in Table 2-7.

Table 2-7: Energy and power potentials of biomass availability

Municipality	Biomass [t/yr]	Energy potential [MWh]	Capacity [MW]
Warnes	146,965	218,241	35
Okinawa Uno	114,850	163,633	26
Pailón	451,368	611,777	97
Santa Rosa del Sara	141,670	199,749	32
Gral, Saavedra	135,155	202,419	32
Mineros	130,251	195,035	31
Fernández Alonso	331,109	487,503	77
San Pedro	663,109	948,002	150
San Julián	626,259	882,289	140
Cuatro Cañadas	471,201	642,498	102
Total 10 municipalities	3,211,936	4,551,146	722
Other 46 municipalities in Santa Cruz	522,577	708,047.68	112
Total Santa Cruz	3,734,513	5,259,194	833
Other 8 departments in Bolivia	59,884	84,333	13
Total Bolivia	3,794,398	5,343,527	847

The biomass energy potential energy in Bolivia is 5.34 GWh, and the corresponding power potential is 847 MW. The national power generation in 2015 was 1,600 MW [14], which means that biomass has the potential to increase the power generation slightly more than 50%. Ten municipalities in Santa Cruz contribute 85% of the total biomass potential in Bolivia. The annual electricity consumption per capita in Bolivia was 0.7 MWh in 2014 [1]; in other words, the residues from the six main crops, generated in ten of 339 municipalities, could supply electricity (4.5 GWh) to 6.4 million inhabitants or 58% of the population. The potential energy from agricultural residues is enough to reduce considerably the consumption of fossil fuels.

2.3.4 Sensitivity analysis

Because most of the assumptions used in the process to estimate the biomass availability come from several studies conducted in different regions, a sensitivity analysis was conducted to identify the factors that most affect biomass potential. The biomass quantification began with determining the RPR. Although several sources were considered in defining the RPR for each crop residue in this study (see Table 2-1), there is a deviation of 50% in the data collected with respect to the average. Therefore, a 50% change is considered in the RPR for each of the six agricultural residues.

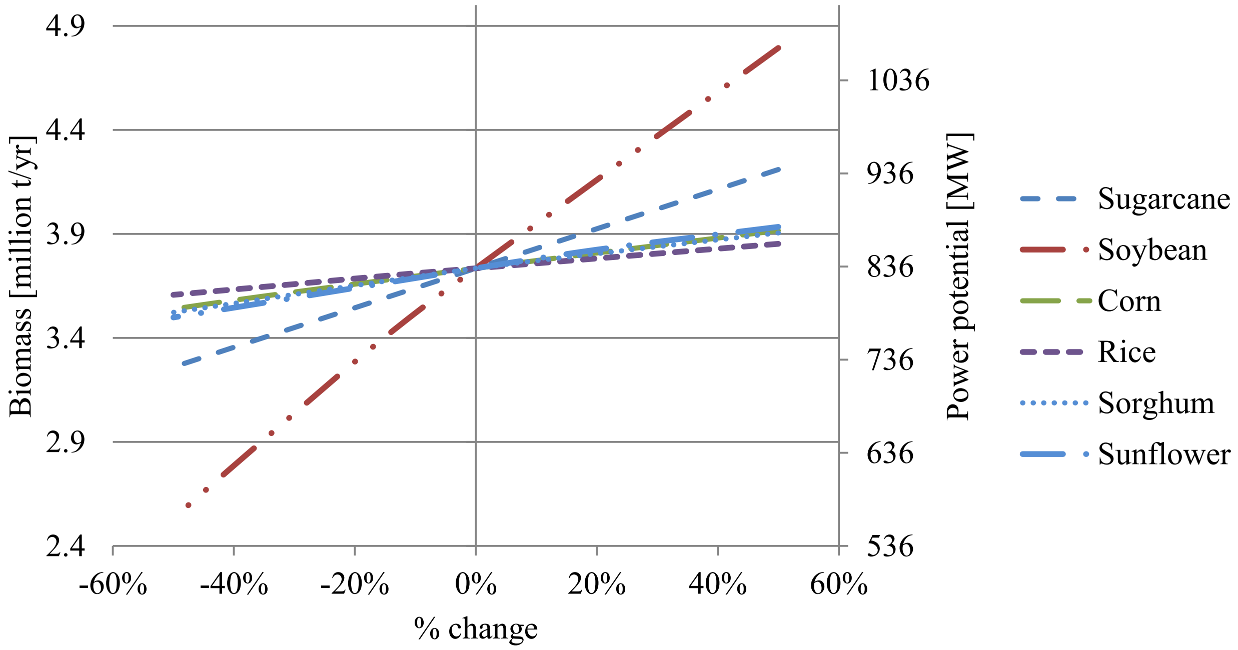


Figure 2-13: Sensitivity analysis of RPR for each type of residue

Figure 2-13 shows the RPR of soybean highly affects the biomass potential. Then, the RPR of soybean should be investigated and carefully determined because using a proper RPR value for the study area will improve the accuracy of the estimated biomass potential.

The quantification process also included soil conservation, animal feeding, machinery capacity, losses, and moisture content, whose impact is shown in Figure 2-14.

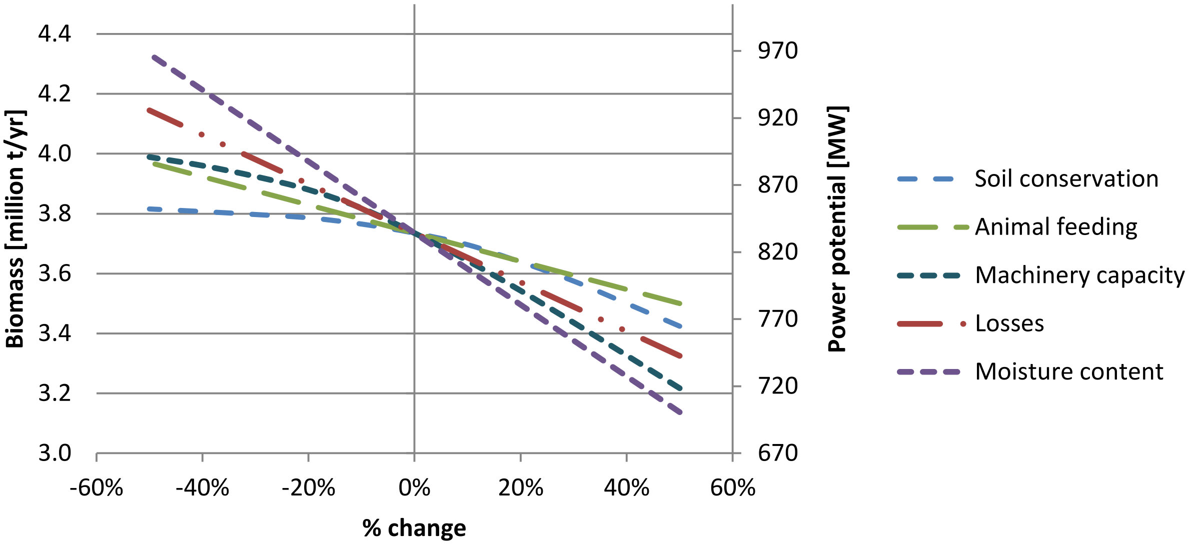


Figure 2-14: Sensitivity analysis of factors used in the biomass quantification process

The biomass potential is most affected by moisture content, followed by losses through biomass collection, storage, and transportation. The highest biomass availability is located in a very humid region; therefore, research needs to be conducted to analyze the moisture content variation across this region and throughout the year in order to understand how moisture content affects biomass potential and energy conversion. Losses can be reduced by a proper biomass handling (e.g., wrapping bales and covering the storage sites).

Further research is also required to find the optimum site for biomass-based energy facilities, considering environmental, social, and economic factors. The most appropriate energy conversion technology needs to be determined based on local requirements and a techno-economic assessment.

2.4 Conclusion

A biomass quantification analysis was conducted for Bolivia. Statistical information on crop production and cropland was collected from the first agricultural census conducted in 2013. The major agricultural crops identified as potential sources of energy are sugarcane, soybean, corn, rice, sorghum, and sunflower. The generation of agricultural residues in Bolivia from these six crops was estimated to be 9.1 Mt/yr. However, this amount falls to 3.8 Mt/yr when several factors are taken into account in quantifying the sustainable dry residue biomass available. Nearly all (98%) of this biomass availability (or 3.7 Mt/yr) is from Santa Cruz, one of nine departments. Ten municipalities in Santa Cruz were identified as major crop residue producers with a biomass availability of 3.3 dry Mt/yr and a potential energy of 4.5 GWh/yr. The corresponding power generation is 722 MW, which is equivalent to 45% of the installed capacity in the country. The estimated biomass quantification has the potential to ensure a sustainable and environmentally friendly source of energy that will help meet national goals.

References

[1] Ministerio de Hidrocarburos y Energía (MHE). Balance energético nacional 2000 - 2014. 2015. http://biblioteca.olade.org/opac-tmpl/Documentos/cg00430.pdf. (Accessed 12.11.16).

[2] Fernandez M. Estimacion del Potencial de Introduction de Energias Renovables 2010;11:1-5.

[3] Ministerio de Autonomías. Agenda Patriótica 2025, Quién hace qué? 2013. http://faolex.fao.org/docs/pdf/bol141864.pdf. (Accessed 11.01.17).

[4] Agenda Patriótica 2025: Los trece pilares de la Bolivia digna y soberana,. 2013. http://www.bolivia.de/fileadmin/Dokumente/DestacadosEmpfehlenswertes_Footer/4AgendaPatriotica2025-%2013%20pilares.pdf. (Accessed 10.01.17).

[5] Ministerio de Hidrocarburos y Energía (MHE). Plan para el desarrollo de las energías alternativas, 2025. 2014. http://www.bivica.org/upload/energias-alternativas-plan.pdf. (Accessed 17.10.16).

[6] Ministerio de Hidrocarburos y Energía (MHE). Plan eléctrico del Estado Plurinacional de Bolivia 2025. 2014. http://www.cndc.bo/media/archivos/boletines/peebol2025.pdf. (Accessed 20.10. 16).

[7] Programa de electricidad para vivir con dignidad (PEVD). Programa de electricidad para vivir con dignidad. 2014. http://www.pevd.gob.bo/pevd/nosotros/que-es-el-programa-electricidad-para-vivir-con-dignidad-pevd. (Accessed 5.11.16).

[8] Renewable Energy Policy Network for the 21st Century (REN21). Renewables 2016 Global Status Report. 2016. http://www.ren21.net/wp-content/uploads/2016/06/GSR_2016_Full_Report.pdf. (Accessed 10.10.16).

[9] Ministerio de Hidrcarburos y Energía (MHE). Plan de Desarrollo Energetico. Analisis de Escenarios: 2008-2027 2009. http://www2.hidrocarburos.gob.bo/phocadownload/PLAN%20DE%20DESARROLLO%20ENERG%C3%89TICO.pdf. (Accessed 22.10.16).

[10] Vasquez W. Eleven energy plants will produce 420 MW by 2020. La Razon. 2015;La Razon http://www.la-razon.com/economia/Once-energias-alternas-produciran-MW_0_2315168462.html. (Accessed 05.11.16).

[11] Intended Nationally Determined Contribution from the Plurinational State of Bolivia (INDC). 2015. http://www4.unfccc.int/submissions/INDC/Published%20Documents/Bolivia/1/INDC-Bolivia-english.pdf. (Accessed 10.11.16).

[12] Campos M. Guabirá prevé generar 45MW de energía. El Dia. 2013. https://www.eldia.com.bo/index.php?cat=357&pla=3&id_articulo=117356. (Accessed 10.09.16).

[13] Guabirá. Guabirá energía S.A. 2014. http://www.guabira.com/guabira/guabira-energia-sa.html. (Accessed 09.04.18).

[14] Empresa Nacional de Electricidad (ENDE). Memoria anual, 2015. 2016. http://www.ende.bo/public/memorias/memoria-2015-10-final.pdf. (Accessed 15.10.16).

[15] Sanchez MC. Las quemas reducen el rendimiento de plantaciones de caña en Bermejo. Periodico digital de investigacion sobre Bolivia. 2014. http://www.pieb.com.bo/sipieb_nota.php?idn=8950. (Accessed 20.01.17).

[16] Central Intelligence Agency (CIA). South America: Bolivia. 2016. https://www.cia.gov/library/publications/the-world-factbook/geos/bl.html. (Accessed 12.01.17).

[17] World Heritage Encyclopedia. Plurinational State of Bolivia. http://self.gutenberg.org/articles/eng/Plurinational_State_of_Bolivia#cite_note-52. (Accessed 25.01.17).

[18] Gutierrez HH. Exportadores de gas buscan precio justo. Libre empresa. 2017. http://libreempresa.com.bo/evento/20171218/exportadores-gas-buscan-precio-justo?q=evento/20171218/exportadores-gas-buscan-precio-justo&page=3.

[19] Instituto Nacional de Estadistica (INE). Electric Power Coverage in Bolivia. 2012. http://www.ine.gob.bo/pdf/boletin/NP_2013_32.pdf. (Accessed 05.10.16).

[20] Sokhansanj S, Fenton J. Cost benefit of biomass supply and pre-processing. BIOCAP Canada 2006. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.546.5141&rep=rep1&type=pdf.

[21] Sultana A, Kumar A, Harfield D. Development of agri-pellet production cost and optimum size. Bioresource Technology. 2010;101:5609-21.

[22] Instituto nacional de estadística (INE). Primer censo agropecuario 2013. 2013. http://sice.ine.gob.bo/censofichacna/. (Accessed 10.02.17).

[23] Helwig T, Jannasch R, Samson R, DeMaio A, Caumartin D. Agricultural biomass residue inventories and conversion systems for energy production in Eastern Canada. Prepared for Natural Resources-Canada. 2002;23348. http://agrienvarchive.ca/bioenergy/download/REAP_NRCAN-inventory-final.pdf. (Accessed 09.06.18).

[24] Oursbourn C, Lacewell R, LePori W, Patton W. Energy potential from agricultural residues in Texas. Southern Journal of Agricultural Economics. 1978:73-80.

[25] Scarlat N, Martinov M, Dallemand JF. Assessment of the availability of agricultural crop residues in the European Union: potential and limitations for bioenergy use. Waste management (New York, NY). 2010;30:1889-97.

[26] Babu S, Rana D, Yadav G, Singh R, Yadav S. A review on recycling of sunflower residue for sustaining soil health. International Journal of Agronomy. 2014. https://www.hindawi.com/journals/ija/2014/601049/abs/. (Accessed 18.06.18).

[27] Lal R. World crop residues production and implications of its use as a biofuel. Environment International. 2005;31:575-84.

[28] Carrasco N, Zamora M, Melin A. Sorghum Manual. 2011. http://inta.gob.ar/sites/default/files/inta_manual_de_sorgo_renglon_191.pdf. (Accessed 18.10.16).

[29] Roberts JJ, Cassula AM, Prado PO, Dias RA, Balestieri JAP. Assessment of dry residual biomass potential for use as alternative energy source in the party of General Pueyrredón, Argentina. Renewable and Sustainable Energy Reviews. 2015;41:568-83.

[30] Prihar S, Stewart B. Sorghum harvest index in relation to plant size, environment, and cultivar. Agronomy Journal. 1991;83:603-8.

[31] McIntire J, Reed JD, Tedla A, Jutzi S, Kebede Y. Evaluating sorghum cultivars for grain and straw yield. Red. 1988;2:53.6.

[32] Forster-Carneiro T, Berni MD, Dorileo IL, Rostagno MA. Biorefinery study of availability of agriculture residues and wastes for integrated biorefineries in Brazil. Resources, Conservation and Recycling. 2013;77:78-88.

[33] Hoskinson RL, Karlen DL, Birrell SJ, Radtke CW, Wilhelm W. Engineering, nutrient removal, and feedstock conversion evaluations of four corn stover harvest scenarios. Biomass and Bioenergy. 2007;31:126-36.

[34] Perlack RD, Wright LL, Turhollow AF, Graham RL, Stokes BJ, Erbach DC. Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. 2005. https://www1.eere.energy.gov/bioenergy/pdfs/final_billionton_vision_report2.pdf. (Accessed 18.06.18).

[35] Spaeth SC, Randall HC, Sinclair TR, Vendeland JS. Stability of Soybean Harvest Index1. Agronomy Journal. 1984;76:482-6.

[36] Duke, A. J. CRC handbook of alternative cash crops: Boca Raton: CRC Press; 1993.

[37] Leal MR, Galdos MV, Scarpare FV, Seabra J, Walter A, Oliveira COF. Sugarcane straw availability, quality, recovery and energy use: A literature review. Biomass and Bioenergy. 2013;53:11-9.

[38] Wekesa AN. Using GIS to assess the potential of crop residues for energy generation in Kenya [Thesis]. University of Canterbury; 2013.

[39] Tan Z, Liu S, Bliss N, Tieszen LL. Current and potential sustainable corn stover feedstock for biofuel production in the United States. Biomass and bioenergy. 2012;47:372-86.

[40] Liu E. Straw procurement business case. 2008. https://www.gov.mb.ca/agriculture/innovation-and-research/pubs/straw-procurement-final-report.pdf. (Accessed 18.06.18).

[41] Stumborg M, Townley-Smith L, Coxworth E. Sustainability and economic issues for cereal crop residue export. Canadian journal of plant science. 1996;76:669-73.

[42] Montross M, Crofcheck C. Effect of stover fraction and storage method on glucose production during enzymatic hydrolysis. Bioresource technology. 2004;92:269-74.

[43] Statistics Canada: Agricultural Division. Livestock Feed Requirements Study. 2003. http://www.statcan.gc.ca/pub/23-501-x/23-501-x2003001-eng.pdf. (Accessed 12.09.16).

[44] Perlack R.D, Turhollow A.F. Assessment of option for the collection handling and transport of corn stover. 2002. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.562.267&rep=rep1&type=pdf. (Accessed 18.06.18).

[45] Ayamga EA, Kemausuor F, Addo A. Technical analysis of crop residue biomass energy in an agricultural region of Ghana. Resources, Conservation and Recycling. 2015;96:51-60.

[46] Rehman K, Jawaid M, Rashid U. Biomass and Bioenergy: Processing and Properties: Springer International Publishing; 2014.

[47] Sigua GC, Stone KC, Hunt PG, Cantrell KB, Novak JM. Increasing biomass of winter wheat using sorghum biochars. Agronomy for Sustainable Development. 2015;35:739-48.

[48] Kludze H, Deen B, Weersink A, Acker A, Acker R, Janovicek K, et al. Assessment of the availability of agricultural biomass for heat and energy production in Ontario. 2010. https://www.uoguelph.ca/plant/research/agronomy/publications/pdf/Ontario_Biomass_Availability_Project_Final_Report_2011.01.27.pdf. (Accessed 10.02.17).

[49] Clarke S, Preto F. Biomass burn characteristics. 2015. http://www.omafra.gov.on.ca/english/engineer/facts/11-033.htm. (Accessed 26.11.16).

[50] Esri. Mapping without limits. 2017. http://www.arcgis.com/features/index.html. (Accessed 22.01.17).

[51] Bridgwater AV, Toft AJ, Brammer JG. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. Renewable and Sustainable Energy Reviews. 2002;6:181-246.

[52] Cameron JB, Kumar A, Flynn PC. The impact of feedstock cost on technology selection and optimum size. Biomass and Bioenergy. 2007;31:137-44.

[53] Caputo AC, Palumbo M, Pelagagge PM, Scacchia F. Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. Biomass and Bioenergy. 2005;28:35-51.

[54] Dassanayake GD. Utilization of Triticale Straw for Power Generation [Thesis]. University of Alberta; 2012.

[55] Autoridad de Fiscalizacion y Control Social de Electricidad (AE). Anuario estadístico 2015. 2016. https://www.ae.gob.bo/aewebmobile/main?mid=1&cid=81. (Accessed 15.04.18).

Chapter 3: Developing a Framework to Optimally Locate Biomass Collection Points to Improve the Biomass-based Energy Facilities Locating Procedure – A Case for a South American Country: Bolivia[1]

3.1 Introduction

Energy is intrinsic to development and wellness in any society. Even though fossil fuel consumption noticeably contributes to global warming, the current trend in energy production is expected to continue due to increasing industrialization and population growth. This trend accordingly increases the need to develop renewable energy facilities to replace fossil fuel-based plants, lower greenhouse gas (GHG) emission levels and meet the growing demands.

Biomass, a renewable organic matter, can be used to generate not only heat and electricity, but also biofuels (e.g., biodiesel, biogas, pellets, etc.) depending on the conversion technology (e.g., combustion, gasification, anaerobic digestion, composting, etc.) and biomass availability (agricultural residues, forest residues, municipality solid waste, food processing waste, etc.). However, regardless of conversion technology and biomass feedstock, the biomass-based facility should be located as close as possible to the biomass source in order to minimize the costs associated with collecting and transporting feedstock (biomass delivery cost is about 30% of the energy cost [1, 2]), as well as CO_2 emissions from transportation.

---

[1] Paper submitted as Morato T., Vaezi M., Kumar A., to the journal *Renewable and Sustainable Energy Reviews*, 2018

Similarly, siting a facility needs consideration of several social and environmental parameters. Social factors include road networks, airports, power plants, transmission lines, and urban areas, and environmental factors are protected areas, rivers, lakes, wetlands, etc. Specific constraints associated with each of these factors must be taken into account throughout the analysis. For instance, there are areas where human intervention is banned (e.g., protected areas) [3], areas where closeness to the facility is favored (e.g., roads) [4, 5], and areas with regulations for keeping a minimum distance from the facility (e.g., urban areas) [5]. The geographic location and influence of these constraints can be analyzed using a geographic information system (GIS). This technology uses geospatial data to represent and manipulate geographic compositions. GIS has been used widely in previous studies for locating biomass-based facilities [5-11]. Identifying suitable sites also involves multi-criteria analysis (MCA) of environmental and social factors; the analytical hierarchy process (AHP) [12], which is an MCA method, assigns weights to corresponding environmental and social factors based on a pair-wise comparison. A similar combination of the GIS and an AHP has been applied in previous studies for locating candidate sites for energy facilities, e.g., solid waste conversion facilities [10], pellet plants [5], and food waste conversion facilities [11]. Afterwards, a location-allocation analysis (a network model which uses the candidate sites, actual road network, and biomass source points) determines the optimal location by analyzing numerous ways to efficiently supply biomass to facilities and minimize the sum of weighted distances [5, 10, 11, 13].

The biomass source used as input data for the network model depends on how biomass is collected. For example, most cities have transfer stations for collecting and sorting municipality solid waste (MSW), whose locations across the city become the biomass source points in the network model [10]. In another example, the input data for locating food waste processing facilities are the location of food processing industries [11]. However, agricultural residues are initially dispersed on fields and a supply chain needs to be developed for collecting and transporting biomass to the facility.

Previous studies on using agricultural and forest residues assumed the conversion facility is located in the middle of a circular area from where biomass is collected at a constant biomass yield and averaged transportation distance [1, 2, 14]. Other studies applied location-allocation modeling with homogeneously distributed biomass collection points (BCPs) across their study area, regardless of the possibility/feasibility of locating such points in a restricted area (e.g., lakes, roads, etc.) [5, 15]. Furthermore, earlier studies [4, 16] assumed agricultural residues, in the form of bales, are stored temporarily next to farms and aside the roads. This results in long collection times due to the high frequency of trucks stopping to load bales at almost every field. The reliability of all these approaches depends on the collection area. If the region, for instance, has a road network with a grid pattern, collecting biomass from circular areas, assuming there is a proportional relationship between travel distance and the square root of plant size, is applicable [2]. However, if roads have evolved following the topography, and biomass yield changes greatly within the region, those assumptions cannot be applied and the use of GIS becomes inevitable through the analysis.

To address these shortcomings, a biomass logistics is proposed here which consists of transporting biomass in the form of bales over short distances from fields to biomass collection points (BCPs) by bale stackers or bale movers, and from BCPs to the biomass-based conversion facilities through long-haul trucks. BCPs receive biomass from small circular areas and are located close to the roads. BCPs are expected to increase the collection time efficiency since trucks do not need to stop frequently at every field for collecting biomass, also it allows the trucks to use the paved roads only rather than gravel roads.

To apply the logistics proposed here, a model is required to strategically locate BCPs. The model should consider the spatial variation of biomass availability, as well as the actual road network in the study region. The model should also give preference to areas with high biomass availability and proximity to road network. In addition, the geographic location of BCPs and the amount of biomass collected at each BCP are more precisely calculated to be later used in the network model for optimally locating the biomass conversion facility.

The aim of this research is to develop a model for locating BCPs considering the road network and the spatial distribution of biomass. The following are the specific objectives of this study:

- To develop a framework for locating biomass collection points using geographic information systems
- To conduct a case study for the country of Bolivia, using the developed framework for locating BCPs to optimally locate biomass-based energy facilities.

3.2 BCP locating framework

Strategically llocating BCPs improves the ability of the network analysis to accurately determine the optimal location of conversion facilities. In this framework, BCPs are located in such a way that high amounts of biomass can be conveniently collected close to the roads and loaded onto trucks. A biomass collection point is defined as the centroid of a circular area where generated agricultural residues are collected. The radius of the circular area depends on the study region. The collection area size determines both the amount of biomass amassed at each BCP and the total number of BCPs in the study area. The radius should be determined based on activities/capabilities of transporting bales from fields to BCPs by bale stackers or bale movers. Previous studies considered different distances for transporting bales from fields to storage sites, e.g., 16 km [17] , 8 km [18], 3-5 km [19], and simply the corner of the field [16]. In this study, 4 km is the assumed distance (the radius of the circular area) for collecting biomass at BCPs. We also assumed an average field size of 300 ha and that each BCP collects biomass from approximately 16 fields. Figure 3-1 shows this study's proposed biomass logistics.

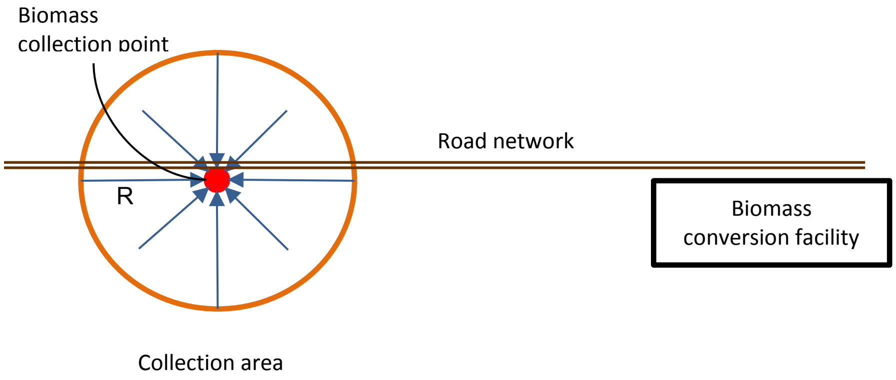


Figure 3-1: Logistics system for accumulating biomass in collection points close to roads and transporting it from those points to conversion facilities through the actual road network

The process developed in ArcGIS to identify collection points is iterative and has the key criteria of high biomass concentration and minimal distance to road network. The flowchart of the iterative process is depicted in Figure 3-2.

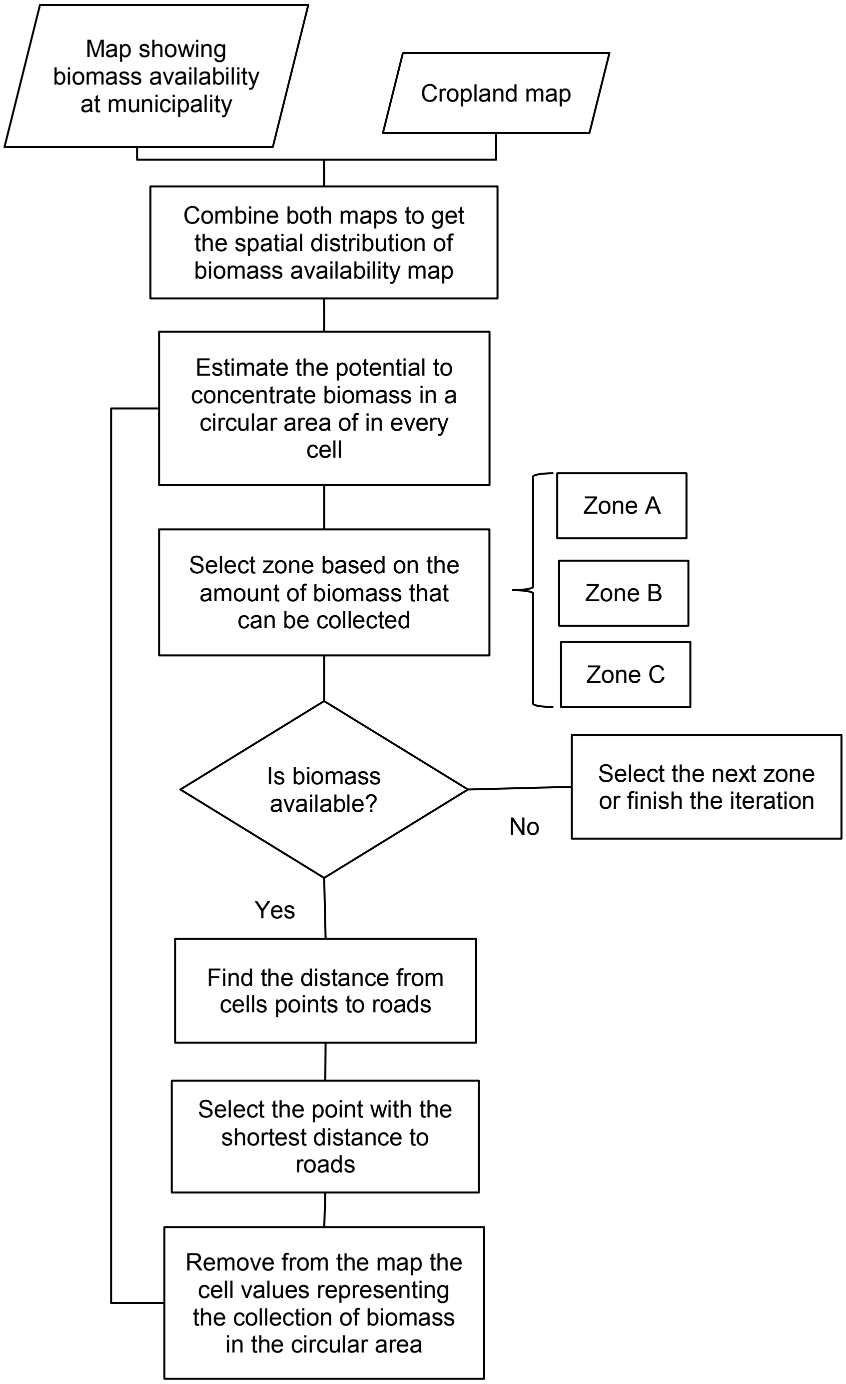


Figure 3-2: Iteration process for locating BCPs

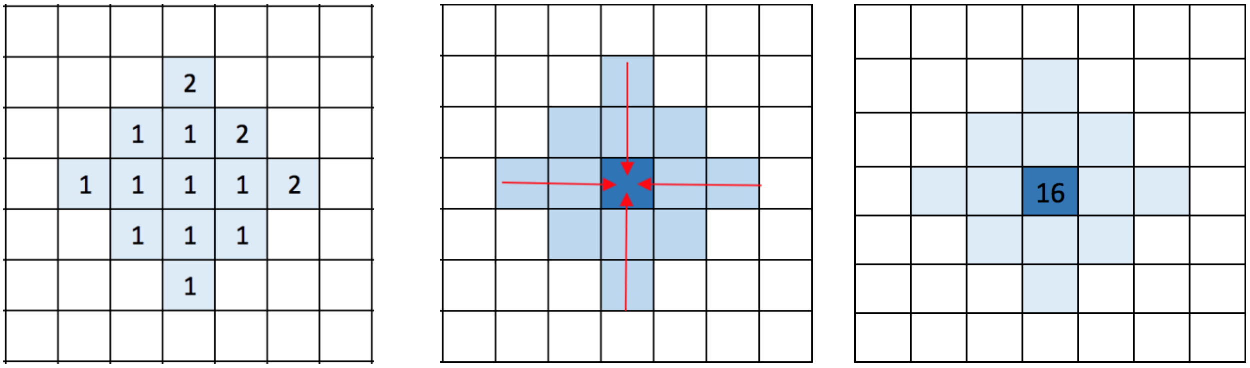
Initially, the information on biomass availability at the smallest territory sub-division of the study region is combined with the agricultural map, which can be extracted from the land cover map, to obtain the spatial location of biomass sources.

A 1 km x 1 km grid was laid over the biomass source map to divide the map area into small quadrants [19]. The cropland area was reduced by geographic features such as roads, lakes, rivers, etc. The cropland area was calculated in each cell and then multiplied by the biomass yield to find the amount of biomass availability in tonnes per year per quadrant as expressed by Equation 3-1:

$$m_{i,j} = a_{i,j} \cdot y_m \tag{3-1}$$

where i, j are the indices for every quadrant in the grid, $m_{i,j}$ is the biomass availability in each quadrant, $a_{i,j}$ is the cropland area in every quadrant, and y_m is the biomass yield, which depends on the municipality.

The first step in the iterative process is to assess the ability to concentrate biomass in every quadrant. In order to do this, the cell values in an area with a 4 km radius were summed up in ArcGIS, and the result was assigned to the cell in the center. The cell sum was calculated for each quadrant in the study area. Figure 3-3 shows a representation of the cell sum operation.



(a) (b) (c)

Figure 3-3: Example of the cell sum method used to calculate the capacity to concentrate biomass in the middle. (a) Example of initial values in each cell, (b) arrows indicating the cell where the sum of the values is assigned, including the middle cell value, and (c) the cell value in the middle of a region

The map obtained in GIS (after the cell sum operation) gives information on each cell's potential to concentrate biomass in an area with a 4 km radius. From this map, a zone with high capacity to collect biomass was selected in every iteration. The zones were classified based on the biomass collection range. The smaller the zone area, the fewer the BCPs, and the higher the number of zones required to cover the whole agricultural region.

After zone A (the zone with the highest biomass collection range) was selected, a central point was created inside each cell that belongs to that zone. The distance from each point to the closest road was calculated, and the model chose a single point, the one with shortest distance to the roads. A buffer with a radius of 4 km was created around the chosen point and the cell values in the biomass availability map (values of biomass availability in dry t/yr per cell) falling inside the buffer area were converted to 0, simulating the collection of biomass in that circular area.

For the second iteration, the sum operation of cells was re-calculated to obtain a new map showing the remaining potential to collect biomass. The quadrant values close to the first BCP fell within this new map because of the removed biomass. The iteration process kept selecting zone A until no more quadrants were available within this zone or the distance from selected point to road network was higher than 4 km. Then the iteration went to the next zone (zone B) and the same algorithm was applied. The iteration process continued in the remaining zones. Finally, all the BCPs were merged into a single map, which was later used in the location-allocation analysis to locate biomass-based facilities. In this analysis, the estimated amount of concentrated biomass in tonnes per year for each BCP was used to minimize the weighted transportation distance.

3.3 Case study: The Department of Santa Cruz, Bolivia

3.3.1 Background

Bolivia is not exempt from increased use of energy to improve social and economic conditions. Currently, a major source of energy in Bolivia is natural gas. About 18% of the natural gas goes towards meeting the domestic energy demand and 82% is exported to Brazil and Argentina [20, 21]. This makes Bolivia the largest gas exporter in South America; however, concerns are arising because the higher gas production rate might not assure its availability for future years. This reality is reflected by the reserve-to-production ratio (RPR) which is the relation between the amount of natural gas that can be economically extracted (volume) and the production rate (volume per unit time). This value gives the expected remaining number of years to use this resource if the production rate remains constant. The RTR was reported as only 13.5 years in 2012 [22]. Moreover, the energy targets set by the Patriotic Agenda in Bolivia [16] encourage an increase in national electricity production to reach the universal electricity access target (to provide access to electricity to all citizens by 2025), reduce the consumption of imported fuels (e.g., diesel), and export the surplus to neighboring countries. There is thus a need for renewable sources to meet the targets and decrease the current dependency on fossil fuels.

Among the several projects on renewable sources to generate energy in Bolivia (e.g., solar, wind, hydro, geothermal) [23, 24], biomass can be used not only to generate electricity but also to produce gaseous and liquid fuels. In addition, biomass, which includes forest residues, agricultural residues, and energy crops, is readily available when needed.

The authors, in a previous study, quantified the biomass potential from agricultural residues available for energy production purposes in Bolivia [25]. According to the crop production statistics reported by the National Institute of Statistics (Instituto Nacional de Estadística [INE]) [26], the annual production of six major crops (soybean, sugarcane, corn, rice, sorghum, and sunflower) contributes to more than 90% of the total agricultural production in the Department of Santa Cruz, one of nine departments of Bolivia and the one with the highest agricultural production (Figure 3-4) [26]. The authors, therefore, investigated these crops solely in the Department of Santa Cruz and estimated that the agricultural residue biomass potential is 3.7 million dry tonnes per year. In addition, geospatial analysis identified areas where most of the residues are generated; these are shown in Figure 3-4. Ten municipalities in Santa Cruz have the potential to generate 722 MW of electricity, assuming a 30% plant efficiency [27-30] and 0.72 capacity factor [31-33]. This power potential is equivalent to 45% of the country's installed capacity, which in 2016 was 1,600 MW [21, 25]. More details on the feedstock potential can be found in Morato et al. [25].

Although there is a potential for development of biomass-based energy production in Bolivia, particularly in the Department of Santa Cruz, there have not been any prior analyses on the economic feasibility of biomass-based energy facilities in Bolivia. There have also not been any study on assessment of optimal facility location and biomass delivery systems. This research is, therefore, aimed at finding the optimum locations of biomass-based energy conversion facility sites and devising the corresponding logistics system considering biomass availability, actual road networks, and other social and environmental factors.

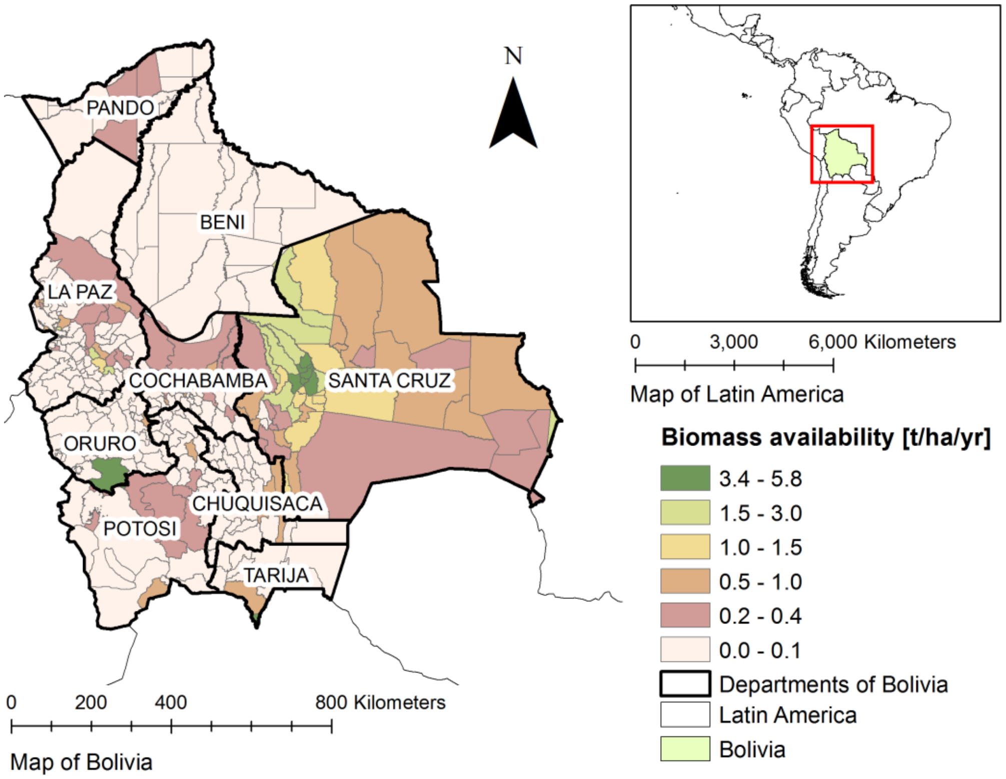


Figure 3-4: Biomass availability map in the nine departments of Bolivia [19]

3.3.2 Method

The method section is divided into three sub-sections: the first contains the process for locating BCPs, the second includes the location analysis of potential candidate sites for conversion facilities, and the third contains the location-allocation analysis using the actual road network. In this third sub-section, the optimal locations are selected among all candidate sites in such a way that the weighted transportation distances from BCPs (supply) to conversion facilities (demand) are minimized.

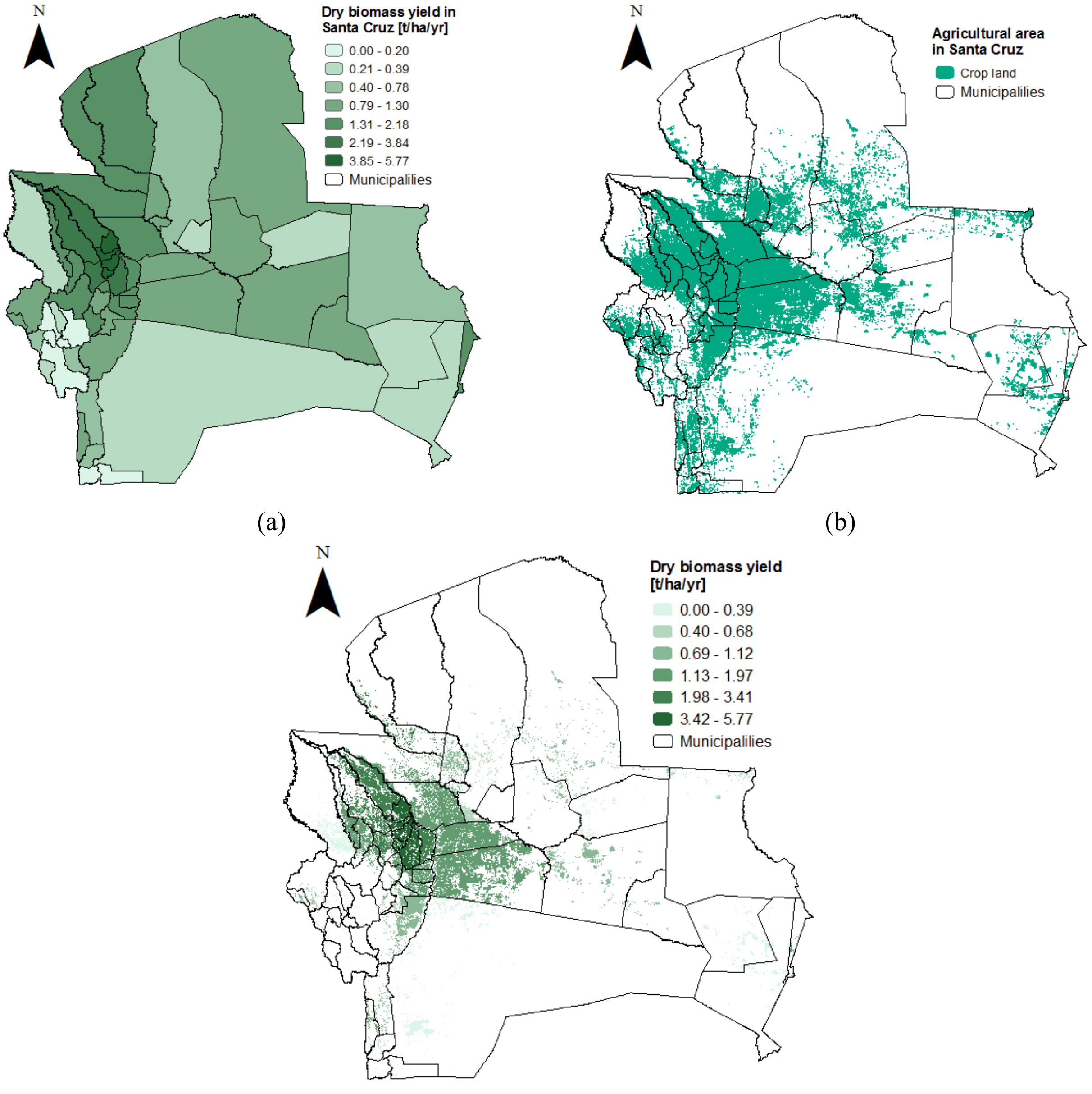
ArcGIS 10.1 software, which uses GIS technology to process geospatial data [34], was used in this study. High-resolution data, in either vector (point, line, or polygon) or raster (cells with 30 x 30 m resolution) format, were used in Model Builder, an application that allows the users to track the sequence of geoprocessing tools. In order to locate, display, and integrate geographic features correctly on the earth's surface, the geographic coordinate system needs to be defined for the geospatial data used in this study. The projected coordinate system, which transforms a portion of the earth's surface into a flat plan was WGS 1984 UTM Zone 20S.

3.3.2.1 Locating BCPs

The framework for locating BCPs using GIS is now applied to the study case, Bolivia. The study area is a good candidate for applying the framework explained in the previous section for the following reasons:

- The road shape does not have a grid pattern due to its topography and frequent river interceptions. Therefore, calculating transportation distances with theoretical equations is not appropriate and a GIS is needed.
- The approach to biomass logistics assumes that long-haul trucks travel only on paved roads (to improve collection efficiency), but not all agricultural fields have direct access to paved roads. Thus, biomass bales need to be transported from fields to BCPs, which are located on the roadside.
- Biomass availability changes spatially with no pattern. Thus, we cannot assume a homogeneous distribution of biomass availability, nor that it decreases radially.

In order to illustrate the location of biomass sources across the study area, the map of biomass availability at the municipal level developed by the authors for a previous study (Figure 3-5 [a]) [25] was combined with the agricultural map extracted from the land cover map (Figure 3-5 [b]). Since the agricultural residues analyzed by the authors earlier [25] come from the six crops that make up 90% of agricultural production in the Department of Santa Cruz (sugarcane, soybean, corn, rice, sorghum, and sunflower), it was assumed that the cropland of these crop residues covers the entire agricultural area map. Figure 3-5 shows the two maps used to create the biomass source map (Figure 3-5 [c]).



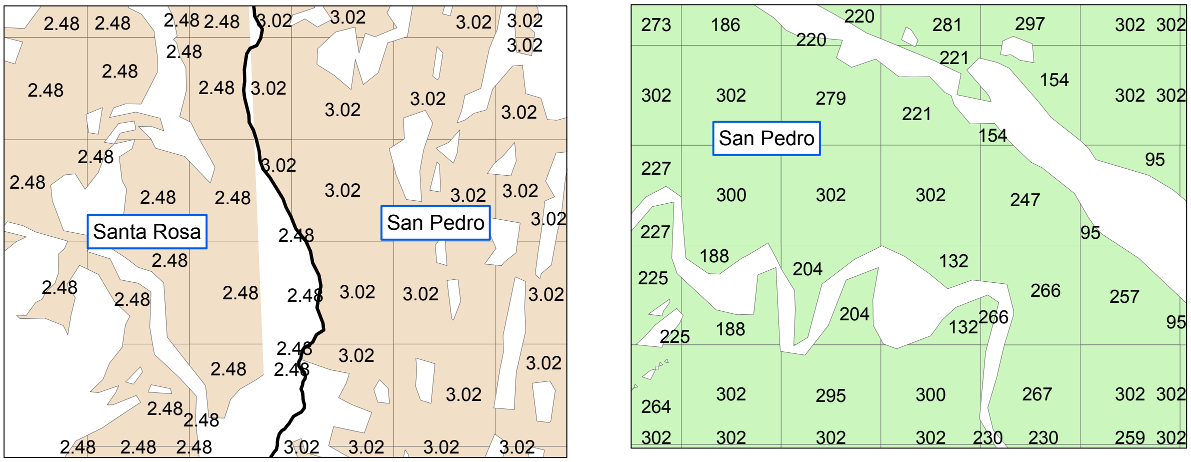
(a)

(b)

(c)

Figure 3-5: (a) Biomass availability at the municipal level, (b) agricultural area, (c) location of biomass source

The biomass availability was calculated at every 1x1 km cell by multiplying the biomass yield times the agricultural area at every cell. Figure 3-6 shows the quadrants' values in two stages: initially, the values refer to the yield, which is constant in every municipality (Figure 3-6 [a]), and later the values refer to the biomass availability which varies, as shown in (Figure 3-6 [b]). At this stage, the amount of biomass varies spatially.



(a) (b)

Figure 3-6: (a) Biomass yield by quadrant [dry t/ha/yr], (b) Biomass availability by quadrant [dry t/yr]

The potential of each cell for concentrating biomass in circular areas of 4 km radius was calculated, and the map obtained based on this potential is shown in Figure 3-7.

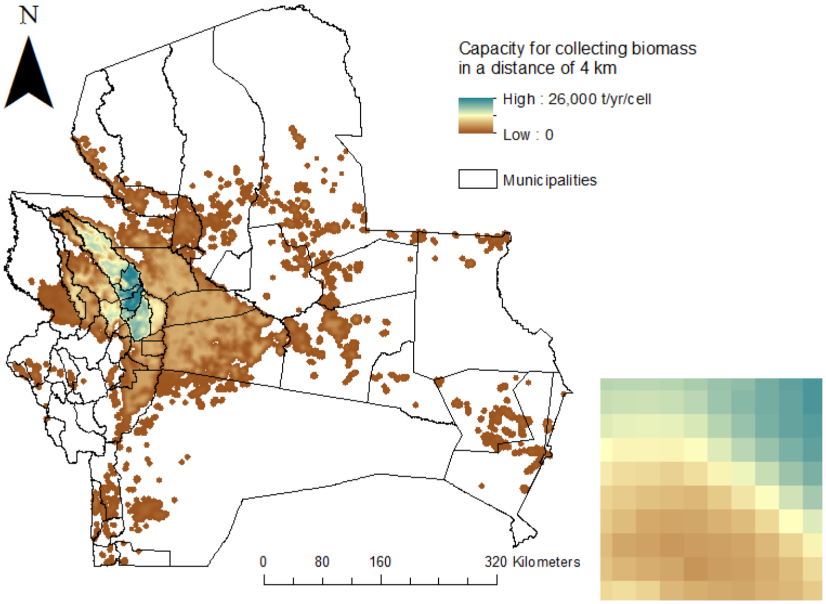
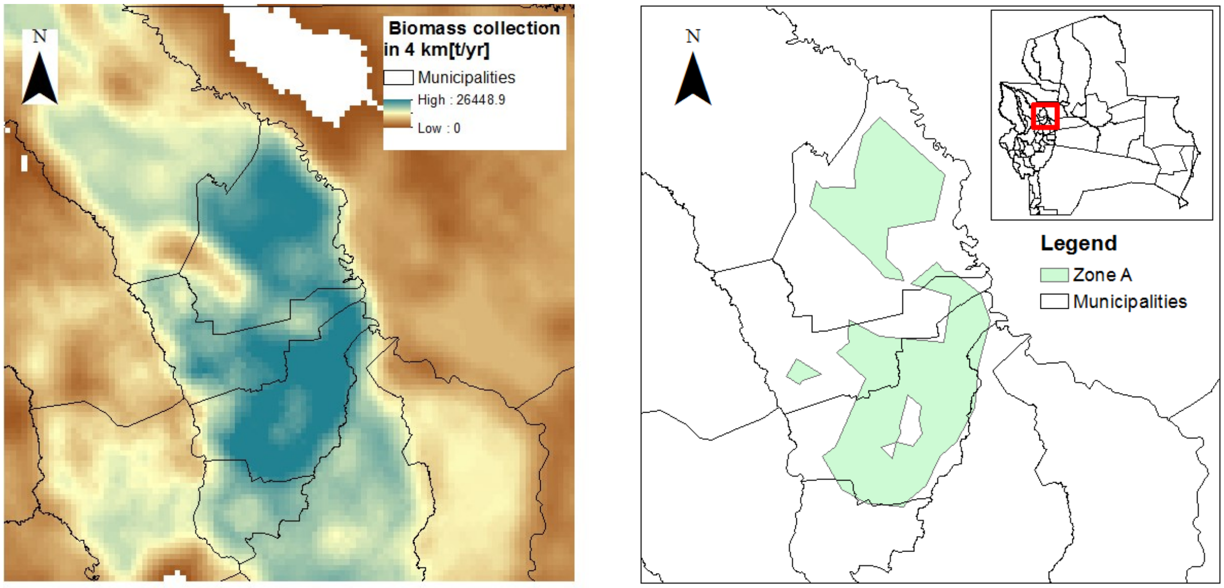


Figure 3-7: Intensity map showing the potential to concentrate biomass in a circular area with a 4 km radius

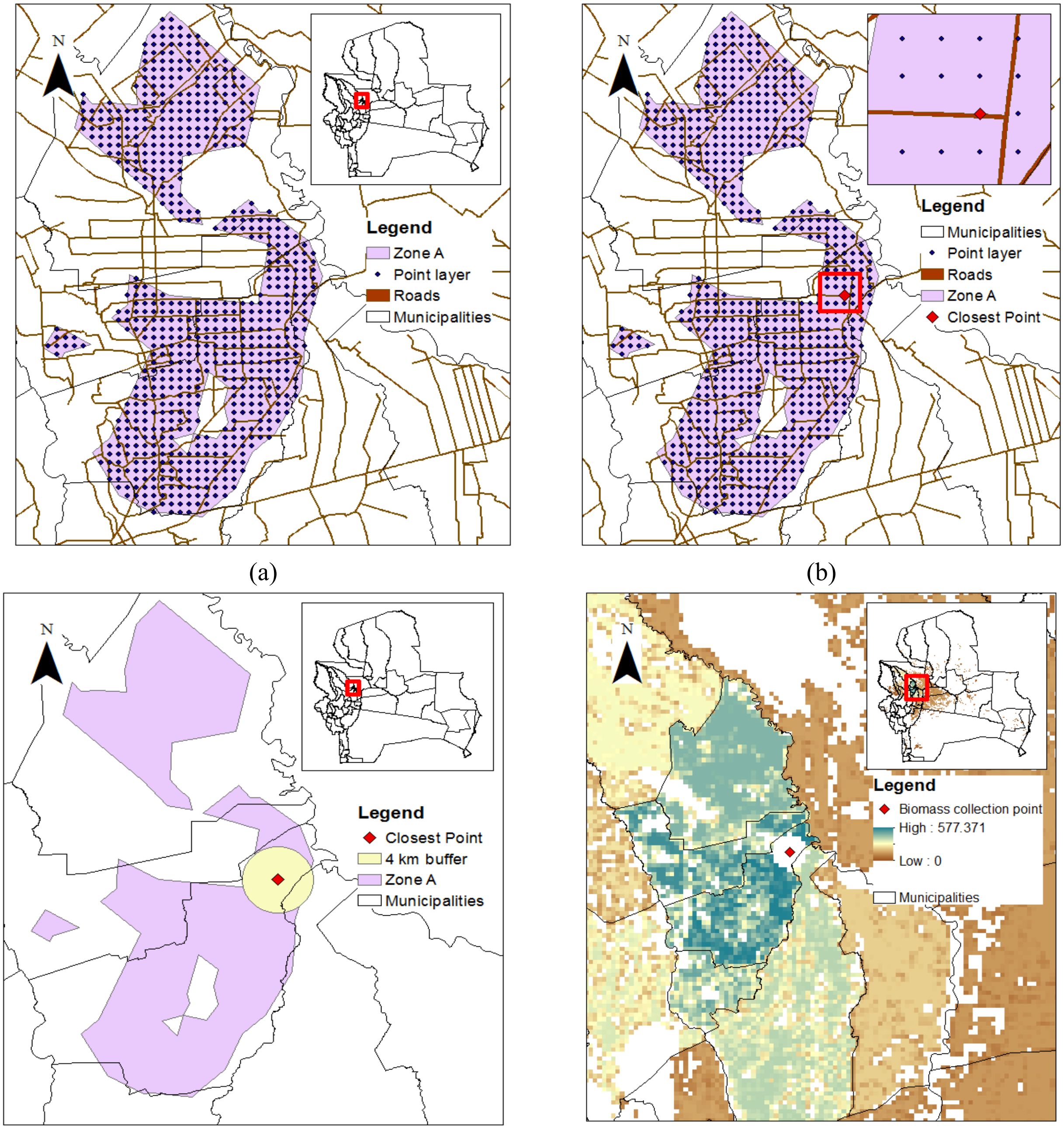
From this map, a zone with high capacity to collect biomass was selected in every iteration. In this study, zone A includes quadrants in which more than 20,000 tonnes of biomass can be collected; zone B, quadrants in which more than 15,000 tonnes can be collected; and zone C, quadrants in which more than 10,000 tonnes can be collected. Initially, the iteration process selected zone A (see Figure 3-8), and it continued to select zone A until there were no more quadrants available with the potential to collect more than 20,000 tonnes of biomass.



(a) (b)

Figure 3-8: (a) Intensity map showing areas with high potential to collect biomass, (b) selected zone with the capacity to collect more than 20,000 t of dry biomass per year

After zone A was selected, a central point was created inside each cell that belongs to zone A. The distance from each point to the closest road was calculated, and the model chose only a single point, the one with the shortest distance to roads. A buffer with a 4 km radius was created around the chosen point and the cell values in the biomass availability map (values of biomass availability in dry t/yr per cell) falling inside the buffer area were converted to 0, simulating the collection of biomass in that circular area. The steps followed in the first iteration are illustrated in Figure 3-9.



(a) (b)

(c) (d)

Figure 3-9: Steps followed for the first iteration in locating BCPs: (a) potential collection points in zone A, (b) selection of the first collection point closest to the road, (c) circular area from where biomass is accumulated and taken to t the central point, and (d) new biomass availability map showing the circular area around the first collection point, which simulates the biomass collection in the middle of the circular area

After considering all the possible quadrants with the capacity to collect more than 20,000 tonnes of biomass, zone B was selected and the same algorithm as for zone A was used. The iteration process was similarly applied to zone C. A map joining all the BCPs located at each iteration was further used in the location-allocation analysis.

3.3.2.2 Locating the conversion facility candidate sites

Geospatial data were used to determine the most suitable sites to locate/build the conversion facilities. ArcGIS allows the user to visualize and modify geospatial data that represent geographic features (e.g., roads, rivers, boundaries, land cover, etc.) on maps; these data were collected from GeoBolivia, a geoportal that provides public access to official spatial data of Bolivia [35]. Figure 3-10 shows the geospatial data and the steps taken to process the data in the exclusion and preference analyses. The criteria used for considering the listed environmental and social geographic features in the exclusion and preference analyses were in accordance with previous studies [5, 11, 36] and proper characteristics of the country (e.g., type of land property) that influence the conversion facility location.

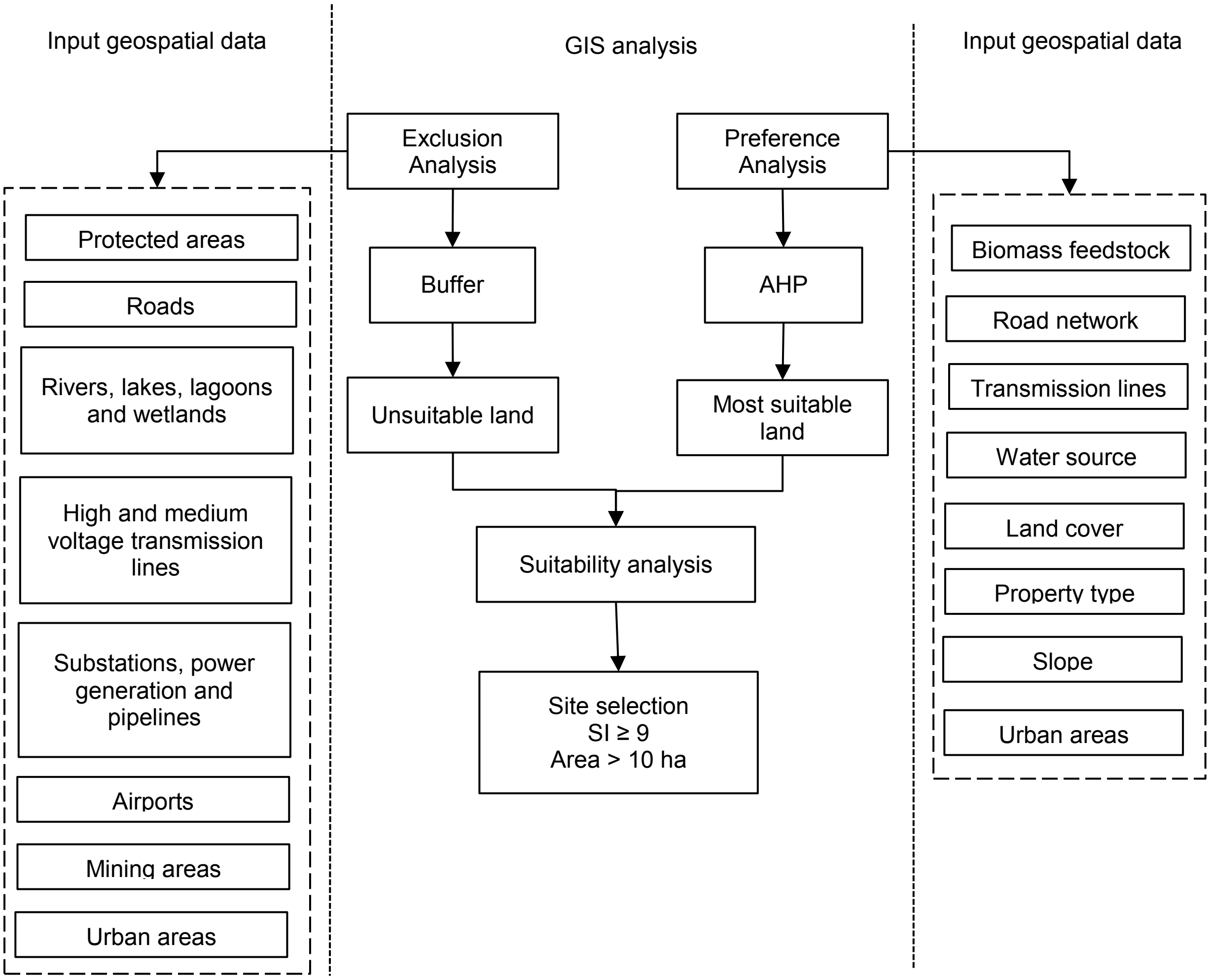


Figure 3-10: Overall methodology for locating suitable sites of conversion facility sites

3.3.2.2.1 Exclusion analysis

The exclusion analysis consists of removing geographic features from the study area. Excluded features include areas where the facility cannot be located, e.g., airports, mining sites, lakes, rivers, etc. Some modifications were made on the feature layers to fulfill the exclusion criteria. For example, airports were edited from points to polygons that included the runway, so that the buffer zone covered appropriately the security area. The second example is the urban areas; they were obtained from the land cover/land use map, but the urban area extent needed to be updated because of its gradual expansion. The layer was changed to cover the entire urban area.

A buffer zone was created for each excluded feature with a dimension that follows safety standards and regulations. For example, Figure 3-11 shows the layer of protected areas and the corresponding buffer zone, which is 5 km.

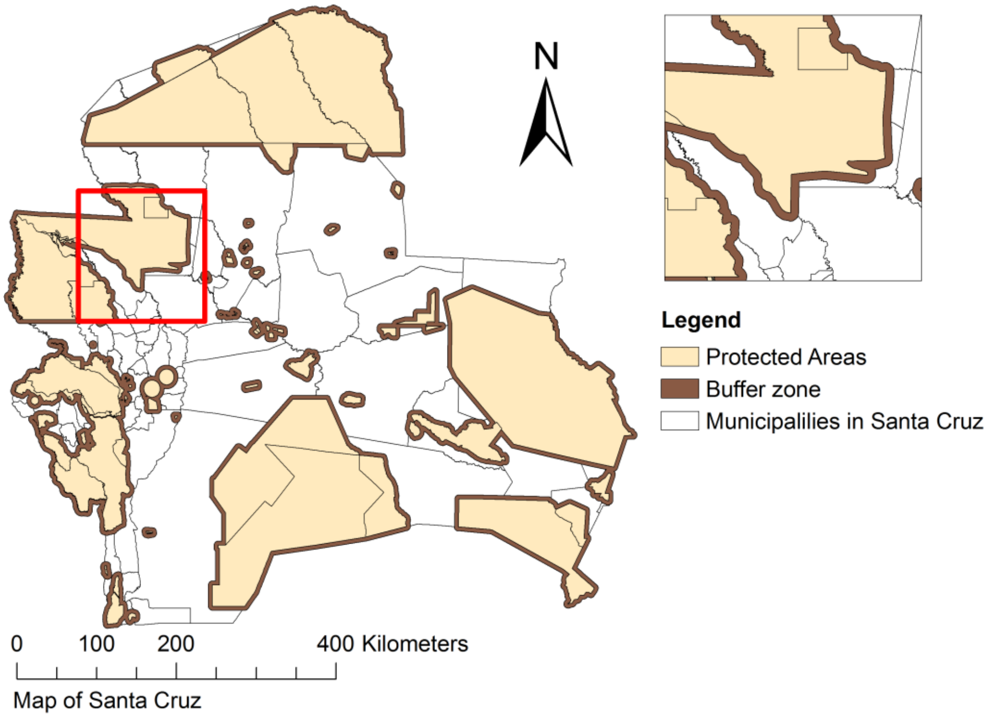


Figure 3-11: Protected areas and buffer region

The multiple features used in the exclusion analysis are detailed in Table 3-1 with corresponding buffer distances. Each excluded feature was created on a separate layer. The excluded feature and its buffer area in each layer had specific attribute data (e.g., road names or river names), and the suitable area had no data. This difference allows the user to convert any attribute data from the excluded areas into 0, and areas having no data into 1. Later, the exclusion layers were overlaid into a single binary raster file with cell values of 0 or 1, indicating non-suitable ("0" for areas inside buffer borders) and suitable ("1" for areas outside the buffer border) sites for conversion facilities as expressed by:

$$E_{i,j} = \begin{cases} 0, & if\ e_{i,j} = Data\ (excluded\ site, inside\ buffer\ borders) \\ 1, & if\ e_{i,j} = No\ data\ (suitable\ site, outside\ buffer\ borders) \end{cases} \tag{3-2}$$

where $\mathbf{i}, \mathbf{j}$ are the indices of every 30 x 30 m cell in the study map, $\mathbf{e_{i,j}}$ is any attribute information in each cell associated to the individual exclusion maps, and $\mathbf{E_{i,j}} = 0$ or 1 is the cell value in the exclusion map (after combining individual excluding layers). The rationale is to attribute the value 0 to the cells that are occupied by any restricted feature and 1 if the cell is vacant.

Table 3-1: The multiple constraints used for the exclusion analysis with corresponding buffer distances

Restriction	Shapefile name, year	Minimum distance	Buffer distance source
Protected areas	National protected areas, 2015	5,000 m	[3]
	Departmental protected areas, 2015		
	Municipal protected areas, 2015		
	Private Reserve of Natural Heritage - agrarian superintendency, 2002		
	Private Reserve of Natural Heritage - forestry superintendency, 2002		
	Forest reserves, 2002		
Rivers, lakes, lagoons and wetlands	Lakes and lagoons, 2006	150 m	[37]
	Rivers, 2002		
	Wetlands, 2009		
Transmission lines	High voltage electrical network, 2016 (230kV, 115kV, 69kV)	100 m	[38, 39]
	Medium voltage electrical network, 2016	30 m	
Roads	Secondary roads, 2016	50 m	[21]
	Main roads network, 2002	50 m	[21]

Restriction	Shapefile name, year	Minimum distance	Buffer distance source
Industrial and mining	Mining concessions, 2005	1,000 m	[40]
Airport	Airports, 2016	1,000 m	[41]
Substations	Electrical substations, 2016	50 m	[42]
Power generation	Electrical generation, 2015	50 m	[42]
Natural gas and oil pipelines	Pipelines, 2016	100 m	[17]
Urban areas	Edited from land cover map, 2001	300 m	[43]

3.3.2.2.2 Preference analysis

The preference analysis identifies areas of higher priority to locate the facility. This analysis is divided into two stages: stage one consists of assigning priority values to multiple-buffer rings around geographic features (e.g., biomass source, road networks, transmission lines, water source, and urban area) or assigning the values to specific areas (e.g., land cover type, land property type, and slope). This study assigned priority values on a scale of 1 to 10, as has been done in other studies [5, 11, 36]: 10 for areas with highest priority and 1 for areas with lowest priority. The assigned priority values for this study are listed in Tables 3-2 - 3-8. The multi-buffer ring region covers a fixed distance of 5 km from corresponding features, and this region is composed by 5 rings, whose distances were established based on an equal interval classification method. The same buffer region was previously considered by Khan [36]. The rationale behind defining this distance depends on the most suitable sites available in the combined preference map (see the second stage). If this map has no sites or has broad sites with high suitability index values (e.g., 9 or 10), the multi-buffer ring region should be increased or decreased, respectively.

Figures 3-12 to 3-19 show individual preference maps for every geographic feature analyzed in this stage and corresponding priority values.

In the second stage, the eight maps generated previously were combined into a single preference map. Since the features analyzed vary in significance, the analytical hierarchy process (AHP), introduced by Saaty (1980) [12] as a multi-criteria decision-making method, was followed to calculate the weight of each geographic feature. The first step in the AHP is to develop a pairwise comparison in a matrix table, in which the 1-9 scale of relative importance is used. The feature with low preference receives a value of 1 and the other feature can receive a value from 1 to 9, depending on its relative importance compared to its pair: 1 if both features have the same importance, and 9 if the feature is considerably more important than the other. Following the AHP method, mathematical operations in the matrix table were applied to find the weight values, and further parameters (e.g., eigenvector, relative weight, consistency ratio) were calculated to verify the validity of corresponding weight values. The feature layers were then combined with respective weight values to obtain the preference map (see Equations [3-3] and [3-4]).

$$\sum_{k=1}^{k=N} w_k = 1 \tag{3-3}$$

$$P_{i,j} = \sum_{k=1}^{k=N} w_k \cdot p_{i,j}(k) \tag{3-4}$$

where i, j = are the indices of every 30 x 30 m cell in the map, $P_{i,j}$ can take values from 0 to 10 and are the cell values in the preference map, k = 1 to 8 are the indices for the preference layers generated, N = 8 is the total number of layers, w_k is the weight value obtained from the AHP method, each layer (k) has a specific w_k value from 0 to 1, and $p_{i,j}(k)$ are preference values in each cell that depend on the individual feature layer (k) and can take values from 0 to 10.

3.3.2.2.2.1 Preference analysis of biomass sources

Proximity to the biomass sources is one of the most important factors in locating a biomass-based conversion facility since short distances decrease transportation costs. The agricultural map, extracted from the land cover/land use map of Bolivia [35], was used as the biomass source map. Table 3-2 shows priority values of different areas depending on the proximity to biomass sources, and Figure 3-12 shows the multiple buffer rings created for biomass sources. Higher priorities were given to shorter distances to biomass sources.

Table 3-2: Priority values based on distance from biomass sources

Distance from croplands [m]	Values
0 – 1,000	10
1,000 – 2,000	8
2,000 – 3,000	6
3,000 – 4,000	4
4,000 – 5,000	2
> 5,000	1

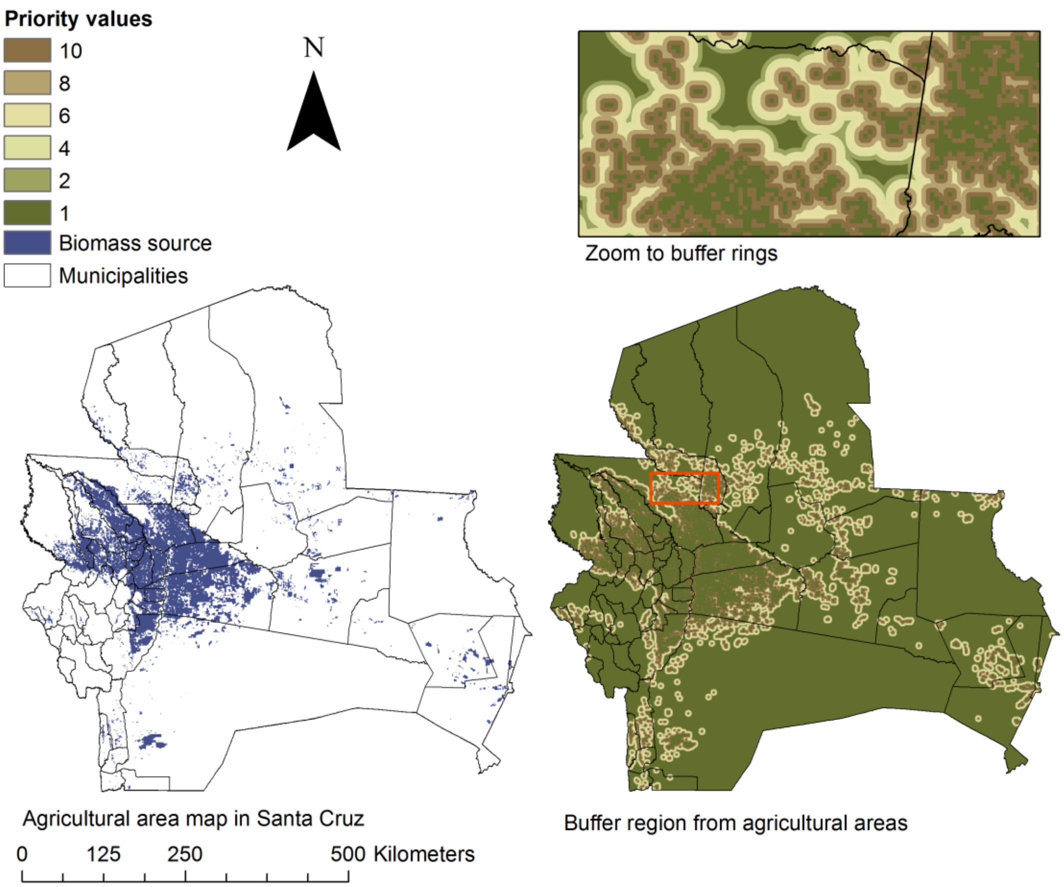


Figure 3-12: Intensity map showing priority values for sites around the biomass source area

3.3.2.2.2.2 Preference analysis of roads

The roads are classified in two groups: main roads and secondary or dirt roads. Both were included in the preference analysis. The multiple buffer rings consist of assigning higher values to areas closer to roads, as has been done in previous studies [5, 10, 11]. In this study, we are assuming that areas close to main roads are given 20% more preference than areas close to secondary roads because it is more convenient to locate the facility close to main roads, where trucks can more easily travel to deliver the biomass. Table 3-3 shows corresponding values depending on proximity to roads, and Figure 3-13 shows the multiple rings, giving the highest priority values to areas closer to main roads.

Table 3-3: Priority values based on distance from road network

Distance from main and secondary roads [m]	Values
0 - 1,000	10
1,000 - 2,000	8
2,000 - 3,000	6
3,000 - 4,000	4
4,000 – 5,000	2
>5,000	1

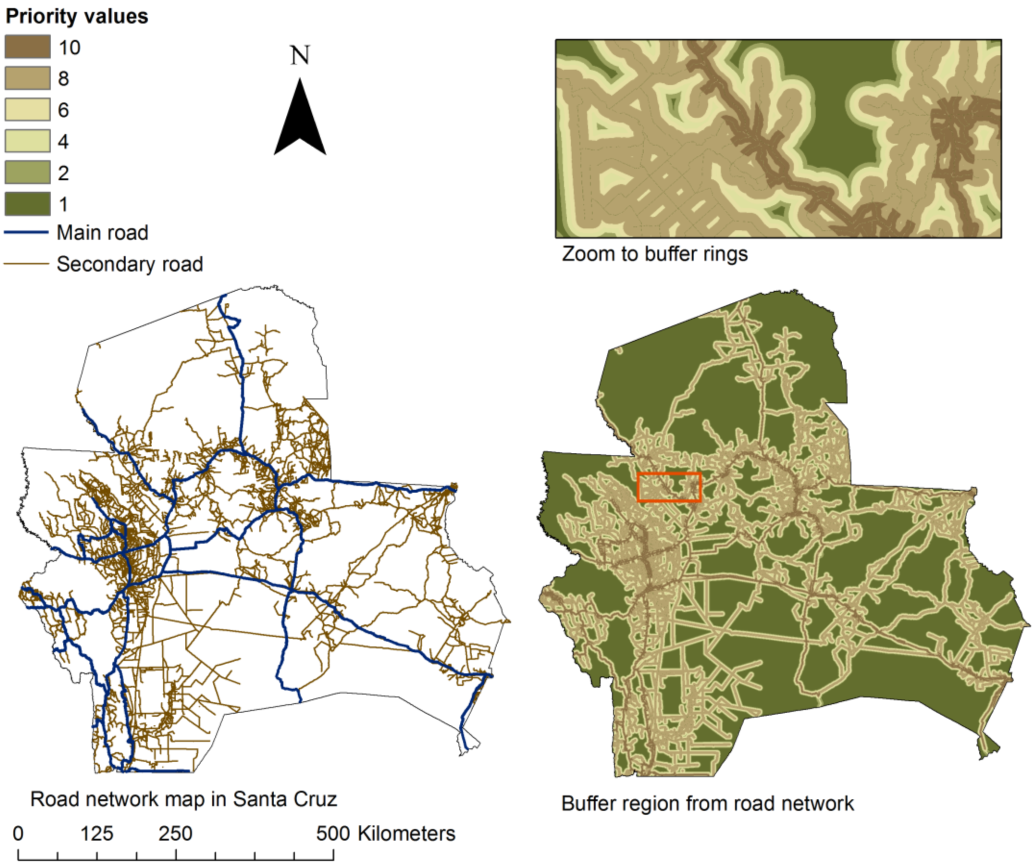


Figure 3-13: Intensity map showing priority values for sites around the road network

3.3.2.2.2.3 Preference analysis of urban areas

In this case, priority was given to land farther from urban areas since the pollutants emitted by biomass-based conversion facilities can spread easily over several kilometers [44]. Therefore, distances farther from urban areas were preferable to avoid harm to public health. Corresponding preference values are listed in Table 3-4, and Figure 3-14 shows preference values based on the proximity to urban areas.

Table 3-4: Priority values based on distance from urban areas.

Distance from urban areas [m]	Values
1 – 1,000	2
1,000 – 2,000	4
2,000 – 3,000	6
3,000 – 4,000	8
> 4,000	10

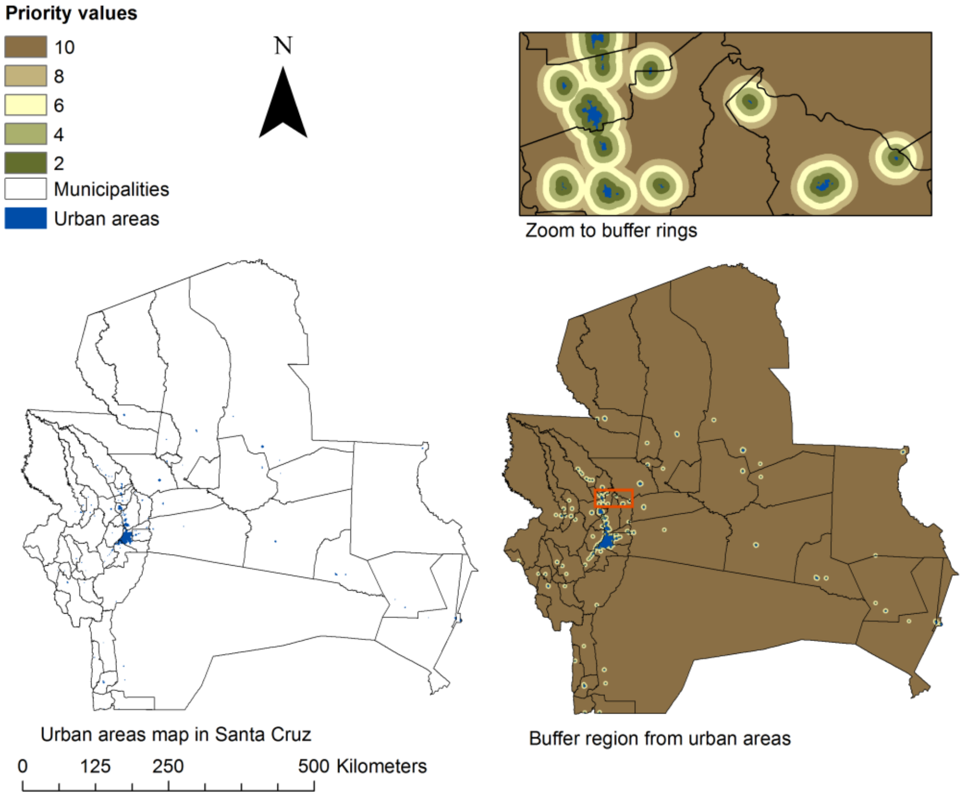


Figure 3-14: Intensity map showing priority values for sites around urban areas

3.3.2.2.2.4 Preference analysis of transmission lines

Transmission lines are important in establishing a biomass-based facility. They provide electricity to the facility and could be used to transfer and distribute electricity if the facility generates power. Transmission lines are classified as medium (11-25 kV) and high voltage (69 - 230 kV) [38, 39, 45]. Electric power is normally generated at 11-25 kV at a power station [46], and substations are used to step up the voltage if the electricity generated needs to be transferred a long distance. The higher the voltage on a transmission line, the smaller the fraction of energy lost in transit [47]. Depending on the transfer distance and the output voltage, the preference towards the transmission type (i.e., high or medium voltage) might change. However, in this study, the same preference values were given to both high and medium transmission lines. Table 3-5 lists priority values based on distances from transmission lines, giving high values to closer areas. Distances from transmission lines and priority values were determined from Khan (2015). Figure 3-15 shows the network system of transmission lines and corresponding multiple buffer rings.

Table 3-5: Priority values based on distances from transmission lines.

Distance from transmission lines [m]	Value
0 - 1,000	10
1,000 - 2,000	8
2,000 - 3,000	6
3,000 – 4,000	4
4,000 - 5,000	2
>5,000	1

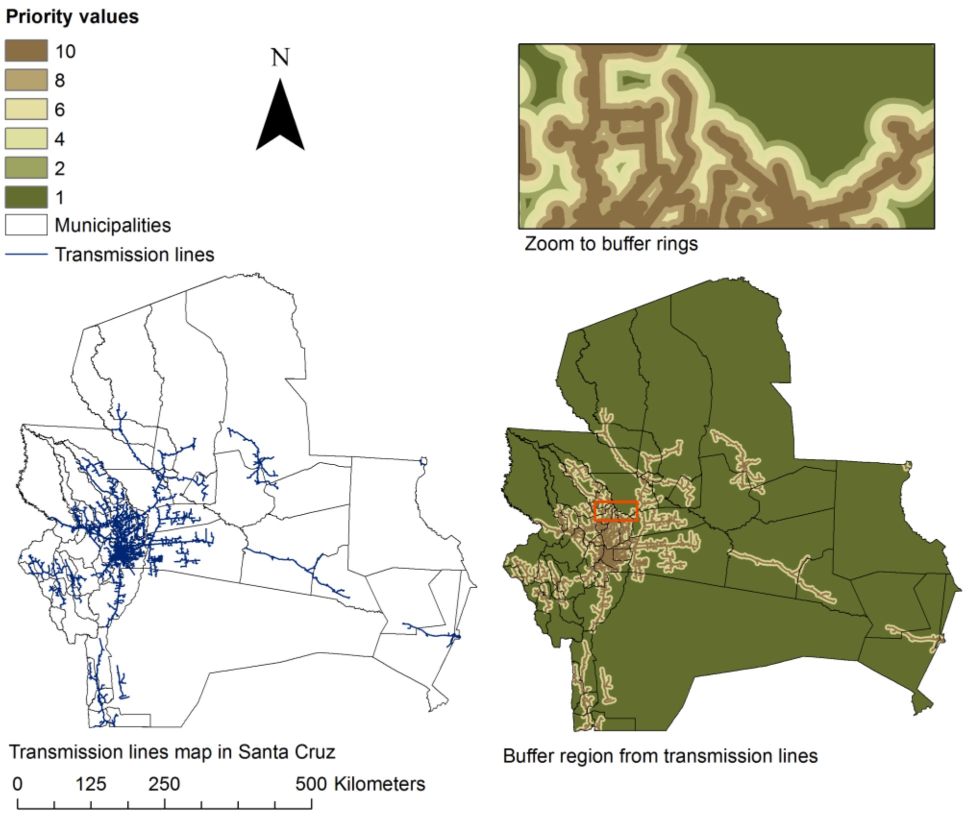


Figure 3-15: Intensity map showing priority values attributed to areas around transmission lines

3.3.2.2.2.5 Preference analysis of slope

The digital elevation model (DEM) database [35], which is a representation of the altitude data of the terrain's surface, was used to obtain the slope map by converting altitude data into slope data in degrees using ArcGIS. Previous studies considered that low slope values are preferable for building a conversion facility [5, 36]. A priority value of 10 was assigned to areas with slopes less than 15° and 1 for slopes greater than 15° (see Equation 3-5). The southwest side of the department received a value of 1 and some spread small regions, as shown on Figure 3-16.

$$ps_{i,j} = \begin{cases} 10, & if\ s_{i,j} < 15° \\ 1, & if\ s_{i,j} \geq 15° \end{cases} \tag{3-5}$$

In Equation 3-5, i, j are the indices of every 30 x 30 m cell in the slope map, $s_{i,j}$ are the slope values in every cell, and $ps_{i,j}$ = 1 or 10 are the cell values after the slope condition was applied.

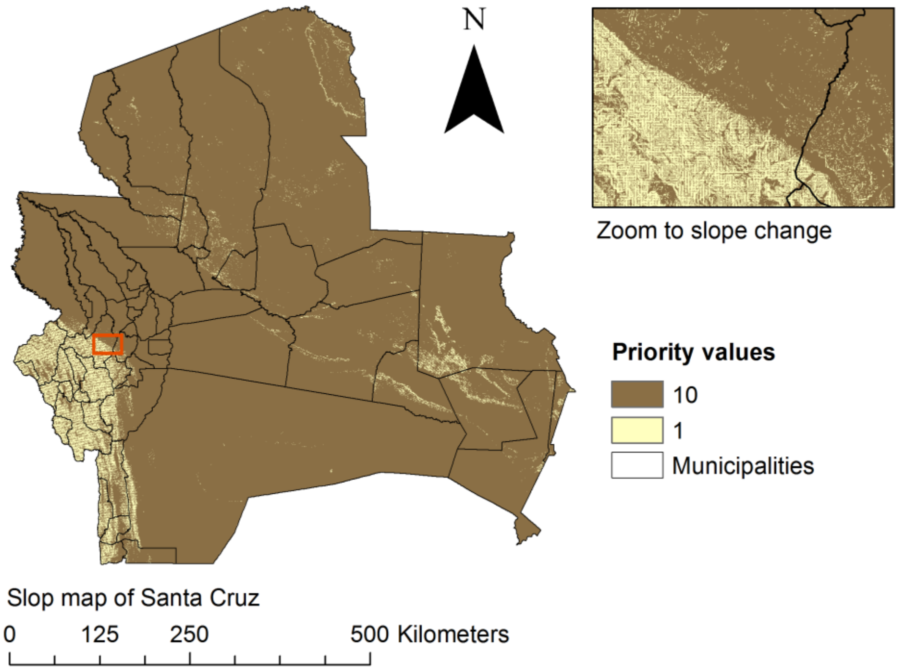


Figure 3-16: Map showing priority values for sites based on slope degree

3.3.2.2.2.6 Preference analysis of water availability

The availability of water is necessary not only in the facility for basic service and conversion processes but also for crop irrigation and yield improvement [5]. Even though most industries use underground water after appropriate physical and chemical treatment [48, 49], it is not possible to ensure underground water availability across the entire study area. Here, water is assumed to be supplied from rivers or lakes. On Table 3-6, higher values are given to places closer to water sources. Figure 3-17 shows multiple buffer rings around rivers and lakes and corresponding priority values.

Table 3-6: Priority values based on distances from water sources.

Distance from water source [m]	Value
0 - 1,000	10
1,000 - 2,000	8
2,000 - 3,000	6
3,000 - 4,000	4
4,000 - 5,000	2
>5,000	1

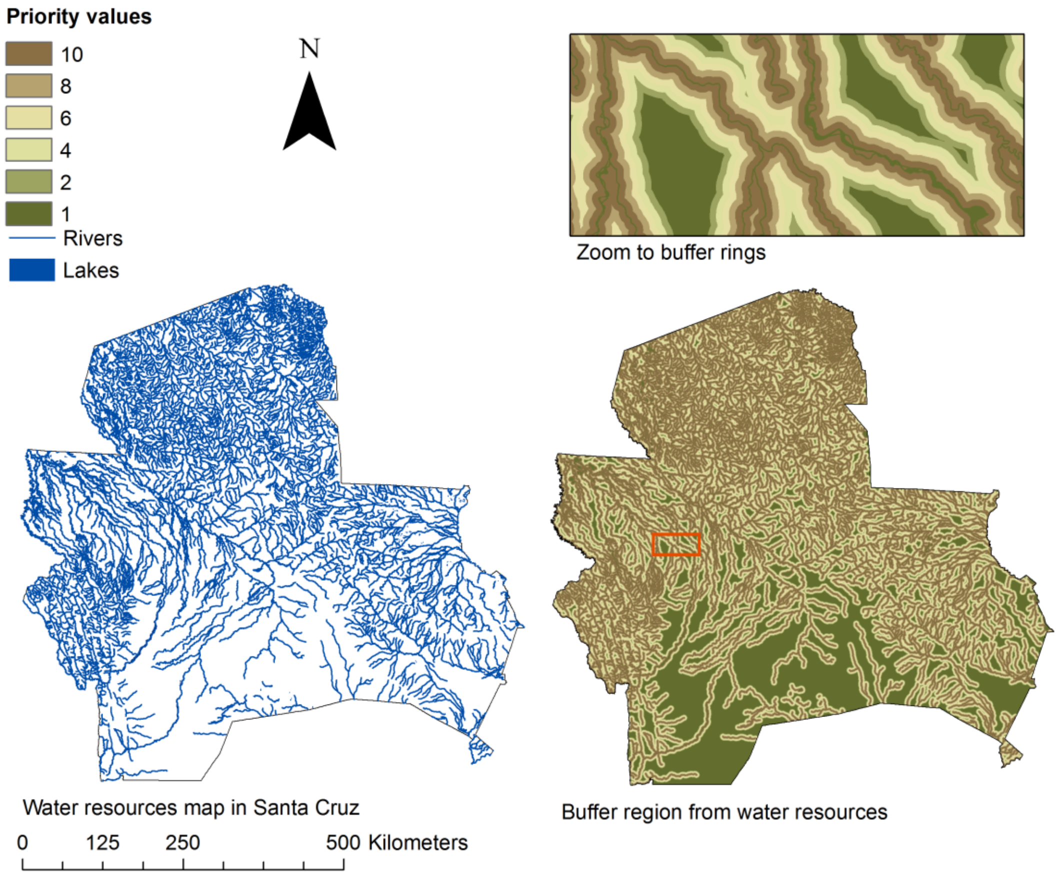


Figure 3-17: Intensity map showing priority values attributed to sites around water sources.

3.3.2.2.2.7 Preference analysis of agrarian property type

Priority values were assigned to the land based on the type of agrarian property, which was set by the National Institute of Agrarian Reform (Instituto National de Reforma Agraria [INRA]) [50]. The INRA [51] law stablished ways to distribute land depending on location, size, and use. For example, some areas cannot be used for commercial revenues [50]. Table 3-7 shows the type of agrarian property together with a brief description and corresponding priority values Figure 3-18 shows the spatial location of different agrarian properties and their priority values.

Table 3-7: Priority grades for types of agrarian property.

Type of land property	Description	Characteristics	Value
Solar farmer	Farmer's residence	The land can be sold. Land tax payment is not required.	3
Small property	The land is worked by the farmer and family. Resources are for subsistence	The land can be sold. The owner does not pay land tax. Size: 0-50 ha	7
Community property	Land collectively titled to communities for their subsistence	The land cannot be sold, nor divided. Land tax payment is not required.	1
Original community lands or Indigenous territories	Land for indigenous communities.	Land cannot be sold. Land tax payment is not required.	1
Medium-sized property	Land where salaried employees and machinery produce goods for market	Land can be sold. Owners pay land tax. Size: 50-500 ha	10

Type of land property	Description	Characteristics	Value
Properties for large agricultural production	Properties with salaried employees and modern machinery for production.	It can be sold. Owners pay land taxes.	10

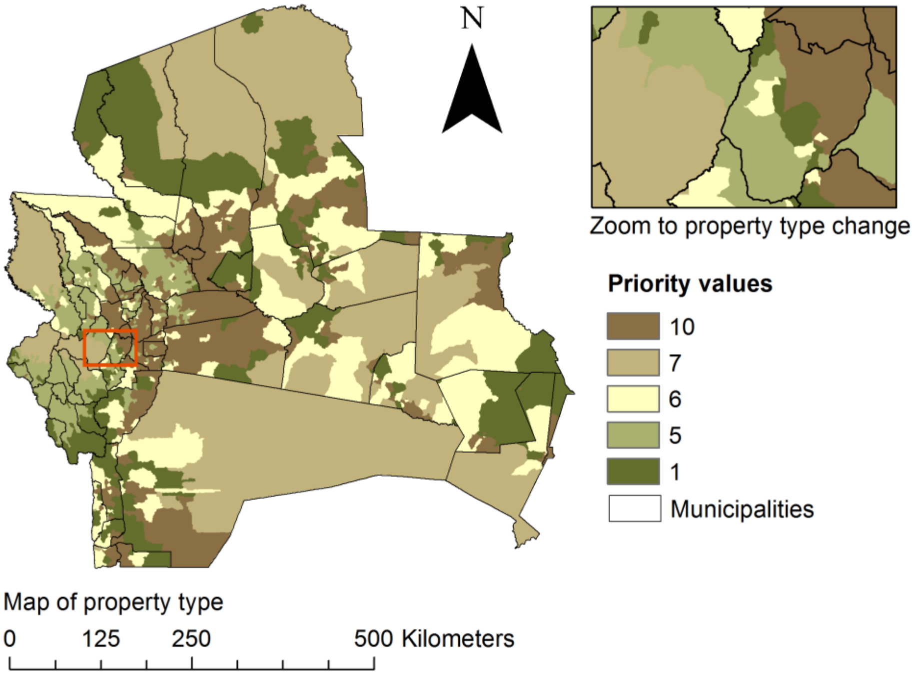


Figure 3-18: Intensity map showing priority values based on property type

3.3.2.2.2.8 Preference analysis of land-cover type

The land-cover map classifies the terrestrial surface based on biophysical properties (e.g., urban area, vegetation, grasslands). The priority values listed in Table 3-8 are assigned based on the type of surface cover. High values were given to land with appropriate characteristics for building a facility (e.g., grasslands) [5, 36].

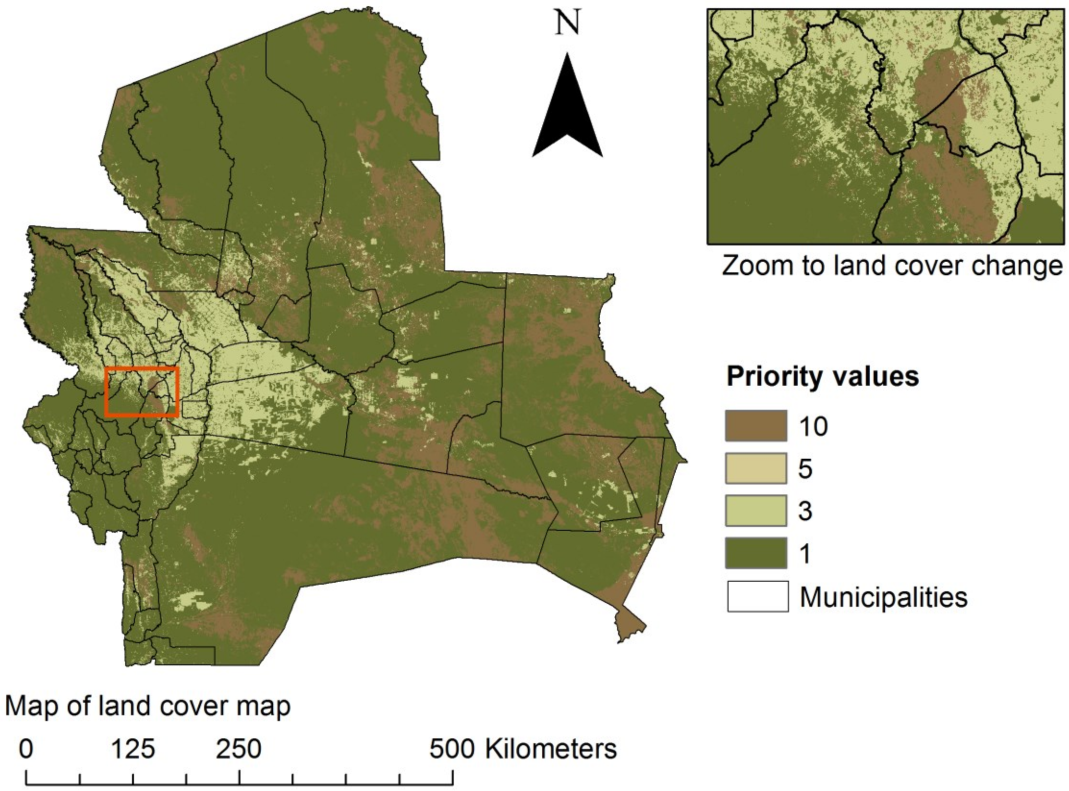


Figure 3-19 shows the spatial location of preferable areas according to the surface cover.

Table 3-8: Priority grades for types of land cover.

Type of surface cover	Value
Urban and rural areas/Sand dunes/Water bodies	1
Dense forest: Amazon, Andean, Chaco, Chiquitano	2
Forest	3
Agriculture	4
Shrubland/Vegetation	5
Agro industry/Commercial plantations	6
Grasslands	10

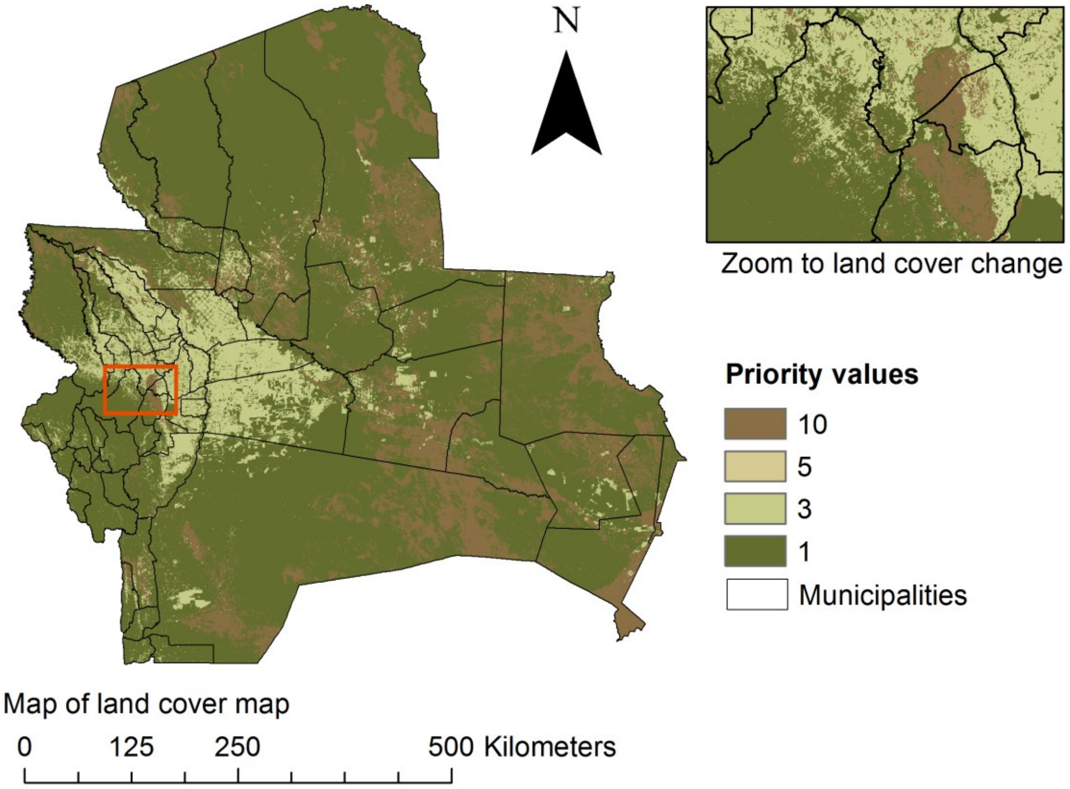


Figure 3-19: Intensity map showing priority values attributed to sites depending on the type of land cover

3.3.2.2.2.9 Suitability analysis

The suitability analysis gives information on the most suitable sites to locate biomass-based conversion facilities. In order to create the suitability map, both exclusion and preference maps are combined. Since the exclusion map is a raster file with cell values of 1 or 0, and the preference map is also a raster file with cell values ranging from 0 to 10, a multiplication at the cell level was calculated using Equation 3-6:

$$SI_{i,j} = E_{i,j} \cdot P_{i,j} \tag{3-6}$$

where i, j are the indexes of every 30 x 30 m cell in the suitability map, $E_{i,j}$ = 0 or 1 are cell values in the exclusion map, $P_{i,j}$ are cell values in the preference map and can take a value from 0 to 10, and $SI_{i,j}$ are cell values in suitability map and can take a value from 0 to 10.

Cells with values of 9 and 10 were selected from the suitability map. These cells are the most suitable areas to locate conversion facilities. Assuming that the minimum area required to build a conversion facility is 10 ha and the minimum distance between facilities is 10 km [5], centroid points in each suitable area were located to represent candidates sites for biomass conversion facilities.

3.3.2.3 Optimal biomass-based conversion facility location

The location-allocation analysis, a type of network analysis, was used in this stage to determine optimal facility locations, the ones with minimal transportation distance between biomass source and facility. Three elements – supply, demand, and network – are required for the location-allocation analysis (see Figure 3-20). The supply points are the BCPs, the demand points are the facility candidate sites, and the network is the actual road network. Only some of the candidate sites form part of the solution because the network analysis identifies optimal sites. The network dataset was created using the actual road network map [35], which was updated using the world basemap, a map service from ArcGIS, to increase the connection options between supply and demand points.

Actual biomass-based energy facilities have a broad capacity range [32, 52]. Since 50 MW is the average capacity of most combustion-based facilities [53], the biomass demand is around 230,000 t per facility (assuming a low heating value of 16 MJ/kg [53], 30% plant efficiency [27-

30], and 0.72 capacity factor [31, 33]). The number of facilities is determined based on this facility demand and the total biomass that can be collected in all BCPs.

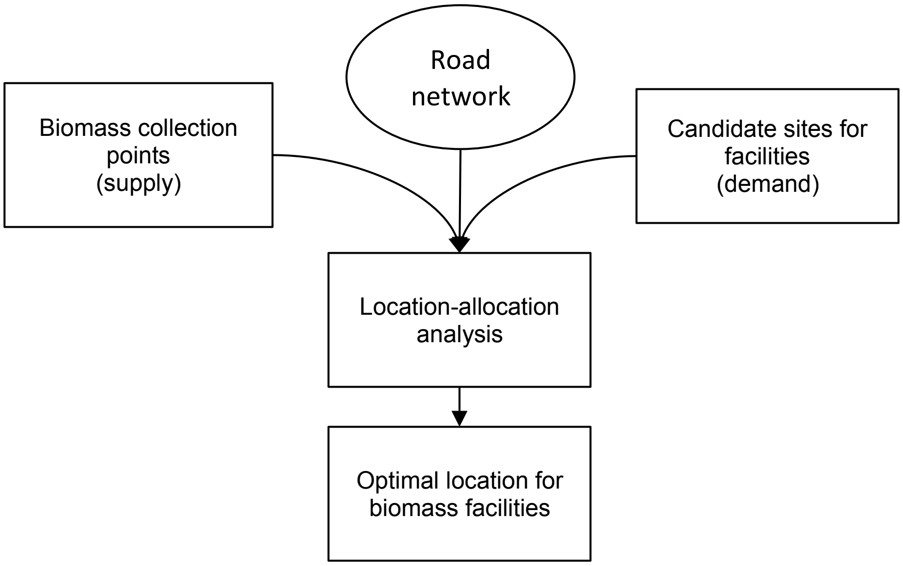


Figure 3-20: The overall process of selecting optimal conversion facility sites

3.3.3 Results

3.3.3.1 Location of BCPs

The framework developed in this study was applied to the study case, Bolivia. The areas with high potential to collect biomass are located in a few municipalities in the central west side of the Santa Cruz Department. The iterative algorithm classified three different zones based on the capacity to collect biomass. The biomass accumulated in each collection point in thousand dry tonnes per year in zones A, B, and C is 20-25, 15-20, and 10-15, respectively (see Figure 3-21).

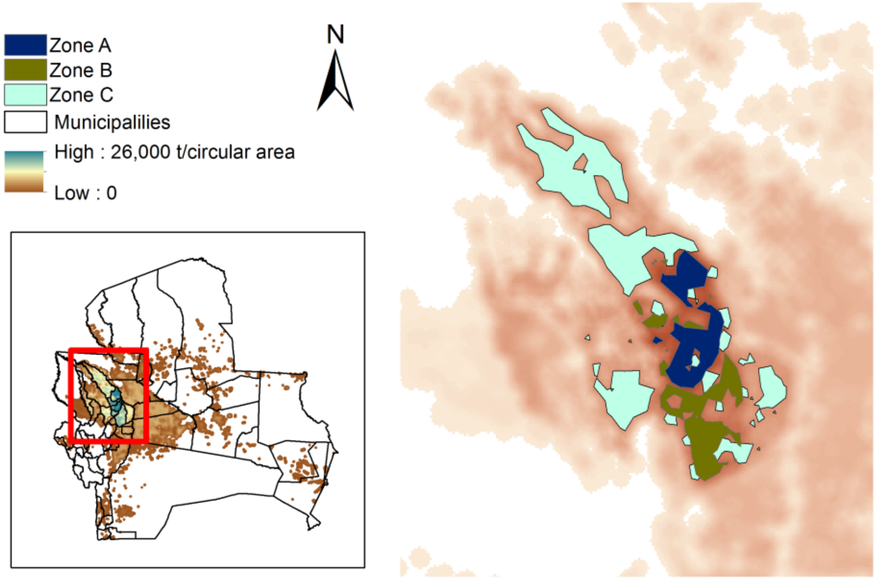
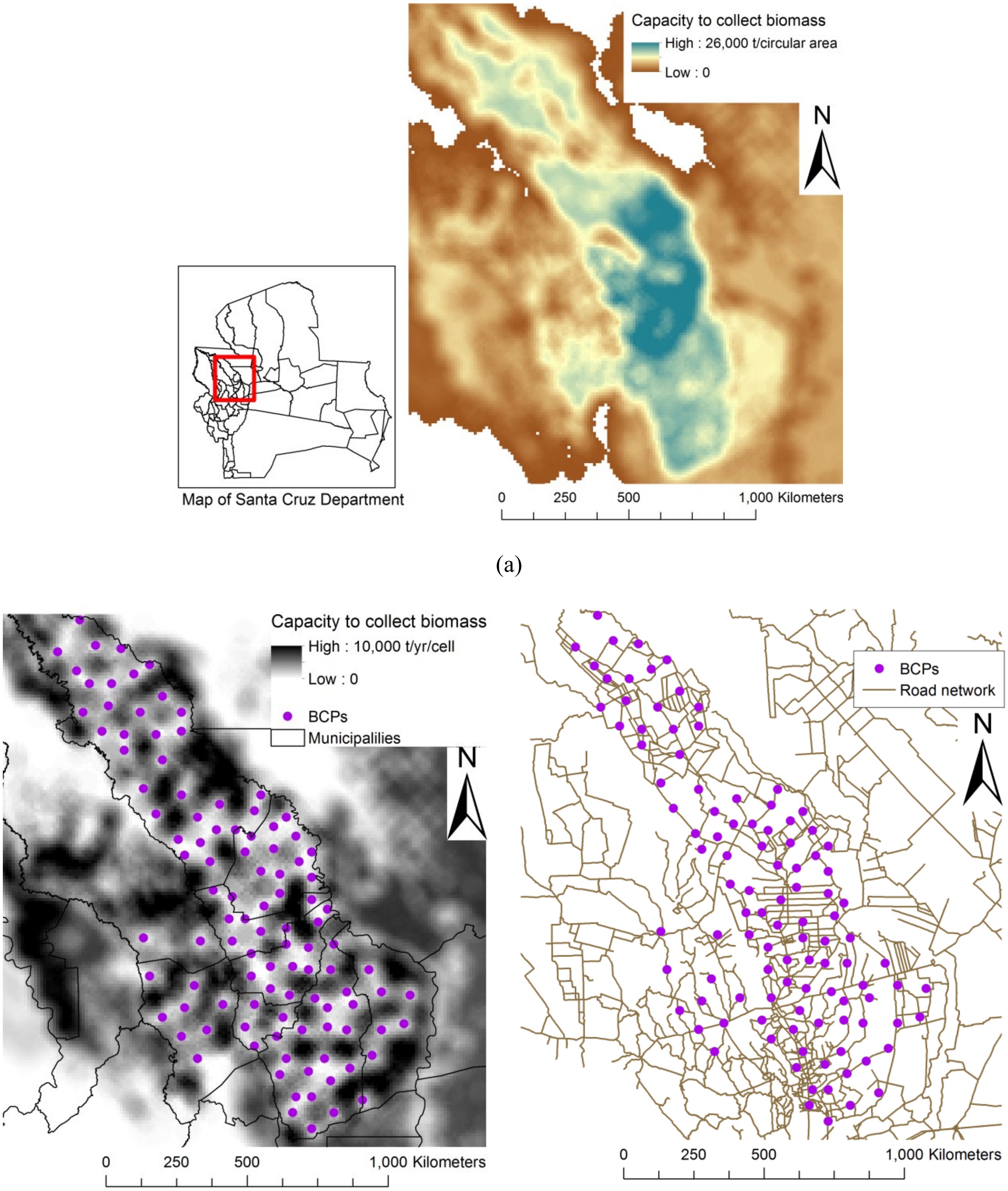


Figure 3-21: Classification of zones based on biomass availability

The iteration process used here was developed by giving priority to high biomass availability and short distance to the roads. Figure 3-22 (a) shows the areas with high potential to collect biomass, and Figure 3-22 (b) shows that following the iterative process, the potential is reduced by 38%. 107 BCPs were sited. The white area around each collection point represents the removal of biomass to the central point. Figure 3-22 (c) verifies the criteria set in the iterative process for prioritizing short distances to roads, that is, that all collection points are right beside roads.



(a)

(b)

(c)

Figure 3-22: Maps showing the location of BCPs giving priority to biomass availability and road network: (a) areas with higher capacity to collect biomass, (b) representation of the biomass removal to central collection point, and (c) BCPs located near roads

An important advantage of the model for locating BCPs is that it considers that biomass availability is not constant and does not have a geometric pattern. It decreases radially from the dark green area (see Figure 3-22 [a]) but not proportionally. Moreover, the model also considers the second priority criterion, the road network, which does not have a grid pattern (see Figure 3-22 [c]), but BCPs are located close to roads for truck accessibility.

BCPs accumulate different amounts of biomass. A few BCPs accumulate a significant portion of the total biomass availability, as shown in Table 3-9, which summarises the information obtained from the iterative process. The estimated dry biomass potential in the Department of Santa Cruz is 3.7 million tonnes per year [25]. The total biomass collected through the iterative process is estimated to be 1.5 million tonnes per year, or 40% of the total biomass availability.

Table 3-9: Summary of collection points by zone

Zone	Biomass collection range [t]	Number of collection points	Biomass collected [t]
A	20,000 - 26,000	17	367,561
B	15,000 - 20,000	24	383,678
C	10,000 - 15,000	66	740,143
Total	**10,000 - 25,000**	**107**	**1,491,382**

3.3.3.2 Location of candidate sites for biomass-based energy facilities

Candidate sites were located in the most suitable areas after exclusion and preference analyses were performed and the resulting maps were combined. The exclusion map is shown in Figure

3-23 (a). Most of the removed areas are protected areas. The preference analysis considered several geographic features (see Figure 3-10), and an individual map for each geographic feature was created (see Figure 3-12 to 3-19). Then, all the individual maps were merged into a single map. To combine these maps, a weight value was assigned to each geographic feature. The weight values were calculated following the AHP method, which requires pair-wise comparison of each geographic feature in pairs. The comparison is shown in Table 3-10 in a matrix format. The geographic features were placed in the top row and the first column, and the cell values in the table show the relative importance. The importance rank is from 1 (equally important) to 9 (meaning the feature in the left column is considerably more important than the feature in the top row). Values lower than one mean that the feature in the top row is more important than the feature in the left column by the reciprocal of this decimal.

Table 3-10: Ranking of importance by comparing each geographic feature in pairs.

Parameter	Biomass supply	Road	Transmission line	Water availability	Slope	Urban area	Land cover	Type of property
Biomass supply	**1.00**	2.00	5.00	6.00	9.00	6.00	5.00	7.00
Road	0.50	**1.00**	4.00	6.00	8.00	6.00	5.00	6.00
Transmission lines	0.20	0.25	**1.00**	5.00	7.00	6.00	6.00	7.00
Water availability	0.17	0.17	0.20	**1.00**	7.00	5.00	3.00	4.00
Slope	0.11	0.13	0.14	0.14	**1.00**	5.00	0.33	0.50
Urban area	0.17	0.17	0.17	0.20	0.20	**1.00**	0.25	0.25
Land cover	0.20	0.20	0.17	0.33	3.00	4.00	**1.00**	2.00
Type of property	0.14	0.17	0.14	0.25	2.00	4.00	0.50	**1.00**

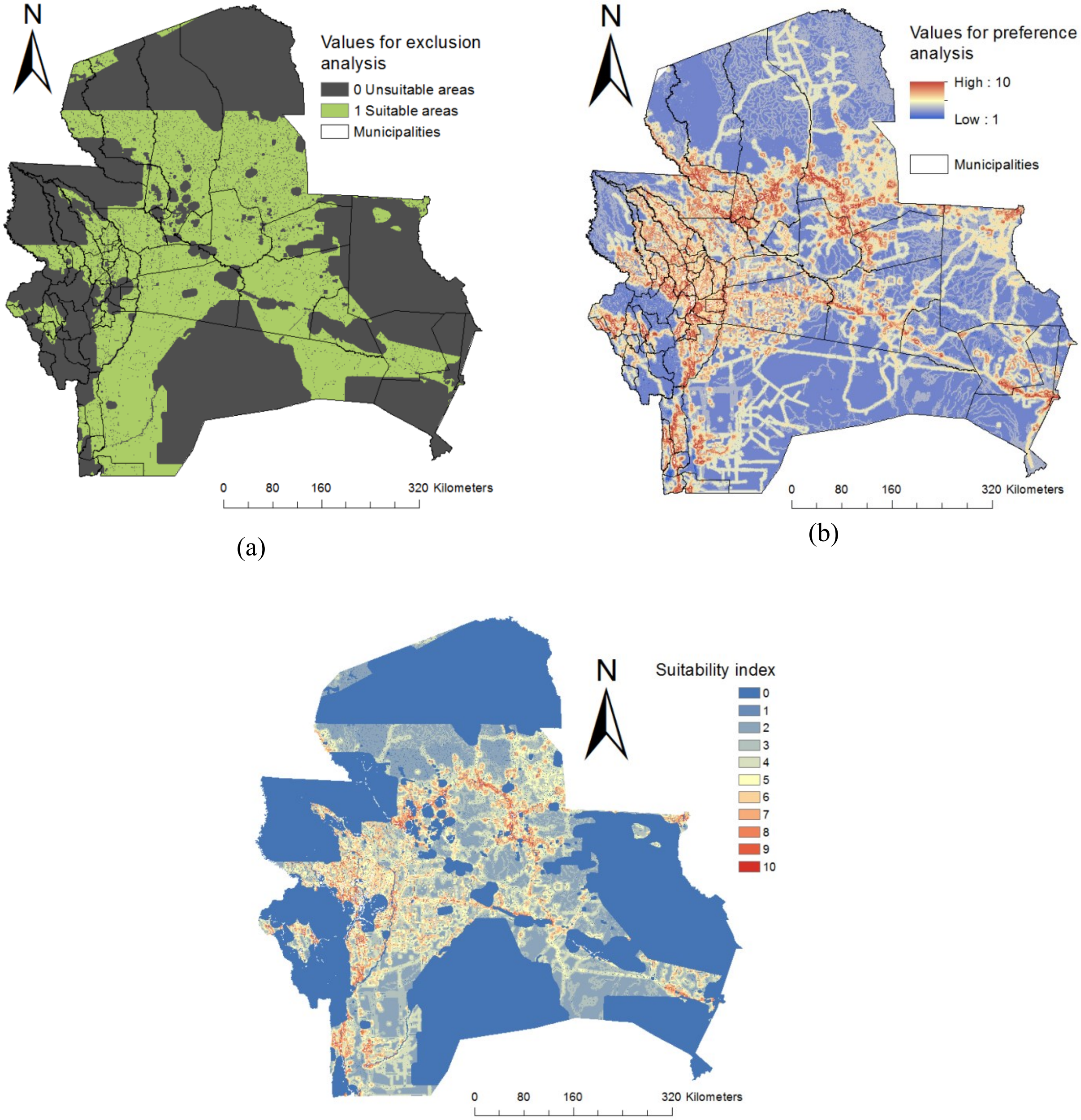
The pair-wise comparison shows that biomass availability and road network have higher importance than all the parameters analyzed. The closeness to agricultural croplands (biomass source) guarantees a sustainable supply of feedstock. The high importance of the road network is because of the facilities' need for feedstock transportation. Also, short distances to transmission lines and water resources are important since the costs to connect the conversion facility to electricity and water supply will be affected by the location of lines/resources. A slope increases building costs and may affect biomass transportation time and costs. Most of the land in Santa Cruz is flat, and the highest slope is in the southwest, far from croplands [54]. For this reason, the slope feature has a low preference value.

This study does not assess a preference towards existing diesel power plants even though a government objective is to offset the consumption of this imported fossil fuel. Diesel is currently used in small capacity power plants to distribute electricity to isolated systems. It would be appropriate to give preference to sites close to diesel-based power plants, so that biomass can replace this fossil fuel; however, the study considers the targets set for 2025 where most of the isolated systems will be interconnected to the grid [55].

Following the AHP method, a series of matrix operations were calculated to find the weight values for each geographic feature analyzed, as shown in Table 3-11.

Table 3-11: Weight values obtained from an AHP

Parameter	Weight value	Parameter	Weight value
Biomass source	0.32	Land cover	0.06
Road network	0.25	Type of property	0.04
Transmission lines	0.17	Slope	0.04
Water source	0.10	Urban areas	0.02



(a)

(b)

(c)

Figure 3-23: Maps in each stage of the process used to identify the most suitable sites to locate biomass-based energy facilities: (a) Exclusion analysis map: representing unsuitable and suitable area, (b) preference analysis map: representing areas with grading priorities, and (c) suitability analysis map: showing areas with suitability indexes (SI)

After maps with corresponding weight values are combined, the resulting preference map (shown in Figure 3-23 [b]) was combined with the exclusion map (Figure 3-23 [a]) to obtain the suitability map (see Figure 3-23 [c]), which shows areas with values from 0 to 10. Unlike the preference map, which shows areas ranked from 1 to 10, the suitability map has a suitability index from 0 to 10. The value “0” in the suitability map is from the screened out areas in the exclusion map.

After the most suitable areas (i.e., those with suitability indexes of 9 and 10) were selected, centroid points were created in the selected areas following two restrictions: areas smaller than 10 ha were removed since 10 ha is assumed to be the minimum area required for a biomass facility, considering the space for biomass storage [5], and 10 km was assumed to be the minimum distance between facilities. The centroid points are the candidate site locations: 1130 sites in 45 municipalities, as shown in Figure 3-24. Six municipalities where large agricultural activity takes place make up 40% of the candidate sites. Other candidate sites were located in a line that matched the main road routes following the criterion of proximity to roads used in the preference analysis.

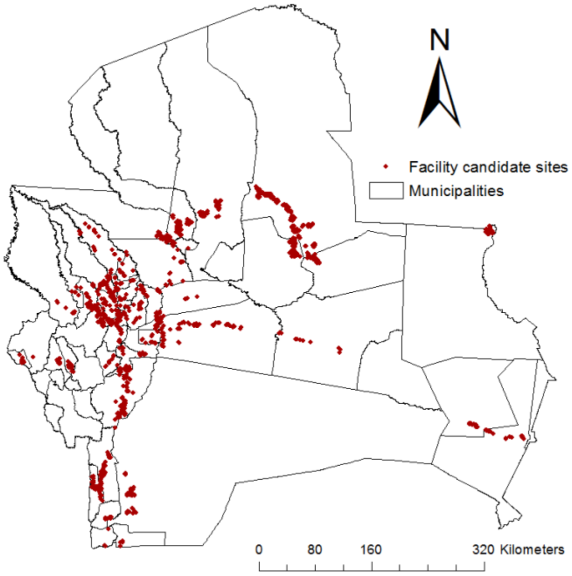


Figure 3-24: Map showing potential locations for biomass-based energy facilities

3.3.3.3 Location-allocation analysis

Facility candidate site (demand), biomass collection point (supply), and real road network (connection) maps were used to identify the optimal location for biomass-based facilities. Since the total biomass collected is 1.5 M dry t/yr and assuming an average capacity of 50 MW per facility, seven facilities are located in the study area. The most common plant size according to IRENA [53] is 50 MW, with annual biomass demand of 230,000 dry t per facility. Figure 3-25 shows not only the optimal locations of biomass-based energy conversion facilities but also connecting lines between BCPs and their corresponding conversion facilities. The optimal facility sites are located near roads, in accordance to the preference criteria for facilitating biomass transportation.

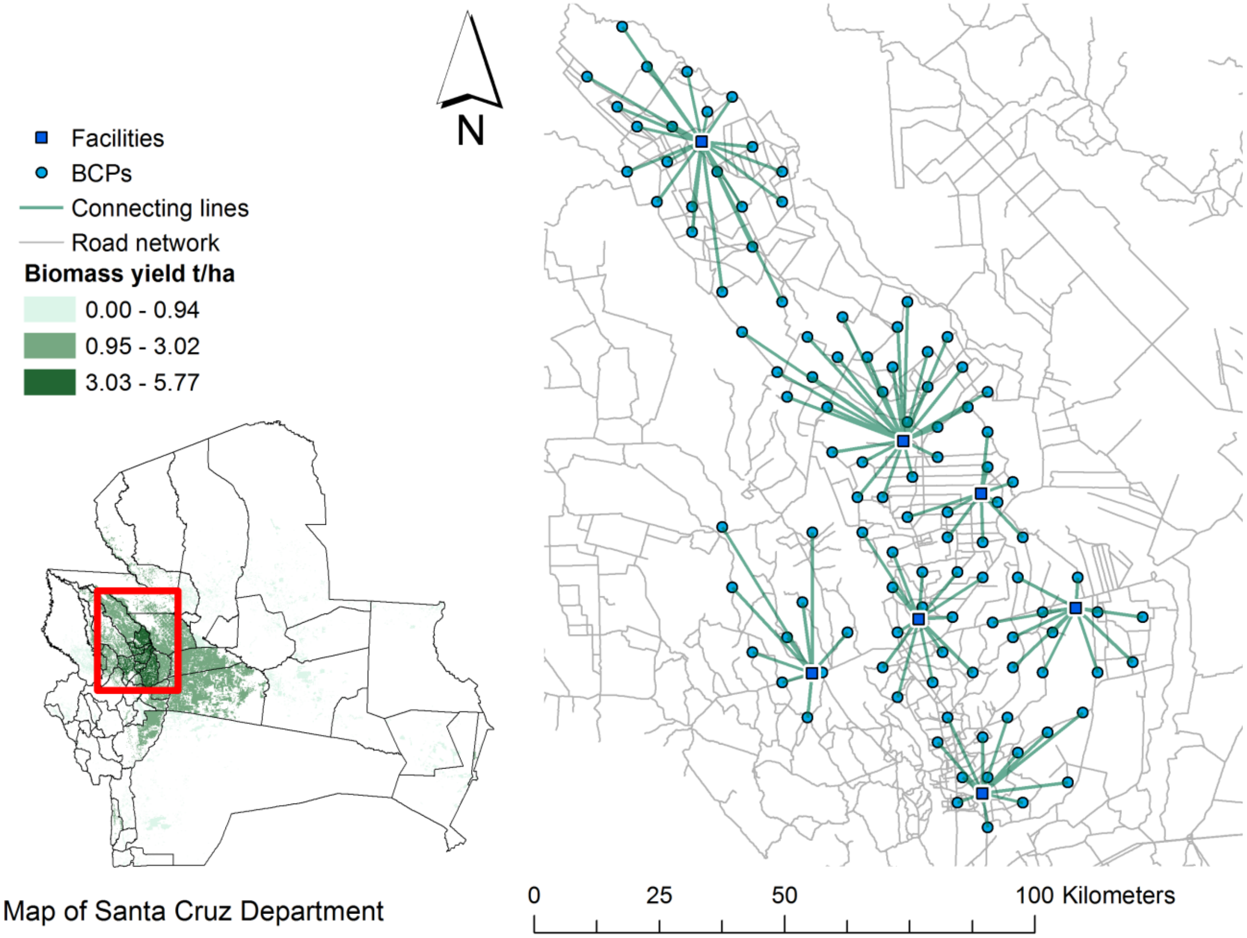


Figure 3-25: Optimal locations of seven biomass-based energy facilities and corresponding supply from collection points

Table 3-12 lists the amount of biomass that can be transported to each facility per year and the transportation distance from collection points to corresponding facilities. The estimated capacity assumes a heating value of 16 MJ per kg, 30% plant efficiency [27-30], and 0.72 capacity factor (or 6307 operating hours per year) [31-33]. Figure 3-26 shows the location of the seven biomass-based conversion facilities, their corresponding plant size and the municipality name to which they belong.

Table 3-12: Optimally located facilities and corresponding information

Facility number	Municipality	Number of collection points for each facility	Dry biomass delivered [t/yr]	Capacity [MW]
1	Fernández Alonso	27	390,000	82
2	San Pedro	22	250,000	53
3	General Saavedra	14	240,000	51
4	Warnes	13	180,000	38
5	Okinawa Uno	12	150,000	32
6	Portachuelo	10	110,000	23
7	General Saavedra	9	160,000	34
Total		**107**	**1,480,000**	**313**

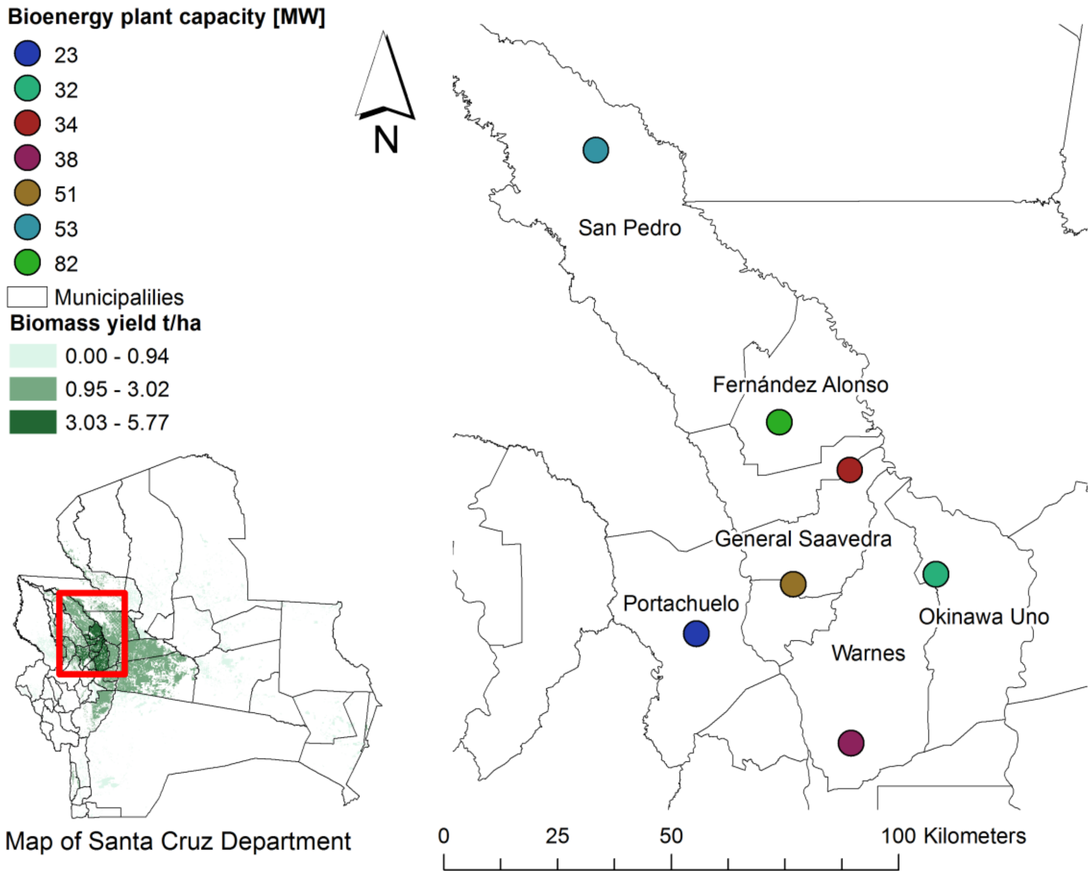


Figure 3-26: Location of biomass-based conversion facilities and their capacity

The number of facilities was determined based on the average power capacity of existing biomass facilities (50 MW) [53]; however, this is not the optimal capacity size, and seven might not be the optimal number of facilities. Power generation plants can range from 4 MW to 300 MW [53]. Higher facility capacities can be more economically attractive because the capital cost per megawatt decreases due to economies of scale. A higher capacity implies fewer facilities need to be built but more biomass transported to the facility. As described in this study (see Figure 3-7), biomass availability changes spatially. In order to transport more biomass, travel distance increases as biomass decreases radially. Long transportation distances increase costs, which may not be compensated by the low cost per megawatt of higher plant capacities.

On the other hand, if the number of facilities increases, transportation distance will decrease and, with it, transportation cost. However, the cost to build an extra facility has to be compared with the saved transportation cost. These and other factors (e.g., conversion technology) need to be analyzed through a techno-economic assessment, which determines the optimal number and capacity of such facilities.

Other factors may influence the optimal site location over time. These factors include new industrial projects, urban expansion, new road construction, and governmental dispositions, all of which change in time. Although care has been taken to use the most updated information available, locating optimal sites relies on having precise information (e.g., geographic features) and the critical appraisal of factors. To analyze the effects of altering the weights assigned to geographical features and identify those with greater impact, a multi-scenario sensitivity analysis needs to be developed.

3.4 Conclusion

A framework was developed for locating biomass collection points (BCPs) using a GIS environment. The purpose of optimally locating BCPs is to increase the efficiency of biomass logistics. BCPs collect biomass bales from circular areas and are close to road network. Trucks pick up the bales and transport them to the biomass-based facility on paved and main roads. The model developed for locating BCPs consists of an iteration process that prioritizes high biomass collection capacity and short distance to roads. The model is meant to be applicable to regions where agricultural fields do not have access to paved roads in grid patterns and the biomass availability changes spatially.

The framework was then applied to the Department of Santa Cruz in Bolivia. Its biomass has great potential as a renewable source of energy. Most of the biomass availability is located in the east-central part of the department. This region was classified into three zones depending on the biomass collection capacity range. In total 107 BCPs were sited and together amass 1.5 M dry t/yr of biomass per year. Optimal locations for biomass-based facilities were then geographically identified. A suitability analysis was conducted considering economic, social, and environmental factors for locating facility candidate sites. These factors were analyzed quantitatively after a weightage value, obtained from the analytical hierarchy process (AHP), was assigned to each factor. The suitability analysis identified 1130 facility candidate sites in the Santa Cruz Department. A location-allocation analysis was conducted afterwards using the location of the BCPs, the facility candidate sites, and the actual road network. Based on the total biomass collected at BCPs (i.e., 1.5 M dry t/yr) and the most common biomass-based plant capacity, i.e., 50 MW, seven optimal locations for biomass-based conversion facilities were identified. The amount of biomass that can be delivered to each facility depends on the biomass collected at nearby BCPs, ranging from 110,000 tonnes to 389,000 tonnes per year to generate 23 to 82 MW. The framework, as well as the location of BCPs and biomass-based facilities, are expected to provide information to decision makers in order to promote the use of renewable energy sources in Bolivia.

References

[1] Kumar A, Sokhansanj S, Flynn PC. Development of a multicriteria assessment model for ranking biomass feedstock collection and transportation systems. Applied Biochemistry and Biotechnology. 2006;129:71-87.

[2] Sultana A, Kumar A, Harfield D. Development of agri-pellet production cost and optimum size. Bioresource Technology. 2010;101:5609-21.

[3] Servicio Nacional de Areas Protegidas (SERNAP). Las zonas externas de amortiguamiento. http://www.bivica.org/upload/zonas-externas-amortiguacion.pdf. (Accessed 28.05.18).

[4] Sokhansanj S, Fenton J. Cost benefit of biomass supply and pre-processing. BIOCAP Canada 2006. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.546.5141&rep=rep1&type=pdf. (Accessed 20.04.18).

[5] Sultana A, Kumar A. Optimal siting and size of bioenergy facilities using geographic information system. Applied Energy. 2012;94:192-201.

[6] Voivontas D, Assimacopoulos D, Koukios E. Assessment of biomass potential for power production: a GIS based method. Biomass and bioenergy. 2001;20:101-12.

[7] Viana H, Cohen WB, Lopes D, Aranha J. Assessment of forest biomass for use as energy. GIS-based analysis of geographical availability and locations of wood-fired power plants in Portugal. Applied Energy. 2010;87:2551-60.

[8] Singh J, Panesar B, Sharma S. Energy potential through agricultural biomass using geographical information system—A case study of Punjab. Biomass and Bioenergy. 2008;32:301-7.

[9] Graham RL, English BC, Noon CE. A geographic information system-based modeling system for evaluating the cost of delivered energy crop feedstock. Biomass and bioenergy. 2000;18:309-29.

[10] Khan MMU, Vaezi M, Kumar A. Optimal siting of solid waste-to-value-added facilities through a GIS-based assessment. Science of the Total Environment. 2018;610:1065-75.

[11] Ullah M. Techno-economic assessment of utilization of food processing waste for production of energy and chemicals [Thesis]. University of Alberta; 2017.

[12] Saaty TL. Fundamentals of decision making and priority theory with the analytic hierarchy process: Rws Publications; 2000.

[13] Environmental Systems Research Institute (ESRI). Location-allocation analysis. 2017. http://desktop.arcgis.com/en/arcmap/latest/extensions/network-analyst/location-allocation.htm#GUID-A1F63AFF-8333-42A1-A540-6C49E7D717F4. (Accessed 19.05.18).

[14] Overend RP. The average haul distance and transportation work factors for biomass delivered to a central plant. Biomass. 1982;2:75-9.

[15] Perpina C, Alfonso D, Pérez-Navarro A, Penalvo E, Vargas C, Cárdenas R. Methodology based on Geographic Information Systems for biomass logistics and transport optimisation. Renewable Energy. 2009;34:555-65.

[16] Sharma B, Ingalls RG, Jones CL, Huhnke RL, Khanchi A. Scenario optimization modeling approach for design and management of biomass-to-biorefinery supply chain system. Bioresource Technology. 2013;150:163-71.

[17] Kevin C, Mari C, Michael K, Matthew V. Biomass supply chain management in North Carolina (part 2): biomass feedstock logistical optimization. AIMS Energy, Vol 4, Iss 2, Pp 280-299 (2016). 2016:280.

[18] Sokhansanj S, F. Turhollow A. Baseline cost for corn stover collection. Applied Engineering in Agriculture. 2002;18:525.

[19] Velázquez-Martí B, Annevelink E. GIS application to define biomass collection points as sources for linear programming of delivery networks. Transactions of the ASAE (American Society of Agricultural Engineers). 2009;52:1069.

[20] Chávez-Rodríguez MF, Garaffa R, Andrade G, Cárdenas G, Szklo A, Lucena AF. Can Bolivia keep its role as a major natural gas exporter in South America? Journal of Natural Gas Science and Engineering. 2016;33:717-30.

[21] Ministerio de Hidrocarburos y Energía (MHE). Balance energético nacional 2000-2014. 2015. http://www2.hidrocarburos.gob.bo/index.php/publicaciones/balance-

energ%C3%A9tico/balance-energ%C3%A9tico-departamental/category/54-balance-energetico-nacional.html. (Accessed 12.11.16).

[22] British Petroleum (BP). Statistical Review of World Energy. 2016. https://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2016/bp-statistical-review-of-world-energy-2016-full-report.pdf. (Accessed 04.05.17).

[23] Ministerio de Hidrocarburos y Energía (MHE). Plan para el desarrollo de las energías alternativas, 2025. 2014. http://www.bivica.org/upload/energias-alternativas-plan.pdf. (Accessed 17.10.16).

[24] Empresa Nacional de Electricidad (ENDE). Memoria anual, 2015. 2016. http://www.ende.bo/public/memorias/memoria-2015-10-final.pdf. (Accessed 15.10.16).

[25] Morato T, Kumar A, Vaezi M. Assessment of potential energy from agricultural residues in Bolivia. Manuscript submitted for publication.

[26] Instituto Nacional de Estadística (INE). http://www.ine.gob.bo/. (Accessed 18.11.16).

[27] Bridgwater AV, Toft AJ, Brammer JG. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. Renewable and Sustainable Energy Reviews. 2002;6:181-246.

[28] Cameron JB, Kumar A, Flynn PC. The impact of feedstock cost on technology selection and optimum size. Biomass and Bioenergy. 2007;31:137-44.

[29] Caputo AC, Palumbo M, Pelagagge PM, Scacchia F. Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. Biomass and Bioenergy. 2005;28:35-51.

[30] Dassanayake GD. Utilization of Triticale Straw for Power Generation [Thesis]. University of Alberta; 2011.

[31] Autoridad de Fiscalización y Control Social de Electricidad (AE). Anuario estadistico 2015. 2015. https://www.ae.gob.bo/aewebmobile/main?mid=1&cid=81. (Accessed 15.04.18).

[32] Kumar A, Cameron JB, Flynn PC. Biomass power cost and optimum plant size in western Canada. Biomass and Bioenergy. 2003;24:445-64.

[33] Renewable Energy Policy Network for the 21st Century (REN 21). Global status report. 2017. http://www.ren21.net/wp-content/uploads/2017/06/17-8399_GSR_2017_Full_Report_0621_Opt.pdf. (Accessed 18.12.17).

[34] Esri. Mapping without limits. 2017. http://www.arcgis.com/features/index.html. (Accessed 22.01.17).

[35] Vicepresidencia del Estado Plurinacional de Bolivia. Información Geográfica de Bolivia, GeoBolivia. http://geo.gob.bo/portal/. (Accessed 04.05.17).

[36] Khan M. Development of a Decision Making Framework for Solid Waste Management Using GIS-based Site Selection and an Economic Comparison [Thesis]. University of Alberta; 2015.

[37] Poder Ejecutivo. Reglamento de aguas (s/n de 08/09/1879). 1906. https://bolivia.infoleyes.com/norma/2442/reglamento-de-aguas-s-n-de-08-09-1879. (Accessed 27.04.17).

[38] Instituto Nacional de Reforma Agraria (INRA). Normas tecnicas para el saneamiento de la propiedad agraria, conformacion del catastro y registro predial 2008. http://www.inra.gob.bo/InraPb/upload/Norma_Tecnica_VERSION_FINAL_AGUA_%20aprobada%20-%20REVISADA.pdf.

[39] Empresa de luz y fuerza electrica Cochabamba (ELFEC). Norma de distancias de seguridad en lineas de distribucion http://www.elfec.com/sites/default/files/normas.pdf. (Accessed 27.04.17).

[40] Organo Legislativo. Ley de Minería y Metalúrgia (535). 2014. https://bolivia.infoleyes.com/norma/4984/ley-de-miner%C3%ADa-y-metal%C3%BArgia-535. (Accessed 27.04.17).

[41] Ballivian H, Suarez T, Martínez L, Montero C, Careaga G, Cardozo D, et al. Decreto Ley N 2978, 14 de febrero de 1952. 1952:7. http://www.lexivox.org/norms/BO-DL-2978.xhtml. (Accessed 27.04.17).

[42] Agencia Nacional de Hidrocarburos (ANH). IV Reglamento para la construccion y operacion de plantas de destribucion de gas licuado de petroleo (GLP) en garrafas.

http://www.anh.gob.bo/InsideFiles/Documentos/Documentos_Id-62-140311-26.pdf. (Accessed (27.04.17)).

[43] Sanchez G, Aranibar A, Sánchez C, Otasevic J, Guillermo J, Oswaldo R, et al. Reglamento Ambiental para el sector de Hidrocarburos (RASH). Decreto Supremo N 24335 de 19/07/1996. 1996. http://extwprlegs1.fao.org/docs/pdf/bol146679.pdf. (Accessed 27.04.17).

[44] Mcdonald RI, Forman RT, Kareiva P, Neugarten R, Salzer D, Fisher J. Urban effects, distance, and protected areas in an urbanizing world. Landscape and Urban Planning. 2009;93:63-75.

[45] Cooperativa rural de electrificacion (CRE). Manual del Consumidor http://www.cre.com.bo/webcre/hogar/pdf/Manual%20del%20Consumidor.PDF. (Accessed 19.05.18).

[46] Holtzhausen JP, Vosloo WL. High voltage engineering Practice and theory.

[47] Molburg JC, Kavicky JA, Picel KC. The design, construction, and operation of long-distance high-voltage electricity transmission technologies 2007. http://solareis.anl.gov/documents/docs/APT_61117_EVS_TM_08_4.pdf.

[48] Laclette JP, Zuñiga P. Diagnóstico del agua en las Américas 2012.

[49] Bolivia: sector industrial deberá pagar por el agua que se utiliza de manera directa. La Razon. 2010. https://www.americaeconomia.com/economia-mercados/bolivia-sector-industrial-debera-pagar-por-el-agua-que-se-utiliza-de-manera-direct.

[50] Instituto Nacional de Reforma Agraria (INRA). Tipos de propiedad 2012. http://www.inra.gob.bo/InraPb/paginaController?cmd=contenido&id=6650. (Accessed 15.04.18).

[51] Legislativo P. Ley del servicio nacional de reformas agrarias (1715). 1996. https://bolivia.infoleyes.com/norma/1274/ley-del-servicio-nacional-de-reforma-agraria-1715. (Accessed 28.05.18).

[52] International Renewable Energy Agency (IRENA). Renewable power generation costs in 2014. 2015.

https://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Power_Costs_2014_report.pdf. (Accessed 15.04.18).

[53] International Renewable Energy Agency (IRENA). Biomass for power generation. 2012;1. https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-BIOMASS.pdf. (Accessed 05.05.17).

[54] Urquiola M, Andersen L, Antelo E, Luis Evia J, Nina O. Geography and Development in Bolivia2018.

[55] Ministerio de Hidrocarburos y Energia. Plan electrico del Estado Plurinacional de Bolivia 2015. 2014. https://observatorioccdbolivia.files.wordpress.com/2015/08/peebol2025.pdf. (Accessed 20.10. 16).

Chapter 4: Techno-economic assessment of biomass combustion technologies to generate electricity in Bolivia

4.1 Introduction

Bolivia is going through an energy portfolio transition to secure demand supply and society wellbeing. Nowadays, the country depends mostly on natural gas for energy generation; however, renewables (hydro) and non-renewables had almost equal shares in 2000. Since that year, the country has gradually increased its dependency on natural gas, as investment on natural gas-based power plants is economically preferable over investment in renewable technologies. In 2008, the government of Bolivia set the natural gas price for thermoelectric power plants at the fixed low cost of 1.3 $/MCP (Supreme Decree No. 29510) [1] in order to regularize and reduce the electricity price. In the same year, several programs emerged to decrease energy consumption and improve energy efficiency in order to meet growing electricity demand. However, in 2011, the insufficient power reserves caused power shortages and increased the likelihood of electricity rationing [2]. In order to surpass electricity demand and ensure power reserves for the coming years, investment in natural gas-based power plants increased greatly as an immediate need, giving no opportunity to expand renewable energy technologies. At that time, thermoelectric power plants was the best option by far since the technology was simple, the capital investment was nowhere close to that of renewable energy technologies, the fuel was readily available at a subsidized cost[1], thermoelectric power plants needed no extensive initial study and planning, and, finally, the building time was short (e.g., 9 years' facility building time for hydro vs. 3 years

---

[1] The government's main objective in subsidizing fossil fuels was to increase access to such resources as established by the "Universalization" target in the Patriotic Agenda for 2025.

for natural gas-based facilities) [2, 3]. Although thermoelectric power plants solved the lack of power reserves, the national dependency on natural gas increased drastically. Moreover, subsidized fossil fuel prices impose an obstacle to introducing renewable energies and increase the potential for social and economic impact as the gap between international benchmark and subsidized electricity prices gradually increases.

The target set in the Patriotic Agenda for 2025 (Agenda Patriótica 2025) [4, 5] is to increase power capacity from 1,600 MW to 13,600 MW. 74% of the 2025 target will be supplied by large hydro power plants, 4% by other renewable sources, and 10% by fossil fuels. There are two snags with this energy target. The first is related to four proposed large-scale hydro power plants (Tachuela Esperanza, El Bala, Rio Grande, and Binacional Madera) intended to cover more than 50% of the national target; the completion of these plants may be put on hold due to environmental impacts [6-8]. The second concern is the fossil fuel availability intended to cover the 10% share in the power portfolio. British Petroleum (BP) [9] reported that Bolivia's natural gas reserves will last for 14 more years if the production rate remains constant and no new reservoir is explored/approved. Therefore, it is crucial to increase the contribution of renewable energies as Bolivia's natural gas reserves enter the depletion phase.

Efforts have been made to diversify the energy matrix in Bolivia and, since 2014, hydro, solar, wind, and geothermal projects have been implemented [10]. Agricultural residue biomass is an unused and low-cost source of energy that could very well help replace fossil fuels too. A wide variety of agricultural products is produced in Bolivia due to diverse environmental conditions across the country. According to the agricultural census carried out by the National Institute of Statistics (Instituto Nacional de Estadística, INE) [11], the six major agricultural crops produced in Bolivia are sugarcane, sorghum, corn, rice, sorghum, and sunflower, and they are mostly generated in the Department of Santa Cruz. A previous study by the authors [12] estimated the sustainable biomass availability in Santa Cruz as 3.7 Mt/year on a dry basis. The spatial distribution of biomass availability is depicted in Figure 4-1.

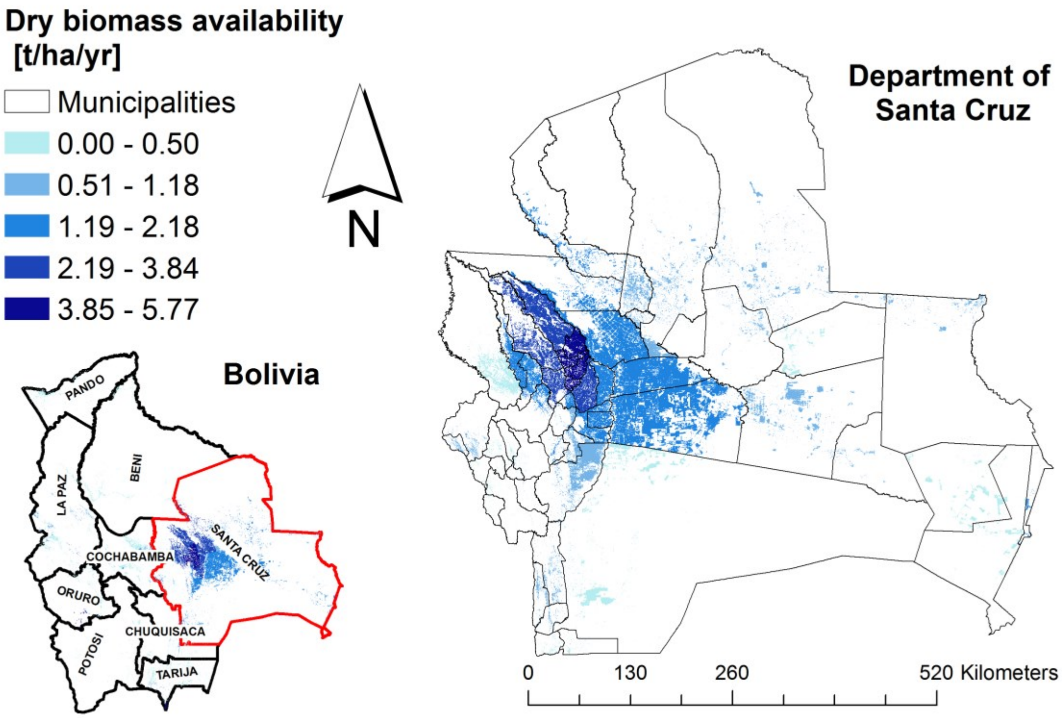


Figure 4-1: Spatial distribution of biomass availability across the country

Sokhansanj et al. and Rosendahl et al. [13, 14] suggest that agricultural residues should be moved from the points of harvesting to biomass collection points right beside the road to facilitate truck pick-up. A previous study by the authors [15] used a geographic information system (GIS) to geographically locate BCPs such that large volumes of biomass are collected close to a road network. In addition, the most suitable facility sites were identified after exclusion and preference analyses removed non-suitable areas (e.g., protected areas, lakes, rivers, roads, etc.) and gave priority to preferred regions (e.g., roads, biomass collection area, transmission lines, etc.). Finally, a network analysis was conducted using the actual road network, BCPs, and facility candidate sites to find the optimum facility location so that biomass transportation cost is minimized.

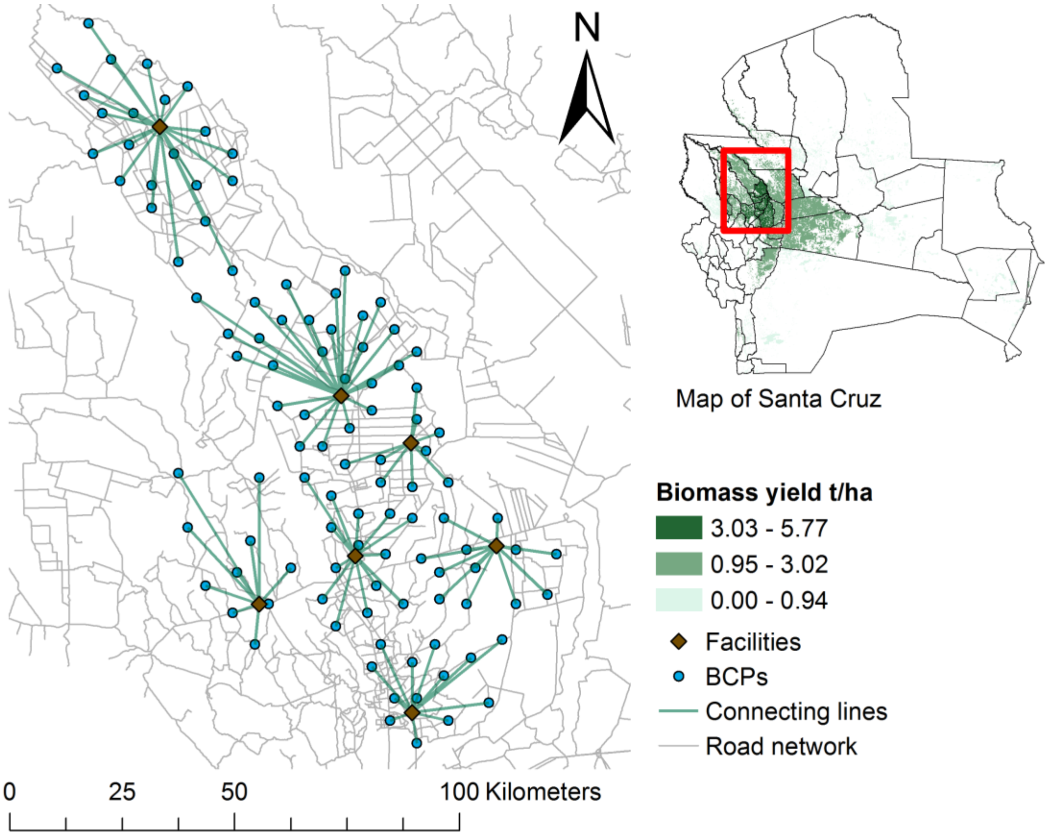


Figure 4-2. Optimal location of biomass-based energy conversion facilities in Santa Cruz, Bolivia

This study is focused on techno-economic assessment of electricity generation from biomass through thermoelectric conversion processes, particularly combustion technology, in Bolivia. Biomass combustion technology is mature, commonly used, and commercially available, and has a relatively low capital cost compared to other thermoelectric conversion technologies, e.g., gasification and pyrolysis.

To the best of the authors' knowledge, there are no previous studies on techno-economic assessment of biomass conversion technologies in Bolivia, particularly the cost of electricity from biomass. This study investigates the costs associated with energy production using agricultural residues that are affected by biomass yield distribution, selection of BCPs, location of the bioenergy facility, biomass cost based on current practice in the country, and the capital cost trend over a capacity range from 5 to 650 MW. This study assesses the economic feasibility of generating electricity using agricultural residue biomass through combustion technology in Bolivia. The following are the specific objectives of the present study:

- To estimate the levelized cost of electricity (LCOE) from biomass,
- To determine the optimal capacity of the biomass-based energy power plant,
- To estimate through sensitivity analyses the impact on electricity cost if critical parameters change,
- To propose alternatives to increase the competitiveness of combustion technology in the electricity market.

This study provides unique information on the costs associated with using biomass in generating electricity in Bolivia. No previous studies considered agricultural residues as a source in large-scale energy conversion facilities, nor analyzed corresponding costs. Policy and decision makers are the main beneficiaries of the results/analysis of this study. The costs obtained here can be also used as indicators for further comparison with other renewable energy technologies. Moreover, the identification of the main barriers currently blocking the introduction of other renewables may be useful for future decisions and re-consideration of the biomass option, should the barriers be removed. The overall work presents an alternative that could help to develop strategic future plans.

4.2 Method

A model was developed to analyze the economics of a biomass-based power plant based on logistics costs, capital investment, operating cost, and revenues. The model developed here is called **EN**ergy from **BIO**mass **T**echno **E**conomic **M**odel (ENBIOTEM). It considers combustion (grate-firing and fluidized bed) as the reference biomass conversion technology. The model estimates the minimum cost of energy required in order to make investment in biomass-based power plant profitable for a given internal rate of return (IRR), combustion technology, and plant capacity. It also estimates the levelized cost of electricity (LCOE) for a range of plant capacities (5 to 600 MW) and identifies the minimum LCOE that corresponds to the optimal plant capacity. The ENBIOTEM model further identifies the key cost parameters through sensitivity analyses. The following sections describe, in detail, the techno-economic model and corresponding parameters.

4.2.1 Biomass feedstock characteristics

Biomass in this study refers to agricultural residues from sugarcane, soybean, corn, rice, sorghum, and sunflower. Agricultural residues have low bulk densities of 80 to 140 dry kg/m^3 [14, 16]. Some drawbacks of low bulk density feedstock are the large spaces required for storage and large trucks required for transportation. These factors accordingly increase biomass delivery cost [13]. Moisture content is a biomass characteristic that affects power generation in the conversion facility. It is assumed that moisture is partially reduced when residues are stored on fields, at BCPs, and in an energy facility. For this study, the moisture content is assumed to be 23%. However, the study area, Santa Cruz, has a humid tropical climate and a more detailed study is needed to assess moisture variance and the effect on fungi formation and power generation. The low heating value (LHV), another biomass specification used in the model, is assumed to be the average of the individual low heating values of the six agricultural residues considered in this study, which is 16.3 GJ/t [12].

4.2.2 Biomass-based energy conversion facility characteristics

In biomass combustion technology, the conversion efficiency depends on several factors, including the biomass feedstock properties (e.g., moisture content, size, LHV) and the generation system (e.g., type of combustor, turbine). While previous studies reported efficiencies of 25%-35% [17-20], 30% is assumed in this study.

Capacity factor is defined as the ratio between the energy generated in a period of time and the total energy that could be generated if the facility runs at the maximum output during the same period and without interruption [21], as expressed in Equation 4-1.

$$\tau = \frac{\mathit{Electricity\ generated\ [MWh/yr]}}{\mathit{Plant\ capacity\ [MW]\cdot 24h/d\cdot 365d}} \tag{4-1}$$

The 2015 annual report of the Electricity Authority (La Autoridad de Electricidad, AE) of Bolivia [22] listed the energy generated and the maximum capacity achieved by thermoelectric power plants, where the capacity factor was calculated and averaged at 0.45. The capacity factor has been calculated from data reported in other studies in Bolivia as 0.86 [23] and 0.61 [24]. REN 21 [25] reports the range of capacity factors for different regions in the world: 0.16-0.93 in

North America, with a weighted average of 0.78, and 0.21-0.95 in South America, with a weighted average of 0.53. Several studies in Canada use a capacity factor of 0.85 [16, 20, 26, 27]. IRENA [28] reports a capacity factor of 0.85 can be achieved, but most power plants using agricultural residues do not usually operate at this level due to variable year-round access to feedstock. Therefore, the capacity factor for the study area should be considered to be lower than 0.85. We assume a capacity factor of 0.60 the first year, 0.66 the second year, and 0.72 from the third year onwards.

The operating hours are the number of the hours per year that the facility generates electricity. To estimate the operating hours, we used Equation 4-2. The capacity factor and operating hours for the first three years are shown in Table 1.

$$OH = \tau \cdot 24h \cdot 365\, d \qquad (4\text{-}2)$$

Table 4-1: Capacity factor and operating hours for the facility during the first three years of operation and onwards

Year	Capacity factor	Operating hours per year
Year 1	0.60	5,256
Year 2	0.66	5,782
Year 3 onwards	0.72	6,307

Equation 4-3 was used in the economic model to estimate the amount of biomass required by the conversion facility to generate a particular electrical power output:

$$M = \frac{W \cdot 3600 \cdot OH}{\eta \cdot LHV} \tag{4-3}$$

where M is the biomass feedstock [t/yr], W is the net electric power output [MW], 3600 is the conversion factor, and η is the power plant's efficiency.

4.2.3 Economic parameters

In order to analyze the cost data collected from different sources and compare our results with previous studies, the currency unit in this study is set to the US dollar and the base year to 2017. For consistency purposes, costs reported in US dollars were inflated to the base year, and costs reported in other currencies were first inflated based on the local rate and then converted to the US dollar using the currency conversion factor for December 2017. Reported capital costs were inflated using the power capital cost index, PCCI. Similar to the consumer price index (CPI), the PCCI is an index tracking the price variation of power generation construction, which includes the cost variations of equipment, materials, etc. This study used the PCCI for North America (NAPCCI) and Europe (EPCCI) tracked by IHS Markit [29]. In order to inflate costs related to biomass logistics collected from Bolivian sources, the regional CPI reported by the Central Bank of Bolivia (Banco Central de Bolivia, BCB) was used [30].

The inflation rate in Bolivia fluctuates from year to year (e.g., 11.85, 0.26, and 7.18% in 2008, 2009, and 2010, respectively) [30-32]. The inflation rate used in the economic model to predict future costs is 2.71%, which corresponds to the inflation rate at the base year of this study, 2017. Moreover, the inflation rate is assumed to remain constant throughout the lifetime of the energy conversion facility. Since inflation rate may play an important role in our economic model, due to its fluctuation, this parameter is further assessed in sensitivity analyses.

While the lifetime of biomass power facilities is usually from 20 to 25 years [33], there have been studies considering 30 years for facilities in Canada [16, 20, 26] and 20 years for facilities (e.g., thermoelectric , hydro, and bagasse-based power plants) in Bolivia [23, 34, 35]. This study assumes the lifetime of the biomass power plant is 20 years.

The internal rate of return (IRR) is assumed to be 12%. Previous economic studies in the electricity sector conducted for Bolivia considered 10% [23] and 12% [24]. Gomes [2] states that the revenue in generator plants should allow an IRR of 12% per year.

Table 4-2 gives the characteristics of biomass feedstock, energy conversion facilities, and parameters used in the economic model.

Table 4-2: Input data used in the economic model

Factor	**Value**
Moisture content	23%
Low heating value	16.3 GJ/t
Plant conversion efficiency	30%
Base year	2017
Inflation rate	2.71%
Lifetime	20 years
IRR	12%

4.2.4 Facility cost and revenue components

The energy production cost structure in the economic model is composed of the cost related to biomass logistics and the cost related to energy conversion, as shown in Figure 4-3.

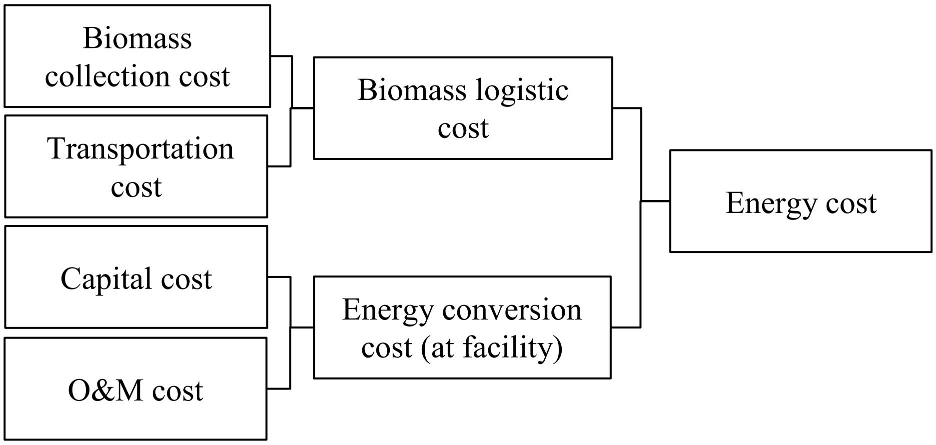


Figure 4-3: Flowchart of cost components in the economic model

4.2.4.1 Biomass logistics cost analysis

The cost of biomass feedstock logistics is comprised of several costs starting from collecting the agricultural residues from the farm fields to delivering to the conversion facility. The chain of processes includes harvesting, nutrient replacement, premium to farmers, baling, transportation to biomass collection points (BCPs), storing at BCPs, and transporting from BCPs to the conversion facility as shown in Figure 4-4. It is assumed that a third-party logistics (3PL) provider is in charge of the biomass supply chain through a contract. The main cost components for the biomass-to-energy conversion facility are capital cost, and operating and maintenance cost. Each cost component mentioned here is explained below.

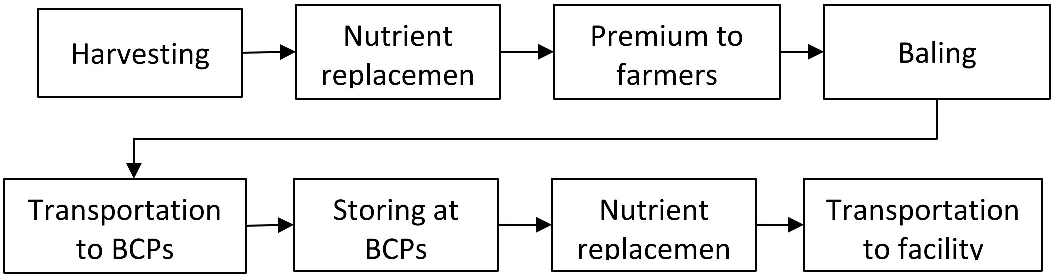


Figure 4-4: Biomass feedstock supply chain

4.2.4.1.1 Harvesting cost

Harvesting cost depends on the technology used and the type of crop residue. Although there is no information on the harvesting cost of agricultural residues in Bolivia, the costs associated with the current practice of harvesting crops were analyzed here. Manual harvesting is still a common practice for small and medium-sized agricultural fields in Bolivia. The cost of manually harvesting sugarcane is 9.3 $/t [36]. Mechanized harvesting makes up 55% of sugarcane harvesting currently [37], is mainly practiced in large-sized farming areas, and is about 8.2 $/t [36]. Since BCPs are located where biomass is produced at high yields, it is assumed that a mechanized system will harvest the residues at 8.2 $/t as well. If residues are harvested in one pass (together with the crop product), there might be savings on fuel consumption, which may decrease the biomass harvesting cost.

4.2.4.1.2 Nutrient replacement cost

A portion of nutrients is taken when the residues are removed from land. Several articles discuss fertilizer requirements associated with agricultural residue removal [38-41]. However, the fertilizers recommended are typically not common in Bolivia; therefore, the nutrient requirements of nitrogen, phosphorus, and potassium (N-P-K) were estimated, and later the appropriate/available fertilizers in Bolivia were selected to calculate corresponding nutrient replacement cost.

The average nutrient content in agricultural residues based on a literature review is listed on Table 4-3. The three main fertilizers in the country are urea, diammonium phosphate (DAP), and triple fifteen (N-P-K) [42]. A lower fertilizer consumption is reported in Bolivia than in surrounding countries [43, 44], mainly due to the high cost of imported fertilizers [45]. The cost of domestically produced urea, a source of nitrogen produced in a recently established ammonia and urea plant in Bolivia, is considered in this study to be 335 \$/t [46]. Diammonium phosphate (DAP), a source of phosphorus, costs 1,226 \$/t; this amount has been reduced by the government as an incentive to improve agricultural production [47]. The third most common fertilizer is triple fifteen (N-P-K); however, since it is expensive and the potassium composition is low (N-P-K = 15-15-15), the present study assumes potassium chloride is used instead of triple fifteen at a cost of 757 \$/t [48]. Although potassium chloride is not common in the country, its consumption is expected to increase due to a fertilizer facility project under construction in the Uyuni salt flats [49].

Table 4-3: Nutrient replacement cost for residue removal

Nutrient	Fertilizer name	Typical nutrient composition (N-P-K)	Fertilizer requirement (% per RR[1])	Fertilizer cost (\$/t-f[2]) (2017)	Nutrient cost per tonne of RR (\$/t-RR)
N	Urea	(46-0-0)	1.17	335	1.8
P	Diammonium phosphate (DAP)	(18-46-0)	0.32	1,226	1.8
K	Potassium chloride	(0-0-60)	1.77	757	8.1
Total nutrient cost					11.7

[1] RR is residue removed

[2] f is fertilizer

4.2.4.1.3 Premium to farmers

The premium is a reward given to farmers as an incentive for supplying feedstock in a sustainable way. Although this cost is crucial in securing farmers' commitment and support [16, 20, 27], we should also consider that some farmers do not use the residues in any efficient manner and, in fact, residues become inconvenient to handle in large volumes. In those cases, farmers even opt to burn residues in open fields, causing social discomfort and environmental pollution. However, if burning residues becomes prohibited, farmers will have to remove the residues and discard them, which may have an associated cost. Thus, there is a possibility of considering zero premium cost and only an agreement with farmers for taking the residues and clearing the fields in exchange. In our economic model, however, we considered a premium to farmers of 6.5 \$/t.

4.2.4.1.4 Baling cost

The baling cost depends on the bale size, how compact the bale is, and baling technology. The baling cost is estimated based on the cost of grass bales used for animal feeding. A manual hay bale costs 13.7 $/t. To manually bale hay, farmers use wood cages of 40 x 70 cm to pack 30 kg of grass [50]. A large baling machine, on the other hand, can produce rectangular bales of 400 kg, also for livestock, at a high selling price of 70 $/t to 140 $/t in Bolivia [51, 52]. This option includes a pre-classification process to remove sticks and other unwanted materials in order to increase product quality. The higher selling price may, as well, be attributed to hay growth and land rental. In our study, there is no cost related to either pre-classification or biomass growth since our energy sources are the available agricultural residues. The baling cost in this study is assumed to be 13.7 $/t.

4.2.4.1.5 Cost of storing biomass and transporting it to BCPs

Biomass can be stored on fields, BCPs, and the conversion facility itself, depending on requirements and availability [13]. The main drawbacks of storage are costs associated with losses and quality degradation (e.g., formation of fungi and spores) [13]. Storing on farms can be acceptable only for a short time since farmers need to prepare the land for the next crop [14]. Biomass is stored at BCPs for a while before being transported to the conversion facility. The storing management at BCPs and conversion facilities requires space coordination between harvesting periods and facility feeding requirements. The only storing cost considered here is at BPCs for land rental, which is assumed to be 3.3 $/t [50], and includes the cost of short transportation (less than 4 km) from the farms to the BCPs. The biomass feedstock costs considered in this study are summarized in Table 4-4.

Table 4-4: Biomass collection costs used in techno-economic model

Factor	Cost ($/t)
Harvesting (cutting, hopping)	8.2
Baling	13.7
Transportation to BCPs and storage	3.3
Nutrient replacement cost	11.7
Premium to farmer	6.5
Total feedstock	43.3

4.2.4.1.6 Biomass transportation cost from BCPs to energy conversion facility

The cost of transporting biomass from BCPs to the energy conversion facility has two components: fixed and variable. Fixed costs include the driver's and assistant's salaries, loading/unloading, any transportation toll, insurance, administration, and preventive maintenance. The variable cost refers to distance traveled and includes fuel, lubricants, and maintenance costs [53, 54]. There is no standard procedure followed by transportation companies to calculate the costs associated with transportation. Transportation cost varies greatly across the country and between companies. In order to estimate the cost components, cost data were collected through personal communications with transportation companies in Bolivia. The collected data are presented in Table 4-5. The companies contacted reported costs for fixed departure and destination points.

Table 4-5: Collected data on transportation costs in Bolivia

Company	From	To	Distance [km]	Capacity [t]	Cost		Cost [$/t]
1	Santa Cruz	La Paz	850	14	8,500	Bs	85
1	Santa Cruz	Cochabamba	476.1	14	5,500	Bs	55
1	Santa Cruz	Mineros	86	14	1,100	Bs	11
2	Santa Cruz	Cochabamba	476.1	_	40	ctv/kg	56
2	Santa Cruz	La Paz	850	_	60	ctv/kg	84
3	Santa Cruz	Camiri	295	25	800	$/trip	32
3	Santa Cruz	Mineros	86	25	600	$/trip	24
4	Santa Cruz	Mineros	86	25	3,200	Bs	17.92
5	Santa Cruz	Mineros	86	20	450	$	22.5
5	Santa Cruz	Camiri	295	20	800	$	40
5	Santa Cruz	Cochabamba	476.1	20	1,200	$	60
6	La Paz	Arica, Chile	488	20	730	$	36.50
7	Arica	La Paz	488	27	1,000	$	37.04
8	Matarani	El Alto	556	28	40	$/t	40
9	Santa Cruz	Cochabamba	476.1	13 or 26	14	Bs/qq	42.61
9	Santa Cruz	La Paz	850	13 or 26	20	Bs/qq	60.87

The collected cost data is plotted in a graph (see Figure 4-5), and through a linear regression analysis the fixed (y-intercept) and the variable (slop) costs were estimated.

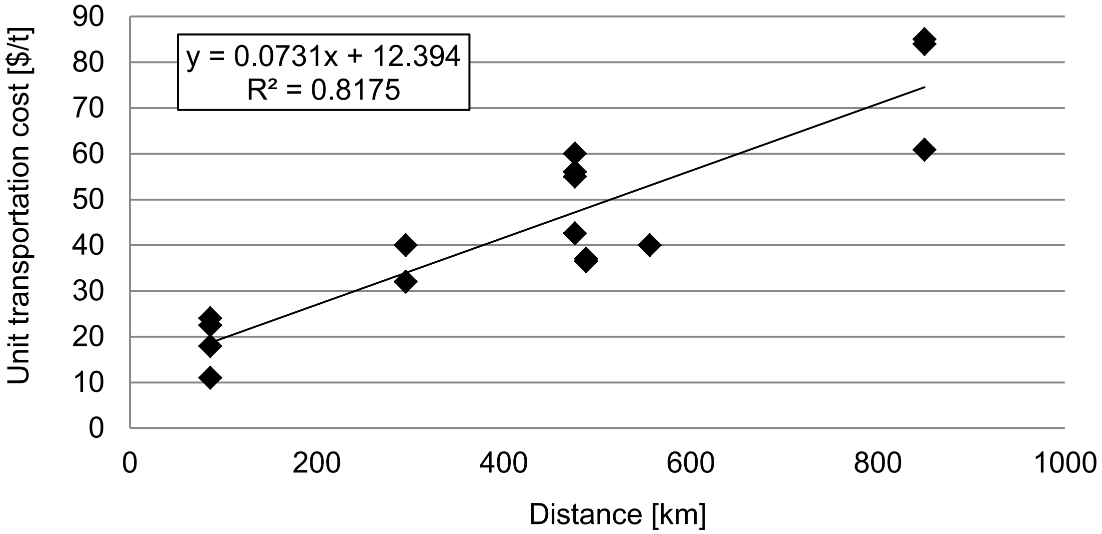


Figure 4-5: Unit transportation cost per distance travelled

The fixed and variable costs for the study area are 0.0731 $/t and 12.394 $/t/km, respectively. For comparison purposes, Table 4-6 shows the two transportation cost components in different regions. The cost components for Canada were collected from previously published studies [27, 55]. The fixed and variable costs for the US [56], Brazil, and Argentina [57] were obtained through regression analysis of transportation costs reported at various distances (the costs were based on the transportation of agricultural products). Fuller et al. [57] mentioned that transportation costs in Bolivia are close to those in Brazil, which is verified in Table 4-6, but Bolivia has the highest fixed cost.

Table 4-6: Comparison of transportation cost components

Region	Fixed cost [$/t]	Variable cost [$/t/km]	Source
US	1.90	0.11	[56]
Canada	5.45	0.22	[27]
Brazil	11.07	0.012	[57]
Argentina	4.067	0.048	[57]
Bolivia	12.39	0.073	Present study

The higher fixed cost may reflect the deficient road conditions in Bolivia (i.e., lack of signaling, geometric design, and deterioration) [58]. The road network in 2008 was comprised of 63% dirt roads, 30% gravel roads, and 7% paved roads [59, 60]. The deficient road condition increases transportation cost and time [59], and the risk of transportation accidents [61]. The lower variable cost is attributed to the subsidised cost of fossil fuels. The biomass logistic system, as stated in several studies, consists of collecting biomass bales from roadside network set up to facilitate truck pick-up [14, 16, 27]. However, as seen in Figure 4-6, which compares the road networks in Alberta, Canada, and Santa Cruz, Bolivia (showing agricultural areas at the same scale), the Alberta road network in follows a grid pattern while the network in Santa Cruz is disorganized, mostly due to topology and inappropriate road building planning. Therefore, assuming a homogeneous distribution of BCPs is appropriate when there is a road pattern, as in Alberta. Some studies consider a circular area from where biomass is collected, assuming constant biomass yield distribution and average transportation distance. However, in our study area, the topology, road shape, and biomass spatial distribution do not allow us to locate BCPs in a uniform distribution, nor assume a singular circular collection area with homogenous biomass yield. Thus, we used a GIS-based model to locate BCPs and estimate road transportation distances.

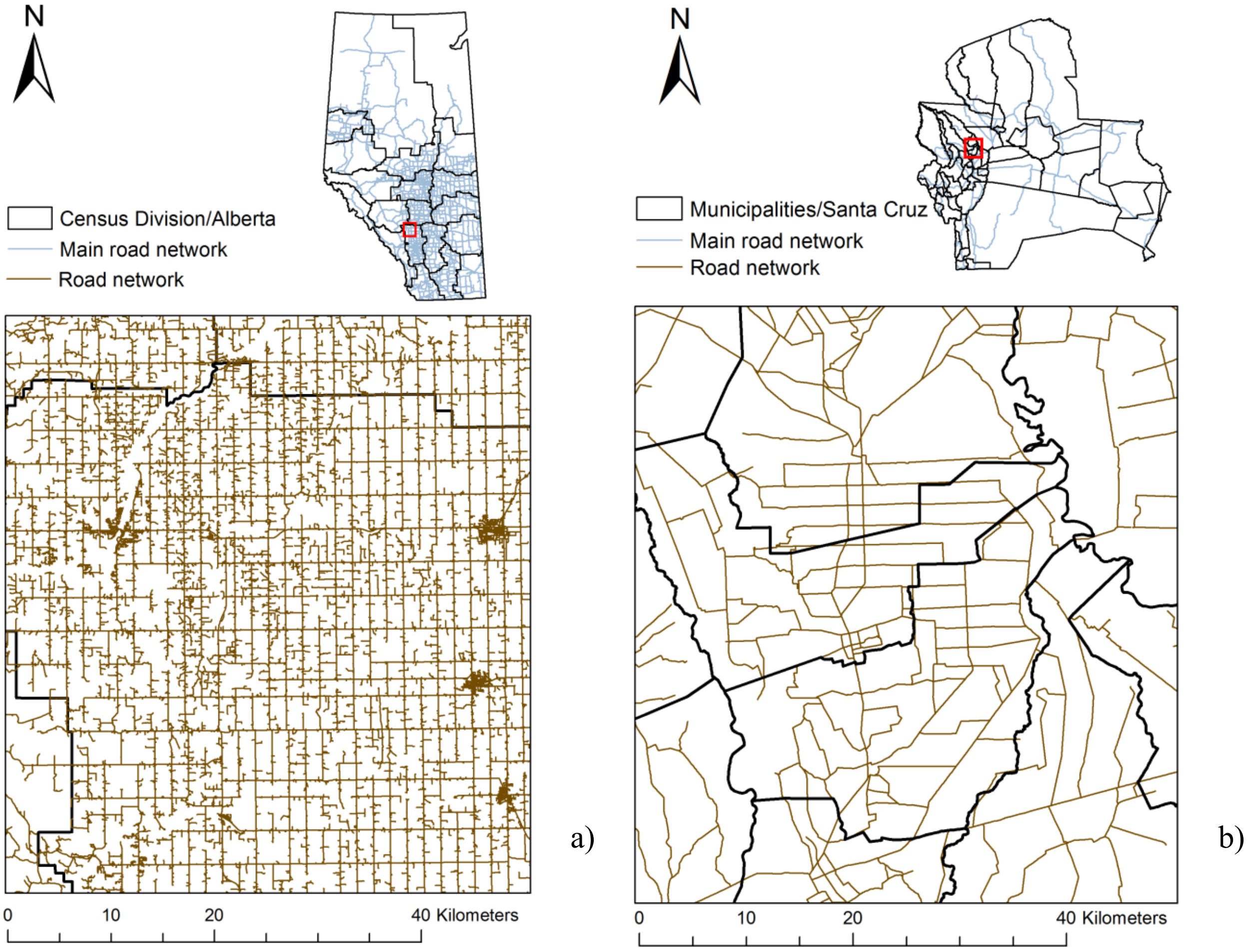


Figure 4-6: Road network comparison between (a) Alberta, Canada and (b) Santa Cruz, Bolivia

In this study, BCPs are located in such a way that it is possible to collect high amounts of biomass at locations close to the paved road network. In a previous study [15], the authors developed a model using ArcGIS for locating BCPs. The method they used is an iterative process that breaks the agricultural area into small square cells of 1 km. Each cell represents a candidate for a BCP, and the volume of biomass that can be collected in each cell is calculated. It is assumed that each cell collects the available biomass in a radius of 4 km. Based on the amount of biomass collected at the cell level, zones are created/classified, as shown in Figure 4-7. The model then selects the zone with high biomass concentration and chooses the closest cell to the road as the first BCP. The biomass around the first BPC is then no longer available; therefore, the biomass collection at each cell needs to be recalculated for the second iteration.

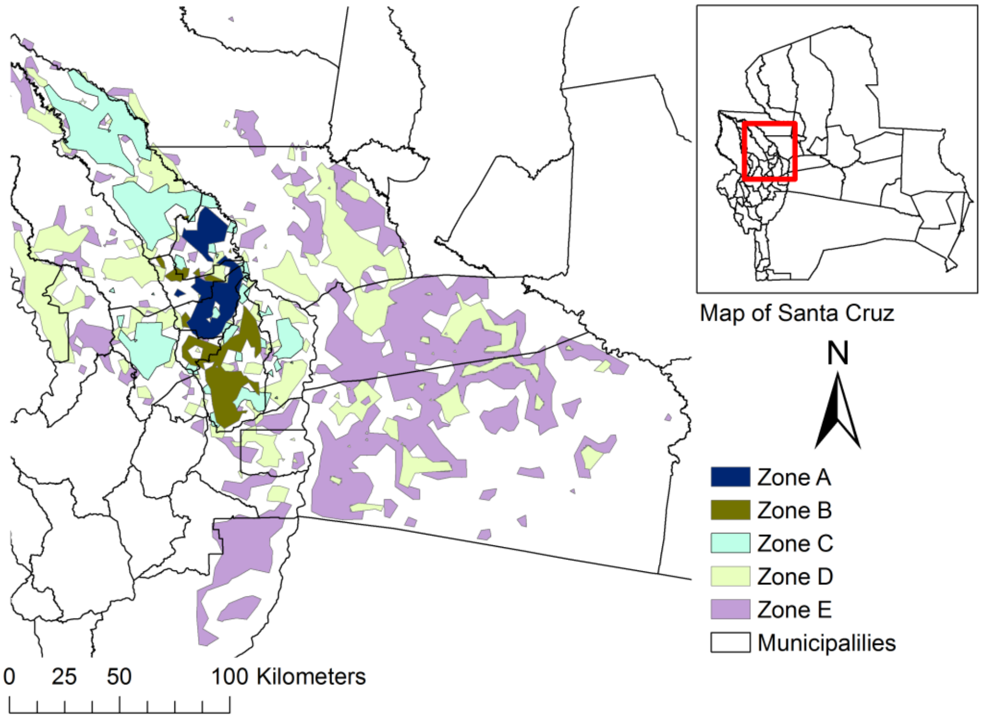


Figure 4-7: Classification of zones based on biomass collection

Following the method we used in the previous study [15], we located BCPs here in five different zones as defined in Table 4-7.

Table 4-7: Classification of biomass collection points per zone

Zone	Biomass collection criteria at BCP	BCPs per zone	Biomass [t] collected	Collection area [ha]	Average yield [t/ha]
A	> 20,000 t	17	367,561	85,452	4.3
B	15,000 -20,000 t	24	383,678	120,637	3.2
C	10,000 – 15,000 t	66	740,143	331,753	2.2
D	6,000 – 10,000 t	152	979,734	764,037	1.3
E	4,000 – 6,000 t	152	681,314	764,037	0.9
Total		411	3,152,430	2,065,916	1.5

In order to analyze the effect of biomass yield distribution, BCPs are located in two stages as follows:

1) BCPs are located in zones A, B, and C as suggested in our previous study [15] (see Figure 4-8[a])

2) BCPs are located in zones A to E. The area for locating BCPs is expanded to areas with lower biomass yield, using the same method as in our previous study [15]. (See Figure 4-8[b])

A location-allocation analysis is conducted in both cases to find the optimal site of a single 300 MW plant. The software ArcGIS calculates the actual road distance between each BCP and the facility. Figure 4-8 shows connecting lines between BCPs and the facility in both stages.

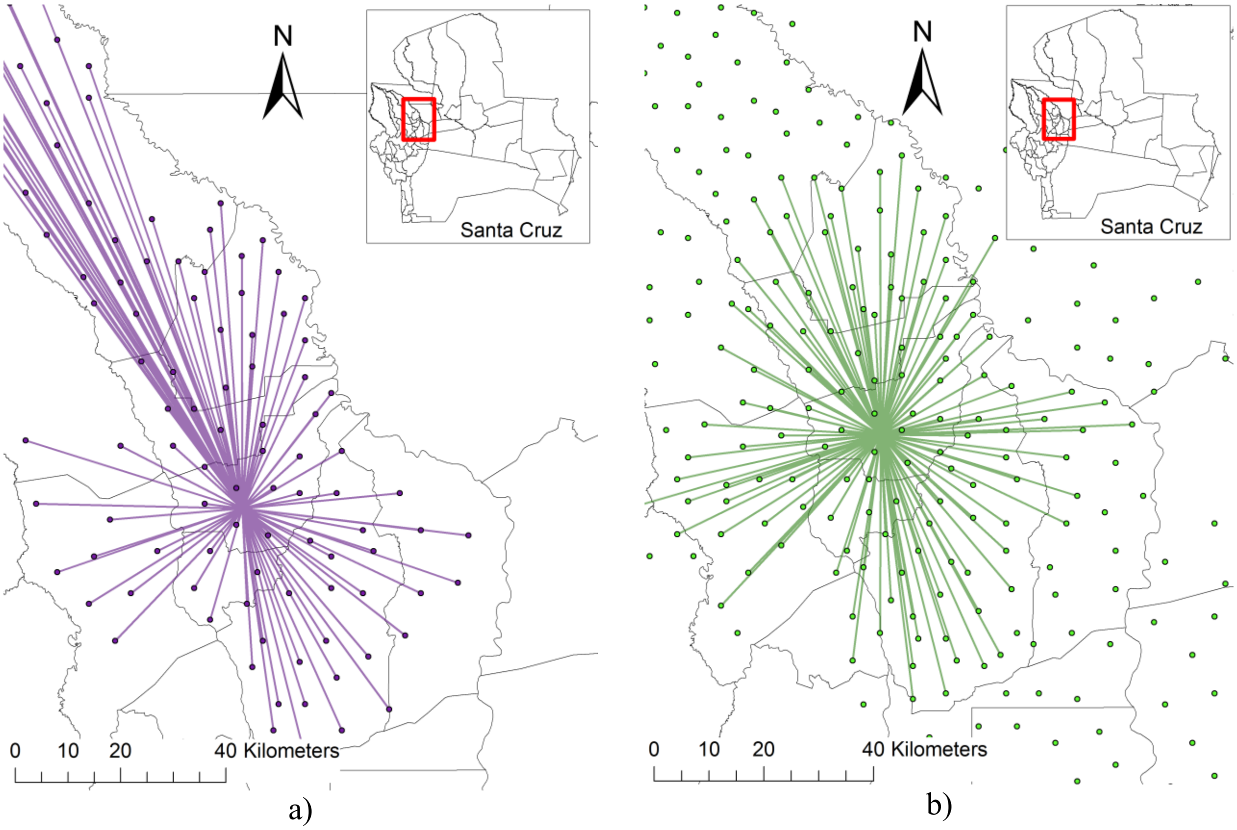


Figure 4-8: Biomass collection points and optimal plant site for 300 MW: (a) BCPs in zones A, B, and C and (b) BCPs in zones A to E

Figure 4-8 (a) shows the longer travel distances to collect feedstock from regions with high biomass availability and Figure 4-8 (b) shows the collection of the same volume including areas with low biomass yield.

Figure 4-9 shows the unit transportation cost graph for collecting biomass at both stages. The first stage, zones A, B, and C, shows that the unit transportation cost rate increases for higher biomass requirements since longer distances need to be traveled for collecting biomass, and yield decreases with distance. The second stage, zones A to E, shows the cost rate increases proportionally with biomass requirements. The unit transportation cost for large biomass requirements is lower when areas of low biomass yield are included for locating BCPs but near the facility. It is believed, though, that eventually the unit transportation cost will increase at a higher rate for very large biomass requirements due to insufficient biomass availability, long transportation distances, and fewer paved road networks at farther areas.

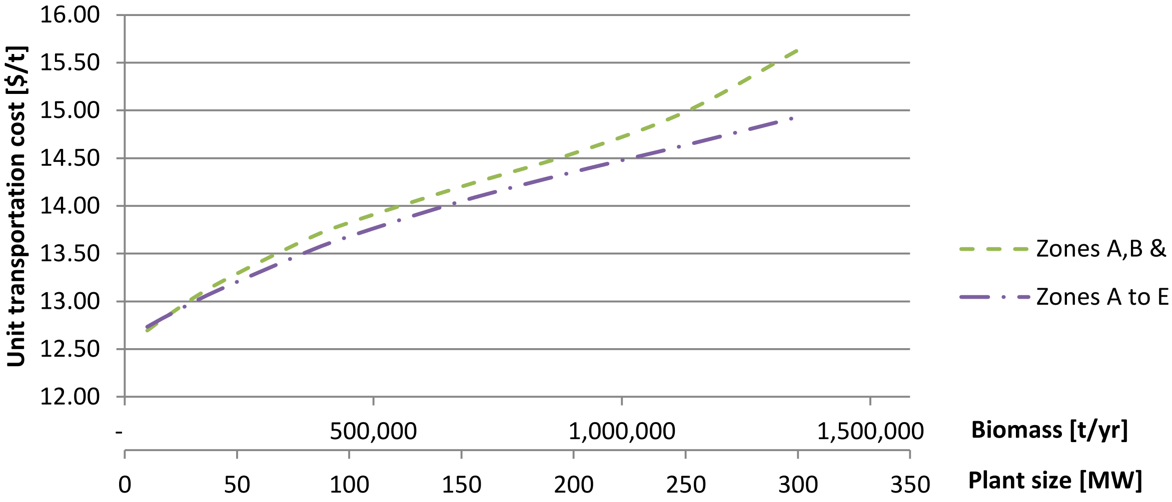


Figure 4-9: Transportation cost dependence on biomass yield distribution: (a) BCPs are located in zones A, B, and C, and (b) BCPs are located in zones A to E.

A location-allocation analysis was conducted to find the best location of the biomass power facility following the same parameters we used in a previous study [15]. The site is located in such a way that the sum of the products of biomass weight at each BPC and its corresponding real transportation distance to the facility is minimized. Figure 4-10 shows the biomass collection area for a 600 MW plant capacity, where BCPs are compacted in the central area and gradually dispersed at farther areas because of limited road networks and lower biomass availability.

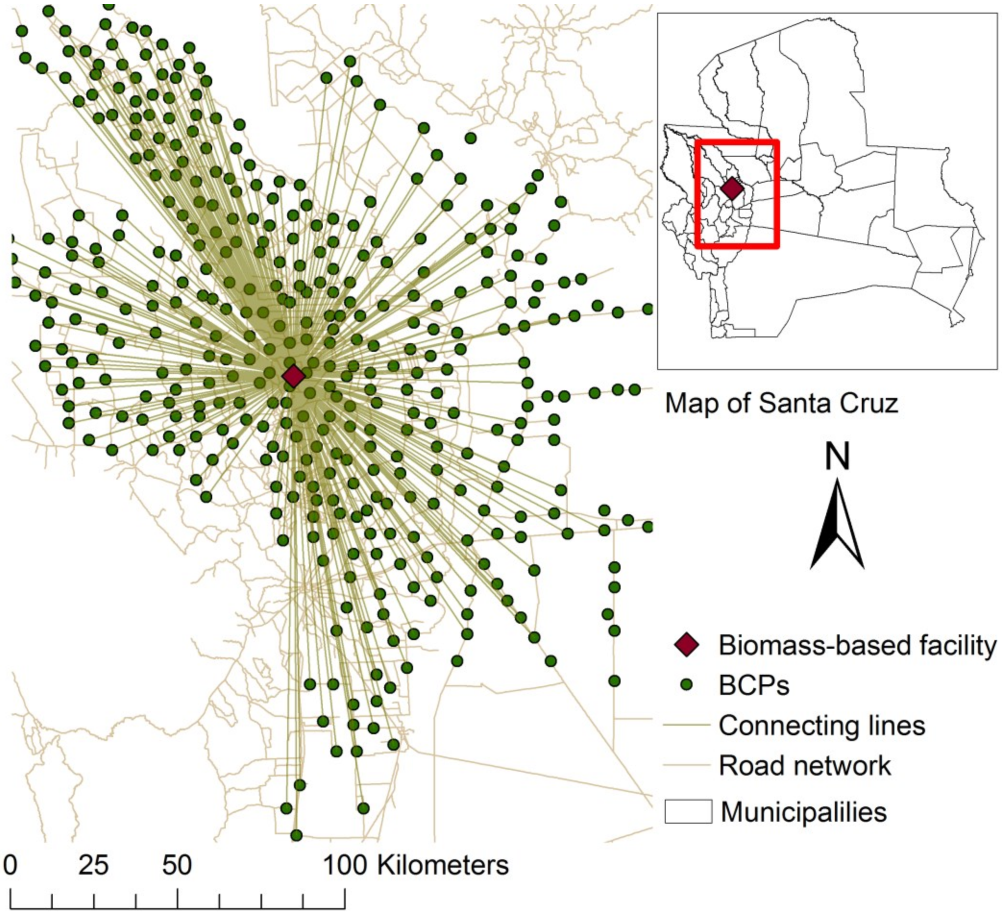


Figure 4-10: BCPs for a 600 MW power capacity

The location-allocation process in ArcGIS provides the transportation distance through the real road network between BCPs and the facility. Through this process, the transportation distance and corresponding cost were calculated for several plant sizes. These costs are shown in Figure 4-11. The unit cost rate increases at large biomass collection volumes. A third order polynomial regression was used in the economic model to estimate the unit transportation cost at different biomass requirements depending on the plant size.

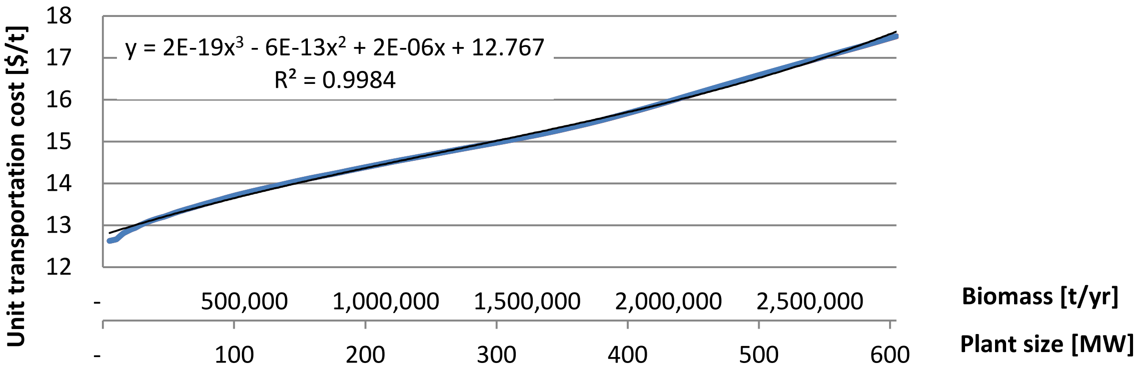


Figure 4-11: Unit transportation cost as a function of required biomass for corresponding plant size

4.2.4.2 Energy conversion cost analysis

As shown in Figure 4-3, the total energy cost is composed of the biomass logistics cost and the energy conversion cost (at facility). In this section, we analyze the energy conversion cost, which includes all the costs associated with the energy conversion that take place at the facility such as capital cost, labour cost, maintenance, general and insurance costs.

4.2.4.2.1 Capital cost

Due to the large range of biomass conversion technologies, various configurations of a particular technology, and types, properties, and availability of feedstock in a particular region, the capital cost of biomass-based energy conversion facilities varies significantly. This study is focused on combustion technology, the most mature and low-priced technology. Data on capital cost was collected from the literature [16, 18-20, 26, 33, 62-73]. Although the capital cost is difficult to compare when cost components are not specified, separation by combustion system type classified the capital costs for grate-firing and fluidized bed (including bubbling and circulating fluidized bed). Care has been taken in collecting data for dedicated biomass combustion.

The most common size for a biomass-based combustion facility is 50 MW; however, the maximum capacity of a single combustion unit has been reported as high as 300 MW for both combustion technologies with no technology limitation [74-76]. After 300 MW, two or more same-size combustion units are considered. The cost of the second or third unit is 95% of the first [16, 18]. The collected data for capital costs were collected from the studies listed in Table 4-8.

Table 4-8: Reported capital costs at several plant sizes using various biomass combustion technologies

Region	**Feedstock type**	**Combustion system**	**Capacity range (MW)**	**Capital cost [million $, 2017]**	**Source**
Denmark	Straw	Movable grate	8.3	91	[62]
Alberta	Wood chips, applicable to any abundant biomass source.	Direct combustion. Conventional steam cycle	up to 500	1,038	[18]
Italy	Wood waste, agricultural crops, by-products, agro-industrial, and wood waste.	Fluid bed combustion, followed by steam turbine cycle	5-50	45-167	[19]
US	Wood, municipal waste, crop residues	Traveling, circulating boiler, and CFB	6-60	26-60	[63]
US	Woody biomass	Combustion steam boiler/turbine	8-20	33-75	[67]

US	Forest and agricultural residues	Water steam boiler, no combustor type specified	3-25	23-113	[64]
US	MSW, agricultural, and wood residues.	Dedicated biopower stoker	25-100	110-279	[65]
US & South America	Agricultural and forestry waste	Grate, CFB/BFB boilers.	6-40	11-80	[77]
Alberta	Agricultural residues	Direct combustion	up to 450	1,340	[16]
Alberta	Triticale straw	Direct combustion	5-500	15-1,257	[20]
US	Urban wood waste, forest and agricultural residues	CHP, no combustor type specified	75-100	291-357	[69]
US	Mill, forest, urban	Grate stoker and fluidized bed	46 & 60	224-297	[70]
Alberta	Woody biomass	CFB	up to 450	643	[26]
US	Wood, agro waste	Biomass steam power plant. Grate and FBC	50	143	[78]

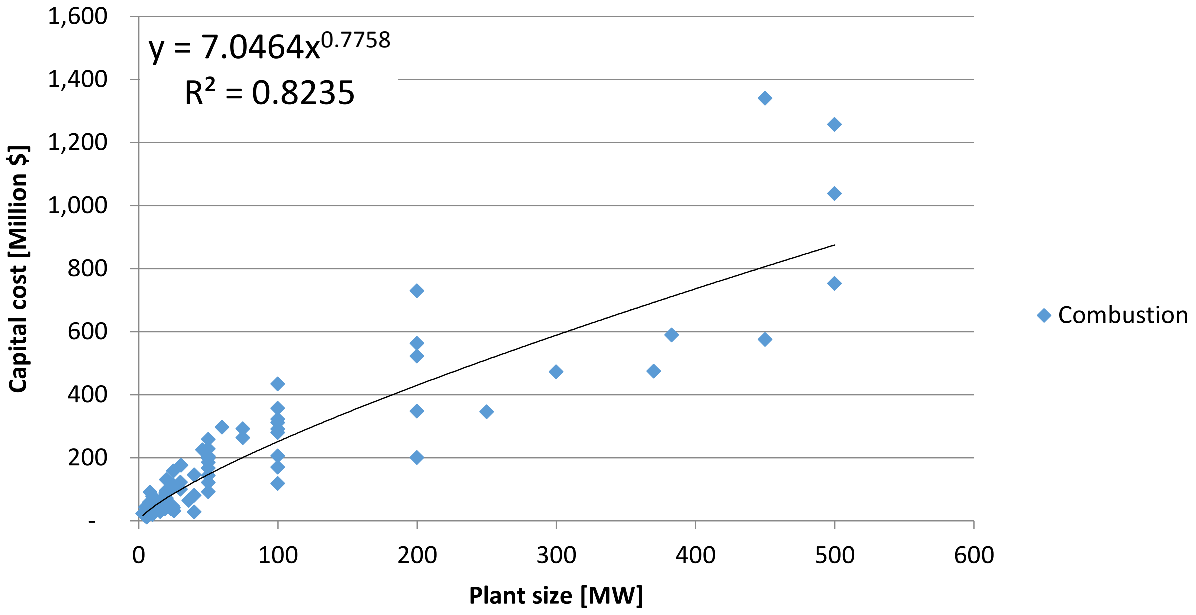
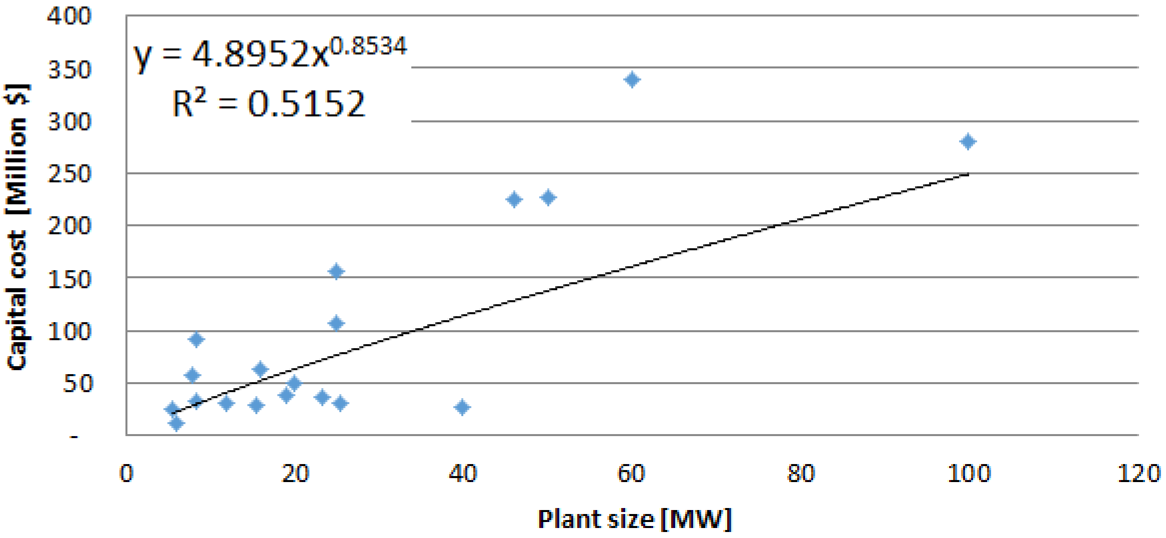


Figure 4-12: Capital cost of various biomass combustion technologies

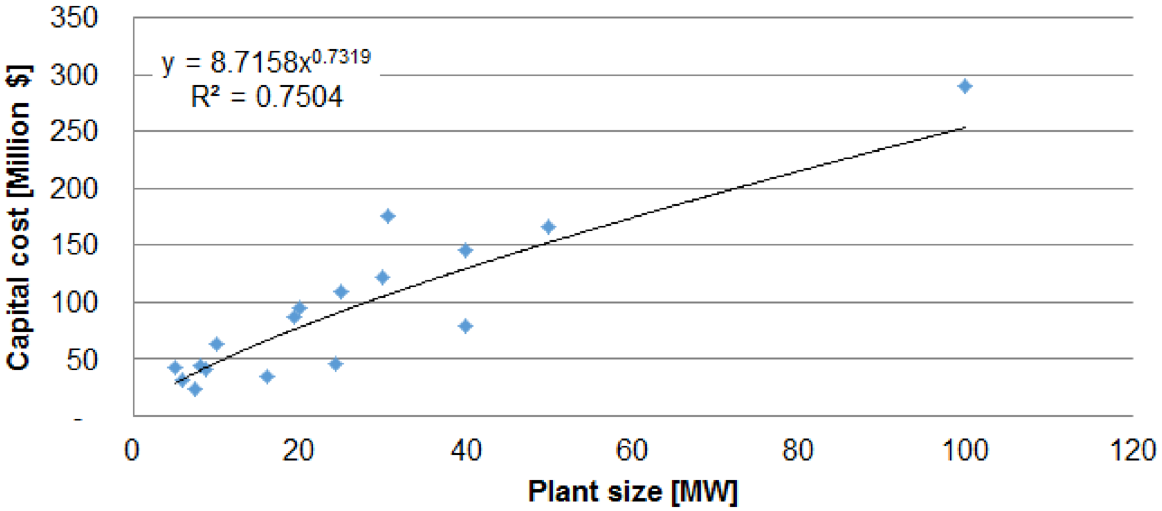
Using the data from the studies listed in Table 4-8, a power regression analysis was applied to capital cost and plant capacity data to obtain Equation 4-4.

$$CC[million\$] = 7.05 \cdot (Capacity\ [MW])^{0.78} \tag{4-4}$$

Equation 4-4 is used to estimate the capital cost of combustion technology as a reference case for a given plant capacity. Most of the sources in Table 4-8 report the capital cost of combustion technology with no subdivision specification. Here, a further technology subdivision based on grate-firing or fluidized bed was considered using only the sources that stated the kind of combustion technology. The capital cost trend for each technology type is shown in Figure 4-13.



(a)



(b)

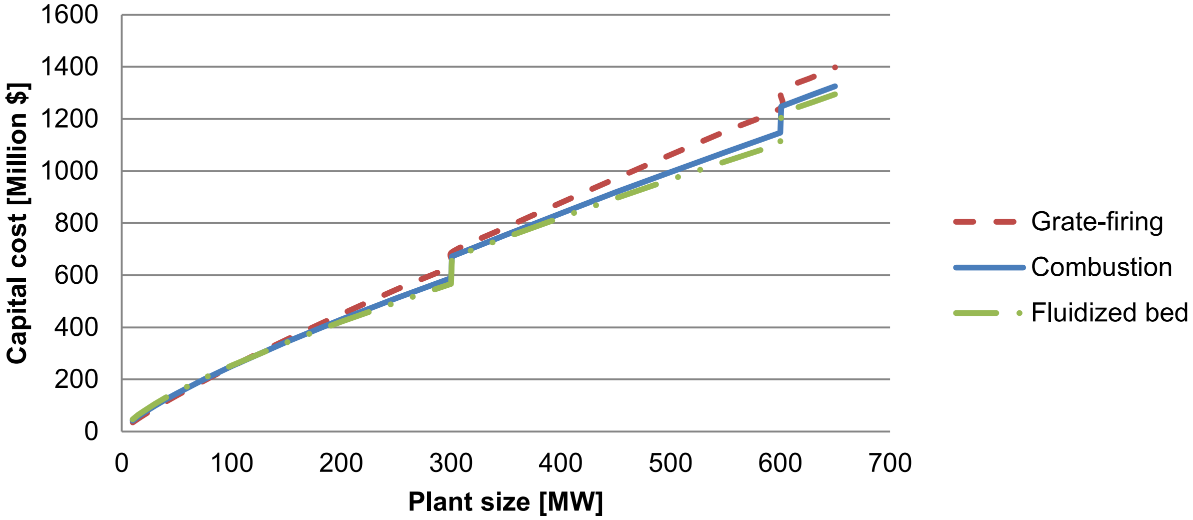
Figure 4-13: Capital cost trend in sub-classification of combustion technologies: (a) grate-firing, (b) fluidized bed

Equations 4-5 and 6 obtained from the regression analysis were used to estimate the capital cost for grate-firing and fluidized bed combustion technology, respectively, for power plant capacities ranging from 5 to 300 MW, the maximum unit size [74-76].

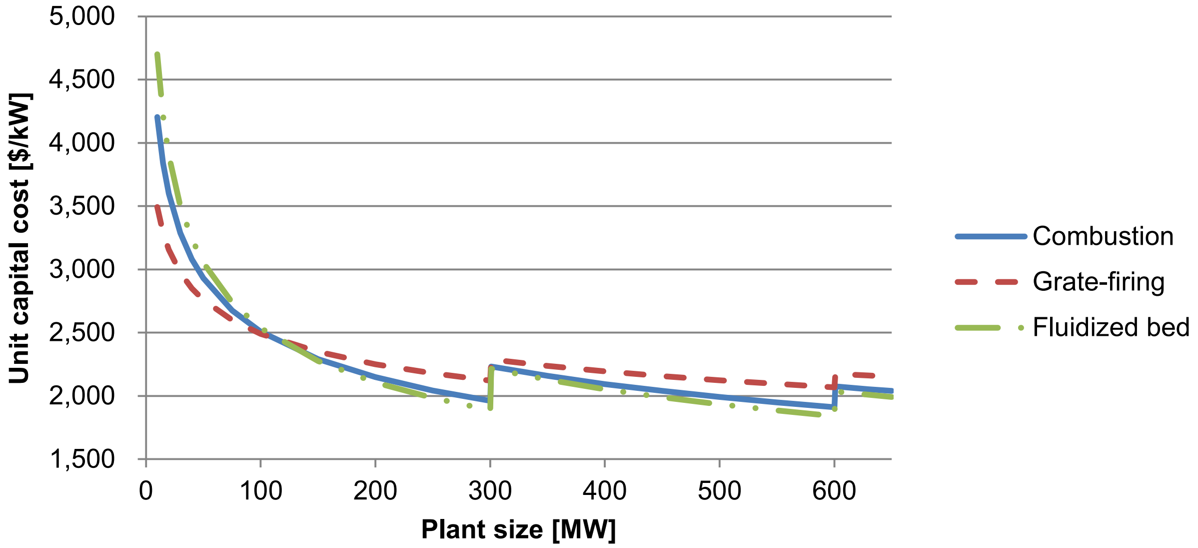
$$CC[million\$] = 4.89 \cdot (Capacity\ [MW])^{0.85} \tag{4-5}$$

$$CC[million\$] = 8.72 \cdot (Capacity\ [MW])^{0.73} \tag{4-6}$$

Although few sources reporting capital cost specify the combustion system type, Figure 4-14 (a) shows consistency in the cost projection by comparing the cost trend of grate-firing and fluidized bed with our reference case. The difference in capital cost between grate-firing and fluidized bed becomes pronounced at large sizes due to economies of scale, which means the capital cost per unit of power decreases when the power plant capacity increases. Figure 4-14 (a) shows that the effect of economies of scale is more evident for fluidized bed than grate-firing combustion, as stated by IRENA [33] as well. Right after 300 MW and 600 MW, the capital costs increase sharply (see Figure 4-14 [a] and [b]). This is due to the maximum capacity limitation and the additional same-size combustion unit for larger capacities. The cost of the second or third combustion unit is 0.95 times the cost of the first [16].



(a)



(b)

Figure 4-14: Effect of economies of scale on the capital cost of combustion technologies: (a) capital cost, (b) capital cost per unit of power

Although Figure 4-14 (b) is obtained from Figure 4-14 (a) and shows the same effect from economies of scale, it allows us to clearly see that the capital cost of grate-firing for small plant sizes is lower than for fluidized bed, but this is the opposite for large plant sizes. It also shows the capital cost per unit product decreases at a low rate for large plant sizes.

4.2.4.2.2 Operating and maintenance cost (O&M)

IRENA classifies the O&M cost as fixed and variable costs [33]. Other sources combine fixed and variable into a single O&M cost. In this study, the O&M cost is composed of maintenance cost, ash transport cost, labour cost, insurance and general costs, as Caputo et al. have done [19]. Maintenance is usually estimated as a percentage of capital cost [17, 19, 64, 77]; here 3% was assumed. The biomass ash, a product from biomass combustion, is transported from the energy facility to either landfills or farm fields. Caputo et al. [19] assume that the ash flow rate is 2% of the total annual biomass combusted. Here, the ash transport cost is assumed to be 2% of the biomass transport cost. The insurance and general cost is assumed to be 1% of capital cost [19].

The labour cost depends on the plant capacity, number of employees, and employee position. Labour cost in bio-energy plants are higher than in fossil fuels plants because of the handling requirement [72]. Table 4-9 shows the employee numbers for different plant capacities reported in previous studies [19, 20, 64, 67, 72, 79].

Table 4-9: Employee numbers in biomass power plants for different capacities

Conversion technology	Plant capacity [MW]	Number of employees	Source
Anaerobic digestion	15-45	19	Ullah et al. [79]
Combustion	7-20	14-25	Turnbull [72]
Combustion	5-20	30	Energize Missouri [67]
Fluidized bed combustion	5-50	12-36	Caputo et al. [19]
Combustion	20-40	20-40	IFC [64]
Combustion	300	69	Dassanayake [20]

In order to estimate the number of employees and positions, we divided the biomass-based energy conversion facility into three sections: biomass reception and handling, energy conversion, and gas cleaning [19]. Workers in the biomass reception and handling area are responsible for coordinating biomass delivery, storage, and biomass availability. The energy conversion area includes the combustor, heat transfer tubs, turbines, and generators. Workers in this area are responsible for operating and controlling the combustion system. Workers in the gas cleaning area are in charge of filtration equipment and ash management. There is one supervisor in each of these three sections. The number of operators in each section changes with plant size (see Figure 4-15 and Table 4-9). Other employees work in areas connected to the previous section (e.g., maintenance, laboratory, and safety and environment) and administration and financing. Finally, at the top of the organization chart are the plant manager and plant engineer.

Figure 4-15 shows employee positions and distribution. The employee number in some positions does not change with plant size, while other positions require more people for larger plant sizes. These positions are highlighted in the diagram boxes. The increase in employee number is not directly proportional to plant size because automated processing at large plant sizes is assumed.

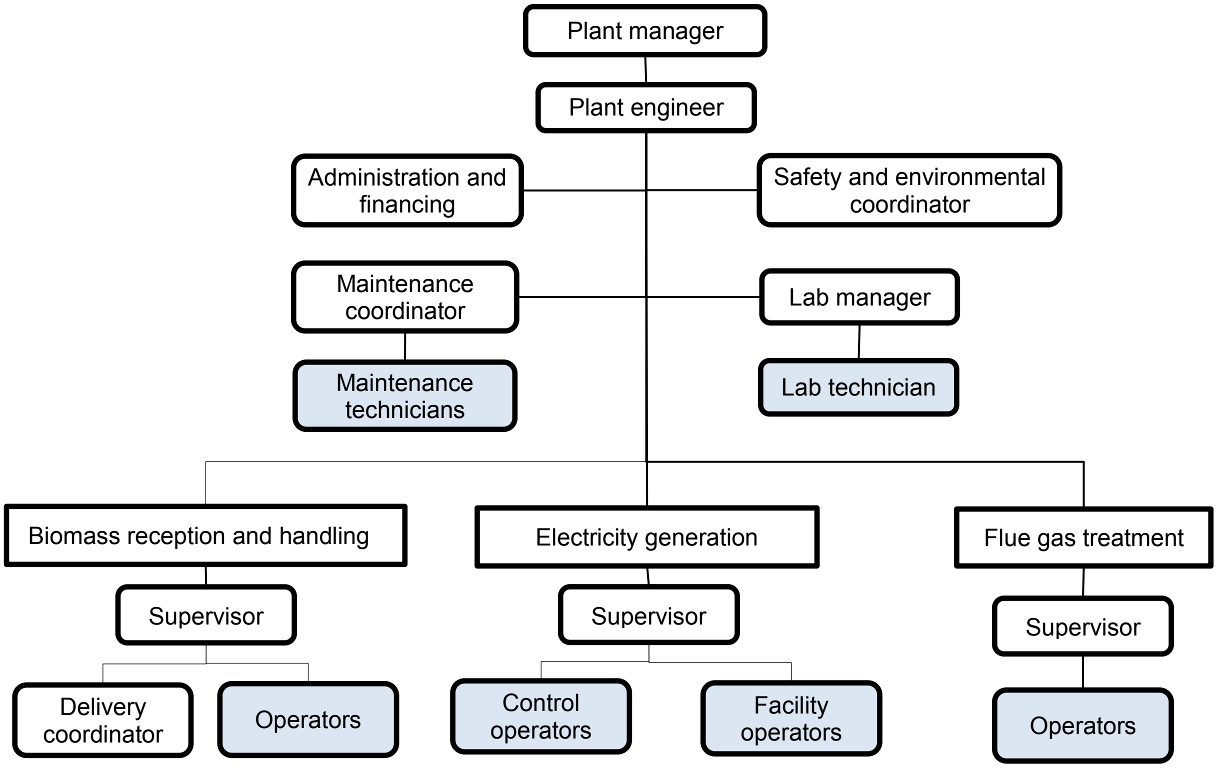


Figure 4-15: Biomass conversion facility employee organization chart

Using the employee organization chart, we determined employee numbers for every position. The salary was based on the salary scale of ENDE [80]. The number of employees and salary cost estimates for different plant sizes are presented in Table 4-10.

Table 4-10: Labour cost estimates

Position	**Labour [$/yr], 2017**	**Plant capacity [MW]**				
		5-15	**15-30**	**30-50**	**50-100**	**100-300**
Plant manager	71,423	1	1	1	1	1
Plant engineer	46,749	1	1	1	1	1
Administration and financing	15,769	2	3	3	4	4
Safety and environmental coordinator	25,044	2	2	2	2	2
Maintenance coordinator	25,044	1	1	1	1	2
Maintenance technicians	20,407	4	6	8	10	12
Lab manager	18,551	1	1	1	1	2
Lab technician	13,914	1	2	3	4	5
Biomass reception and handling						
Supervisor	29,682	1	1	1	1	2
Delivery coordinator	14,841	1	1	1	1	2
Operators	9,276	7	9	11	13	15
Electricity generation						
Supervisor	29,682	1	1	1	1	2
Control operators	17,624	1	2	2	2	4
Facility operators	14,814	1	2	4	6	8
Fuel gas treatment or cleaning						
Supervisor	29,682	1	1	1	1	2
Operators	9,276	1	2	3	4	5
Total employee number		27	36	44	53	69
Total labor cost [$/yr]		549,492	680,279	792,515	920,519	1,215,486

4.2.4.3 Revenue system analysis

In Bolivia, the revenue system is determined by power generator type. Power generators using natural gas, biomass, and hydro can ensure firm capacity; therefore, these facilities receive revenue for the energy they inject into the grid and for the capacity they have to generate electricity instantly. Generators that are not in the regulated market or that provide electricity to an isolated system have a different revenue system [81]. Solar and wind do not receive revenue from capacity because they cannot ensure firm capacity, but they receive a single revenue for the energy they generate, which includes an additional payment and adaptability factors in order to recover the capital cost [81, 82].

4.2.4.3.1 Revenue from energy

The revenue from energy is the amount of money power generators receive for the electricity that is delivered into the national interconnected system. The revenue from energy expressed in \$/MWh fluctuates hourly and mostly depends on consumer demand. The entity in charge of regulating this value is the National Load Dispatch Committee (Comité Nacional de Despacho de Carga, CNDC). Based on values reported by the CNDC [82], the average revenue from energy in natural gas-based power plants is assumed to be 19.5 \$/MWh (for 2017).

4.2.4.3.2 Revenue from capacity incentives

The revenue from capacity is an incentive for generators to invest in new units or equipment in order to increase the electricity generation capacity. A higher capacity reserve offsets the risk of rationing or interruptions due to unexpected higher demand. The revenue from capacity incentives is updated every six months and is defined by the Wholesale Electricity Market

(Mercado Electrico Mayorista, MEM) [82]. Based on recorded capacity incentives from the CNDC [82], a revenue of 9.7 \$/kW-month is estimated for the base year of this study.

4.2.4.3.3 Carbon Credits

A project conducted for Guabirá [34], a bagasse-based power plant in Bolivia, reported the Certified Emission Reductions (CERs) price as 16.25 $\$/tCO_2$ and calculated the emission factor as 0.68 tCO_2/MWh in 2006. However, the carbon credit revenue that Guabirá is actually receiving is 5 $\$/tCO_2$ with an emission factor of 0.7 tCO_2/MWh [83]. The techno-economic model here considers a carbon credit revenue of 5 $\$/tCO_2$ and an emission factor of 0.7 tCO_2/MWh.

4.2.5 Economic model outputs

4.2.5.1 Levelized cost of electricity (LCOE)

The levelized cost of electricity is an important economic indicator widely used to compare technologies [28, 77, 84-87]. The LCOE is calculated on the bases of present value, which includes only the costs to generate electricity: capital cost, fuel cost and O&M cost, and the discounted lifetime energy generation, which corresponds to the earnings from energy [77, 86]. In order to avoid deviations in the economic indicator value due to various regional price systems, revenues, incentives, and financial supports are not included in this calculous [28, 77]. The LCOE is a unique value representing the cost of building and operating the power plant throughout its lifetime and is calculated using Equation 4-7 [85]:

$$LCOE = \frac{Sum\ of\ lifetime\ cost}{Sum\ of\ lifetime\ electricity\ production} = \frac{\sum_{n}^{N} \frac{I_n + M_n + B_n}{(1+i)^n}}{\sum_{n}^{N} \frac{E_n}{(1+i)^n}} \tag{4-7}$$

where I_n is the capital cost in year n, M_n is the O&M cost in year n, B_n is the biomass cost, which includes logistics and transportation costs, E_n is the electricity production at year n, i is the discounted rate, and N is the facility lifetime in years.

4.2.5.2 Energy cost

The energy cost is calculated for the first year of generating electricity; its value increases annually with inflation. This is the minimum cost, expressed in $/MWh, at which electricity is sold for an IRR of 12%. The energy cost considers sources of revenues of capacity incentives and carbon credits as well.

4.2.5.3 Sensitivity analysis

The sensitivity analysis evaluates the impact of cost components and other parameters on the energy cost. The cost components assessed are capital cost, biomass cost (e.g., harvesting, baling, transportation to BCPs, storing, nutrient replacement, and premium to farmer), transportation to the facility, and labour cost. Economic parameters assessed include IRR and inflation rate, and characteristics of the conversion facility include efficiency and capacity factor. The variation in revenue sources (capacity incentives and carbon credits) was also assessed.

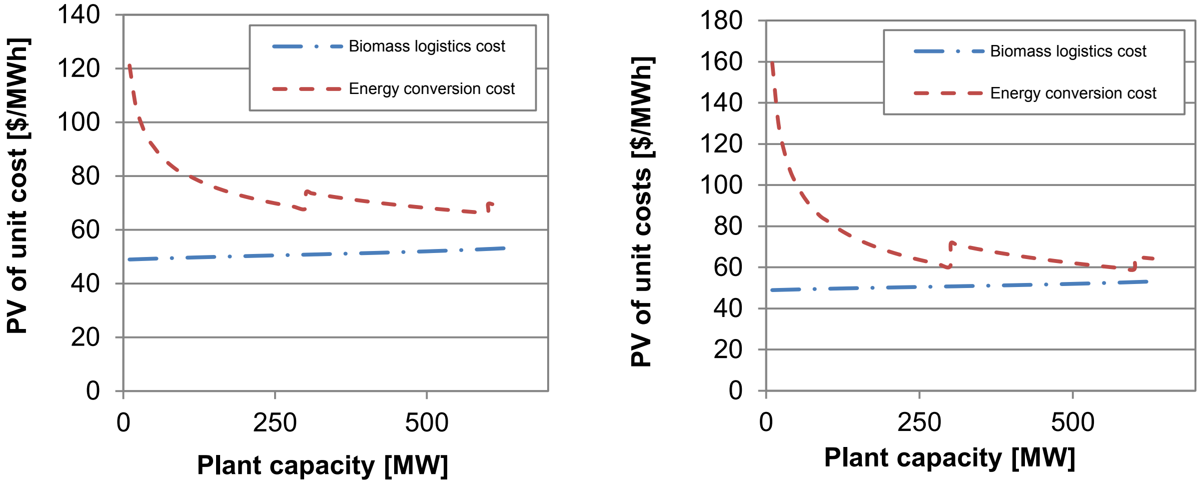
4.3 Results

An economic model called ENBIOTEM was developed to analyze the cost of generating electricity using agricultural residues through combustion technology in Bolivia. The biomass costs corresponding to the chain of processes including harvesting, premium to farmer, nutrient replacement, baling, transportation to BCPs, and storing were analyzed and defined in our base case assumptions. The transportation cost components were estimated through a regression analysis of data collected by personal communication with transportation companies. Using a GIS, we estimated the transportation distances from BPCs to the energy conversion facility, and from that, the cost associated with a given plant capacity. Capital costs of combustion technologies at different capacities were collected from the literature, and through a regression analysis we obtained an equation to estimate capital cost for a given capacity.

For our base case, the model estimated the optimal plant capacity, the levelized cost of electricity, and the energy cost. These results were compared with the levelized cost of electricity reported by others and the current energy cost from various sources in Bolivia.

4.3.1 Optimal plant size and levelized cost of electricity (LCOE)

In order to analyze the optimal plant capacity based on costs, we grouped the costs per unit of energy produced into two groups: costs that increase with increasing plant size and costs that decrease with increasing plant size. The first group is made up of the biomass logistic costs, which include harvesting, premium to farmer, nutrient replacement, baling, transportation to BCPs, storing, and transportation cost from BPCs to the energy conversion facility. This last cost increases at a higher rate for large plant capacities. The second group is made up of the energy conversion costs, which include capital costs and O&M costs (e.g., labour cost, maintenance cost, insurance, and general cost). The ENBIOTEM model was used to estimate these two cost groups; our base case assumptions were kept constant while the plant capacity was changed from 5 to 650 MW. Figure 4-16 shows the biomass logistic costs and energy conversion costs for grate-firing (Figure 4-16 [a]) and fluidized bed combustion (Figure 4-16 [b]). Both figures show the opposite behaviour in the two cost groups: increasing the capacity reduces costs due to economies of scale but increases transportation costs due to increased travel distances to collect larger volumes of biomass.



(a) (b)

Figure 4-16: Biomass logistics cost and energy conversion cost dependence on plant capacity for: (a) grate-firing, (b) fluidized bed

The sum of all these costs (biomass logistics, capital cost, O&M cost) throughout the lifetime of the facility is the LCOE [$/MWh] (Figure 4-17), which has a minimum value at the optimum plant size. Plant capacities higher than the optimal size are not considered economically viable options. The LCOEs for both technologies (grate-firing and fluidized bed) are compared on Figure 4-17; the LCOE for grate-firing combustion is lower than for fluidized bed for small plant sizes (lower than 50 MW). For capacities above 100 MW, fluidized bed technology offers the lowest LCOE. Figure 4-17 shows that the minimum LCOE is 119 $/MWh for grate-firing and 111 $/MWh for fluidized bed, both for a 300 MW plant capacity.

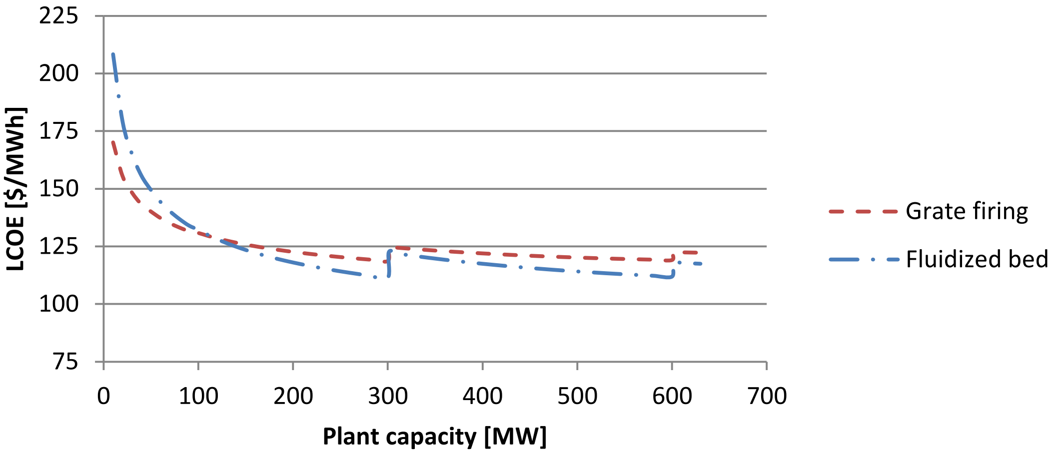


Figure 4-17: Levelized cost of electricity for grate-firing and fluidized bed technologies at different plant capacities

Assuming 300 MW as the maximum unit size significantly increases the LCOE for larger capacities since two units of the same size need to be built. On the other hand, the LCOE decreases at a low rate right before the limit size is reached, which indicates the plant could be built in a range of capacities without significantly affecting the LCOE. For example, the power plant could be built from 200 to 300 MW and 380 to 600 MW without increasing the LCOE more than 6% with respect to the minimum LCOE (111 $/MWh for fluidized bed technology). A similar profile has been reported in previous studies [16, 18, 20].

The LCOE composition for both combustion technologies at the optimal size, 300 MW, is shown in Table 4-11. The main cost difference between these two technologies is attributed to capital cost, which is also reflected in maintenance, insurance, and general costs. The other cost components remain the same for two combustion technologies.

Table 4-11: LCOE components for power generation

Cost component	LCOE [$/MWh]	
	Grate-firing	Fluidized bed
Capital cost recovery	60.6	45.1
Harvesting (cutting, hopping)	7.2	7.2
Baling	12.0	12.0
Transportation to collecting points and storage	2.9	2.9
Nutrient replacement cost	10.3	10.3
Premium to the farmer	5.7	5.7
Transportation to facility	12.5	12.5
Labour	0.8	0.8
Maintenance	14.7	11.0
Insurance and general costs	4.9	3.7
Ash transport	0.3	0.3
Total cost	**131.8**	**111.3**

As shown on Figure 4-17 and Table 4-11, fluidized bed combustion technology has the lower LCOE. For the rest of the analysis, therefore, the focus will be on this technology at the optimal plant capacity of 300 MW.

The LCOE calculated here is compared with other LCOEs reported in previous studies. IRENA [77] reported LCOE values for different renewable energies in various regions; those for biomass technology are listed in Table 4-12, where the weighted average for South America is 99 $/MWh. The LCOE obtained here is 111 $/MWh, 12% higher, but closer to South America’s than other regions.

Table 4-12: Regional weighted-average biomass-based LCOE [77]

Region	LCOE [$/MWh]
Asia	46.7
Africa	57.7
North America	78.1
South America	99.3
Europe	144.9

The LCOE components obtained here were compared with the LCOE components from an economic model presented in a previous study in the same research area, power generation via combustion technology using triticale straw [20]. Figure 4-18 shows that the cost components are proportional. Capital cost and transportation cost are slightly lower in the present study. Capital cost, here, is merely for fluidized bed combustion, while the previous study considered combustion without specifying the type. Transportation cost is lower here because of the low variable cost component, which is an advantage for a biomass facility. The higher cost component in the comparison is the nutrient replacement cost, mostly due to the high importing cost, which negatively affects agricultural residue use for energy generation.

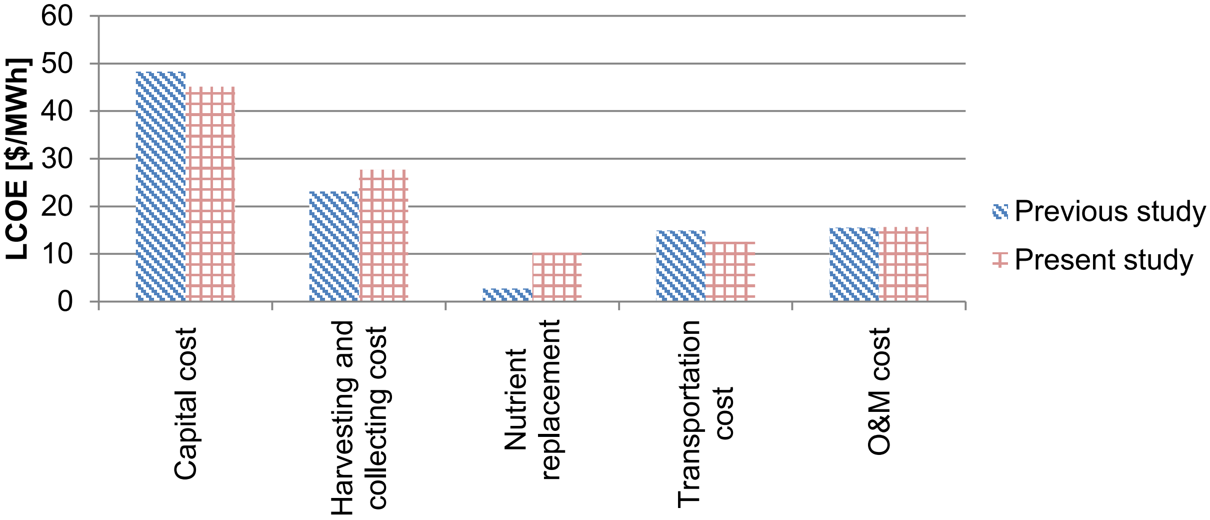


Figure 4-18: LCOE comparison with Dassanayake's study [20]

4.3.2 Energy cost analysis

Assuming the capacity incentives and carbon credits remain constant, the ENBIOTEM model estimates the energy cost in the first year of operation at 12% IRR. The energy cost at the optimal case (i.e., 300 MW plant size for fluidized bed technology at a minimum LCOE of 111 $/MWh) is estimated at 71.56 $/MWh for the first year. The energy cost increases annually due to inflation. The corresponding cash flow for this project is shown in Figure 4-19, which indicates that the cumulative discounted cash flow at the end of the power plant lifetime is zero and the investment cost is recovered after 20 years at a 12% IRR.

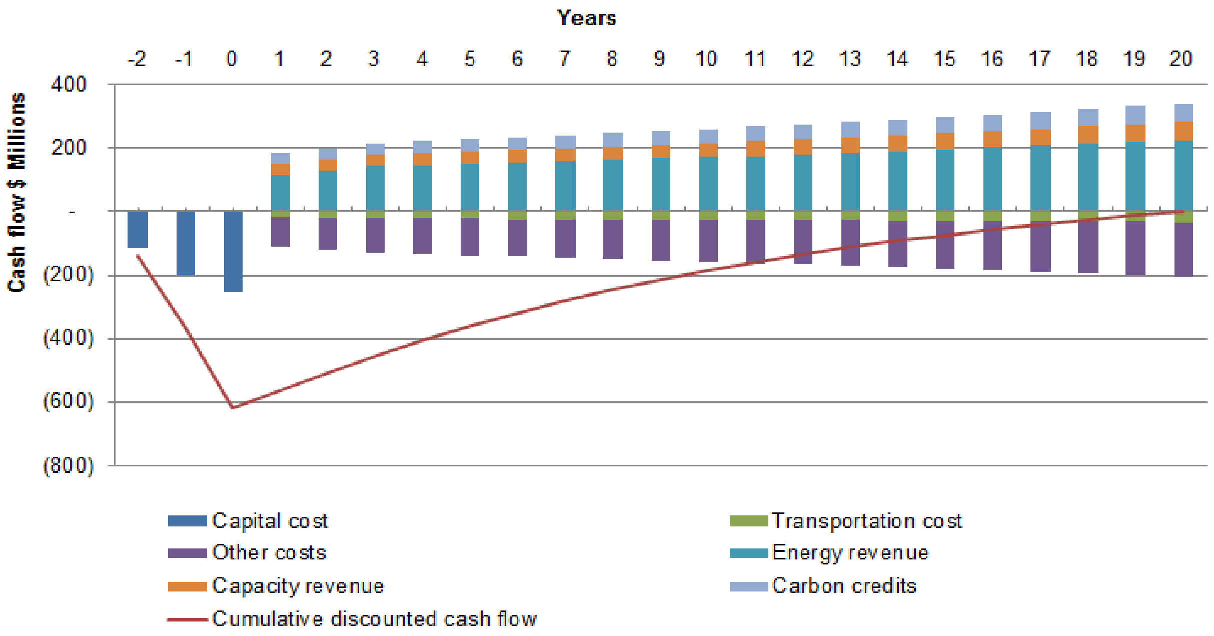


Figure 4-19: Cash flow for fluidized bed combustion technology at 300 MW

The current energy cost from natural gas-based power plants in Bolivia is 19.5 $/MWh, which is lower than the energy cost suggested in this study. A previous study estimated the energy cost for proposed hydro projects in Bolivia [24]. As it can be observed in Table 4-13, the energy costs from these hydro projects are higher than the current energy cost, which implies that hydro is not competitive unless the natural gas subsidy is removed. The energy cost from hydro is lower than the value suggested here, i.e., 71.6 $/MWh. However, the infrastructure of hydro projects involves geographic transformations (e.g., clearing forest areas, deviation of river channels and river levels), relocation of nearby communities, and increase in the vulnerability of protected areas, fauna, and flora species [88, 89]. On the other hand, the use of biomass from agricultural residues means exploiting an available source that is being wasted in a facility whose construction does not require such significant modifications as hydro plants.

Table 4-13: Energy cost estimated for hydro projects [24]

Hydro projects	Capacity [MW]	[$/MWh, 2017]
Misicuni	40	52
Unduavi	45	39
Miguillas	203	54
San Jose	69	31
Rositas	400	54

4.3.3 Sensitivity analysis results

A sensitivity analysis was conducted to study the impact on energy cost of changes in the combustion unit size, main cost components, economic parameters (i.e., IRR, inflation rate), power plant characteristics (i.e., efficiency and capacity factor), and other sources (i.e., capacity incentives, carbon credits).

4.3.3.1 Effect of combustion unit size

Since the optimum size and minimum LCOE were determined through the restricted unit size of 300 MW, we considered other unit size limits in order to see the impact on results, as seen in Figure 4-20.

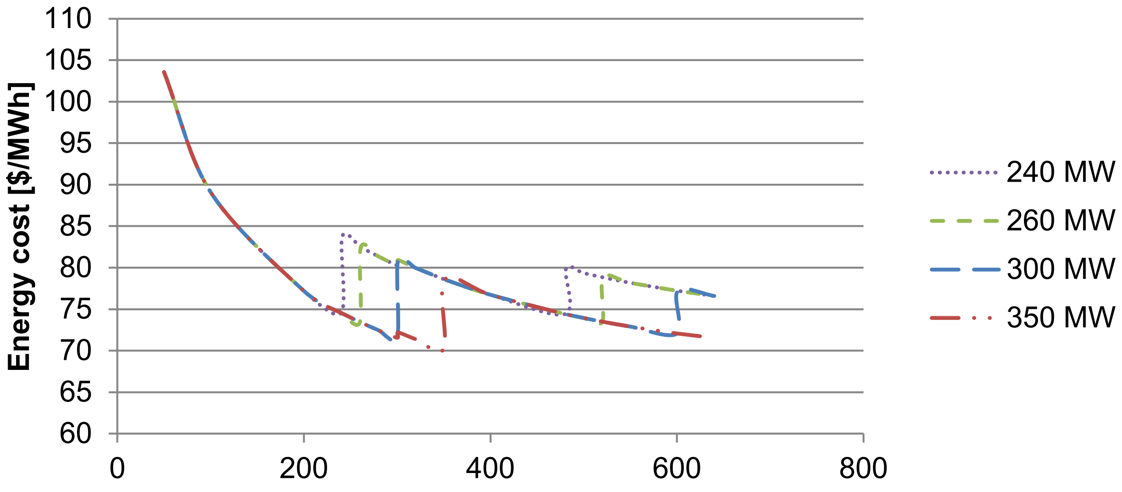


Figure 4-20: Effect of unit size limit on optimal capacity and energy cost

If the unit size increases to 350 MW, the energy cost decreases by only 2%. Table 4-14 shows that the unit limitation is an important parameter for defining the optimal size and energy cost. If the maximum unit size is 240 MW, the optimal size becomes 480 MW, which means two units are considered. In most cases, the optimal plant size is determined by the first unit size limitation.

Table 4-14: Unit size limitations

Unit limitation [MW]	Optimal size [MW]	Energy cost [$/MWh]
350	350	70.2
300	300	71.6
260	260	73.4
240	480	74.4

4.3.3.2 Effect of revenue from capacity incentives and carbon credits

Figure 4-21 shows the effects of changing the capacity incentive and carbon credit revenue on the energy cost. The energy cost could potentially decrease from 71.6 to 64 \$/MWh if carbon credits increase from 5 to 17 \$/tCO$_2$, as a previous study suggested for Guabira, a bagasse power facility in Bolivia [34]. If new policies increase the revenue from capacity incentives from 9.5 \$/MWh to 30 \$/MWh, the energy cost could decrease from 71.6 to 33 \$/MWh. Therefore, there should be more focus on increasing capacity incentives instead of on carbon credits.

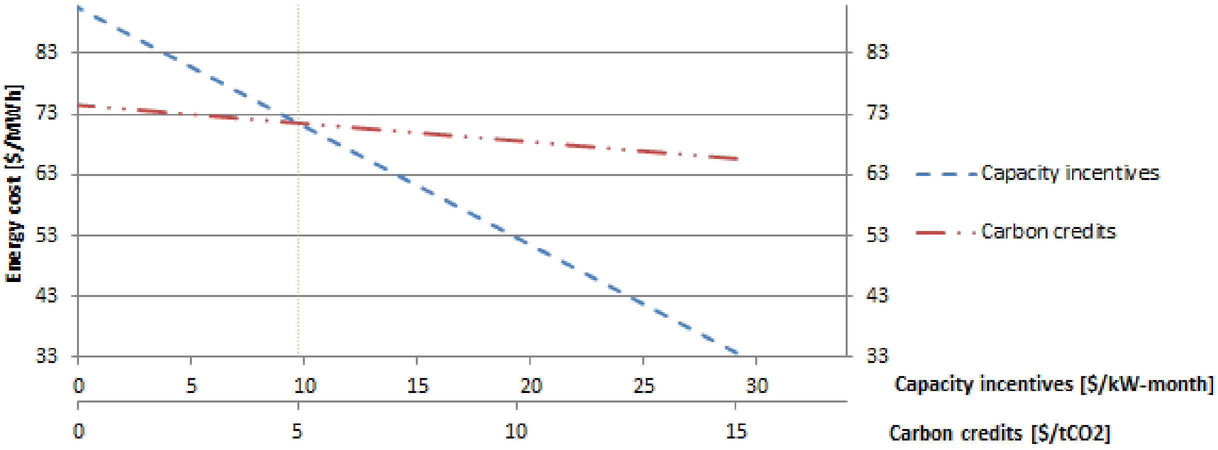
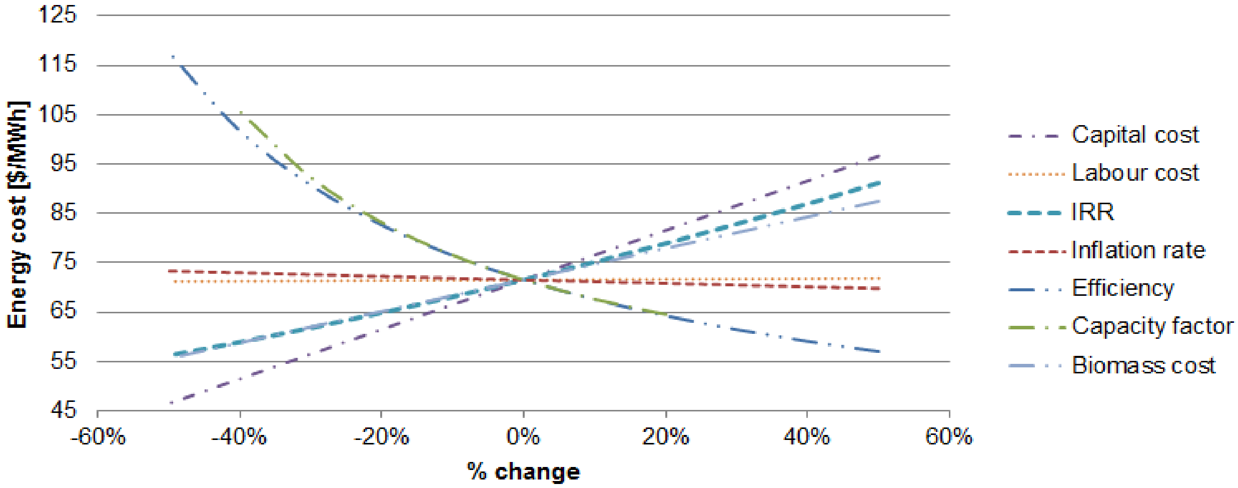


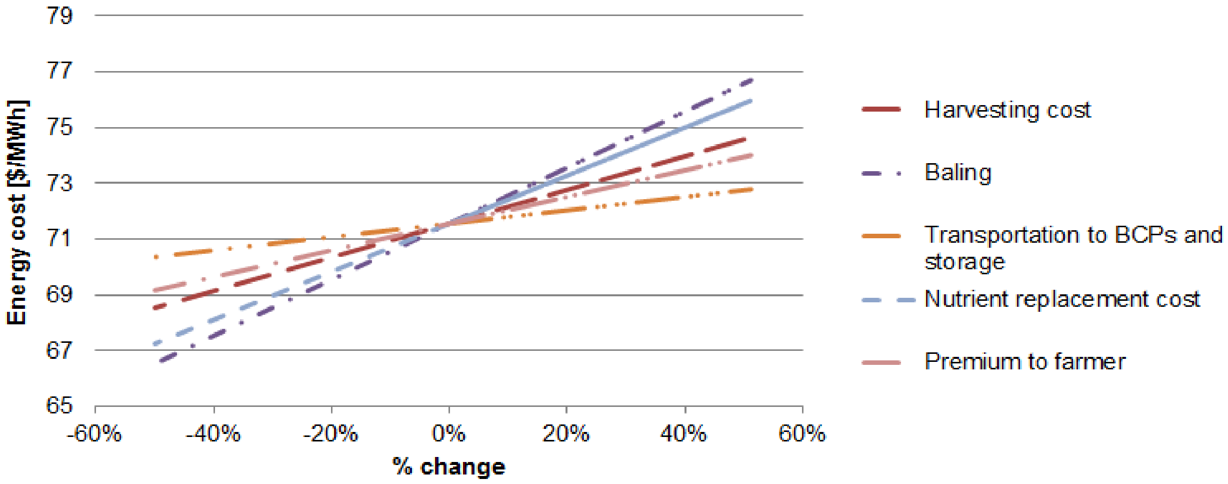
Figure 4-21: Energy cost sensitivity of revenues

4.3.3.3 Effect of cost components and model assumptions

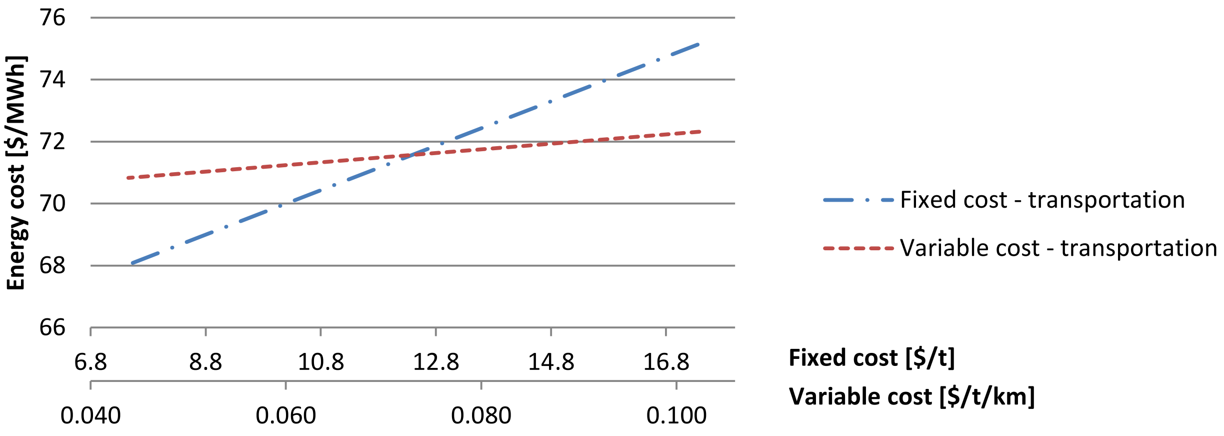
Figure 4-22 (a) shows the energy cost variation by changing the main costs components. The figure shows that decreasing the capital cost causes a major energy cost reduction. The second cost factor that decreases the energy cost significantly is biomass cost, which includes harvesting, baling, fertilizer cost, premium to farmer, transportation to BCPs, and storing. The cost component having the least effect on energy cost is labor cost. The effect of inflation rate has been analyzed as well by increasing it to 4%, but no significant change was seen. Figure 4-22 shows that increasing the efficiency or capacity factor reduces energy costs.



(a)



(b)



(c)

Figure 4-22: Effects of (a) main cost components, economic assumptions, and power plant characteristics, (b) biomass cost, and (c) transportation costs on energy cost

Because biomass cost significantly affects energy cost, the change of costs in each stage of collection and their effects on energy cost are shown in Figure 4-22 (b). Baling and nutrient replacement costs are the two main components affecting energy cost. Baling agricultural residues is not a common practice, but its cost may decrease if more companies undertake this activity. If the nutrient replacement cost decreases from 12 to 5.9 $/t (a 50% decrease), the energy cost could potentially decrease to 67 $/MWh. Currently the fertilizer price in Bolivia is higher than elsewhere. Most fertilizers are imported; however, new national fertilizer facilities may lower costs significantly. The premium to the farmer does not have a significant impact on energy cost; however, if this cost is removed, the energy cost reduces to 66.8 $/MWh.

Figure 4-22 (c) shows the impact of changing the fixed and variable transportation costs on the energy cost. The fixed cost variation has a higher impact than the variable cost. The low variable cost used in this study is attributed to diesel subsidy; however, if the subsidy is removed, the increased variable cost will not significantly affect the energy cost.

4.4 Discussion and recommendations

The energy cost found in this research (i.e., 71.6 \$/MWh) is 3.7 times more than the current cost of energy in Bolivia (i.e., 19.5 \$/MWh), most of which is generated in natural gas–based power plants using subsidized natural gas. We analyze below the ways in which the electricity generated by a biomass-based power plant could become competitive.

The first option is to export electricity to neighboring countries. The electricity price in neighboring countries is relatively high compared to the price in Bolivia [90]. In 2010, the electricity price to final consumers was 9 ¢/kWh in Bolivia, 21 ¢/kWh in Brazil, 13 ¢/kWh in Peru, 23 ¢/kWh in Chile, and 7 ¢/kWh in Paraguay [90, 91]. One of the goals in the Electricity Plan for 2020 is to export electricity [92]. A few years ago, the potential markets were Brazil, Paraguay, Peru, and Argentina, but the situation has changed. Electricity demand in Peru increased at a lower rate than projected; Peru now has an oversupply and is no longer a potential market for Bolivia for at least the next five years [93]. Paraguay generates inexpensive electricity largely from hydro plants that were built many years ago and currently exports electricity to Argentina [93]. Brazil's energy demand is increasing, especially in the northeast; this area might be a market for Bolivia but probably only for a short time because Brazil has mega-projects underway to increase electricity generation from hydro. Argentina is the best destination; there have been previous agreements for selling electricity to Argentina [94] and there is a connection planned from Yaguacua in Bolivia to Tartagal in Argentina, a distance of 110 kilometers [94].

The government of Argentina approved the reduction of subsidies on fossil fuels [95]. The sharp increase in the national electricity price from 37.5 \$/MWh in 2015 [96] to 65.3 \$/MWh in 2017 [97] increased electricity imports from Brazil, Paraguay, and Uruguay [98]. In view of this situation, Bolivia is accelerating the process for exporting electricity to Argentina. Since the big hydro projects in Bolivia are still under study, and construction may take 9 years [2], the most feasible and fast option for Bolivia is to export electricity from natural gas-based power plants, which use natural gas (in this case with no subsidy) at an energy cost of 70 to 72 \$/MWh, a competitive price compared to international costs of around 110 \$/MWh [99]. However, using fossil fuels (with short time availability) is not the best alternative. Increasing the use of natural gas in power plants for energy production increases dependence on natural gas. It is important to highlight here Argentina's strategy, which is to increase the share of renewables. Increasing the price of electricity (70 \$/MWh by 2019 [100]) makes renewables a competitive option and eventually Argentina's energy price will be lower than that of imported fossil fuels and electricity from neighboring countries [101]. Therefore, Bolivia should focus on short construction-time power plants using renewable sources (i.e., biomass from agricultural residues) to generate and export electricity to Argentina during the years when its national energy portfolio transition takes place.

In terms of Bolivia's energy situation, although natural gas will be available only for the next 14 years, the power generation sector still depends heavily on this fossil fuel due to its low subsidized price. Although the country invests in exploration, no new natural gas reservoirs have been approved. Therefore, the country urgently needs to modify the energy cost system in order to introduce renewable energy into the power energy portfolio.

The second option to make biomass a competitive source of energy is to increase the energy cost from thermoelectric power plants by removing its natural gas subsidy. The following assumptions were made for this proposal:

- The annulment of the Hydrocarbons Law No. 3058, Article 87, which states that the national natural gas prices will not exceed 50% of the minimum export prices [102].
- The reduction of the capital cost of biomass technologies due to continuous technology improvement, competitive procurement, and active research encouraged by policies in favor of climate change [28]. Since biomass combustion is already a mature technology, the potential cost reduction is not as high as other renewable energy technologies. IRENA (2012) reported a 25% reduction by 2020 (3.13 % reduction per year) [33]. IRENA (2015) reported that the capital cost of combustion technology can potentially be reduced by 10-15% by 2025 (11 years from 2014; 1.14% reduction per year). A reduction of 1.5% per year in capital cost is assumed [77].
- Energy cost and natural gas price for thermoelectric power plants change proportionally. For example, the energy cost is 19.5 $/MWh when the natural gas price is 1.3 $/MCF, but if the natural gas price increases to 2.6 $/MCF, the energy cost would be 39 $/MWh [2].
- Since natural gas availability is projected for only the next 14 years, it is assumed that after 2031, the country will start importing natural gas for thermoelectric power plants at the same price as the forecasted export price. The report by the Ministry of Hydrocarbons and Energy projected the export price of natural gas up to 2022 (Figure 4-23) [24]. Here, as an assumption, the projection is extended to 2031 using the same gradient originally proposed by the ministry, and then compared with the trend of the natural gas spot price at Henry Hub [103]. This forecasted natural gas price is used to estimate the energy cost from thermoelectric power plants.

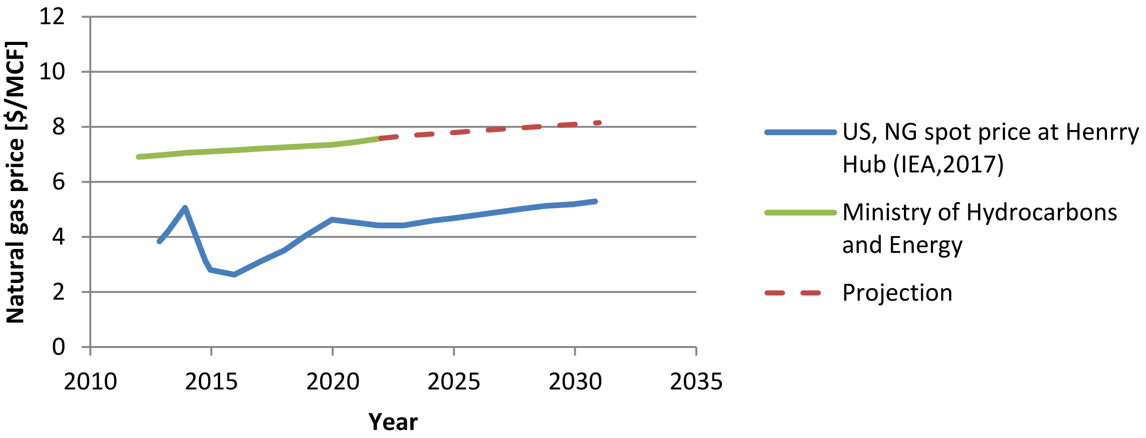


Figure 4-23: Forecasted natural gas price

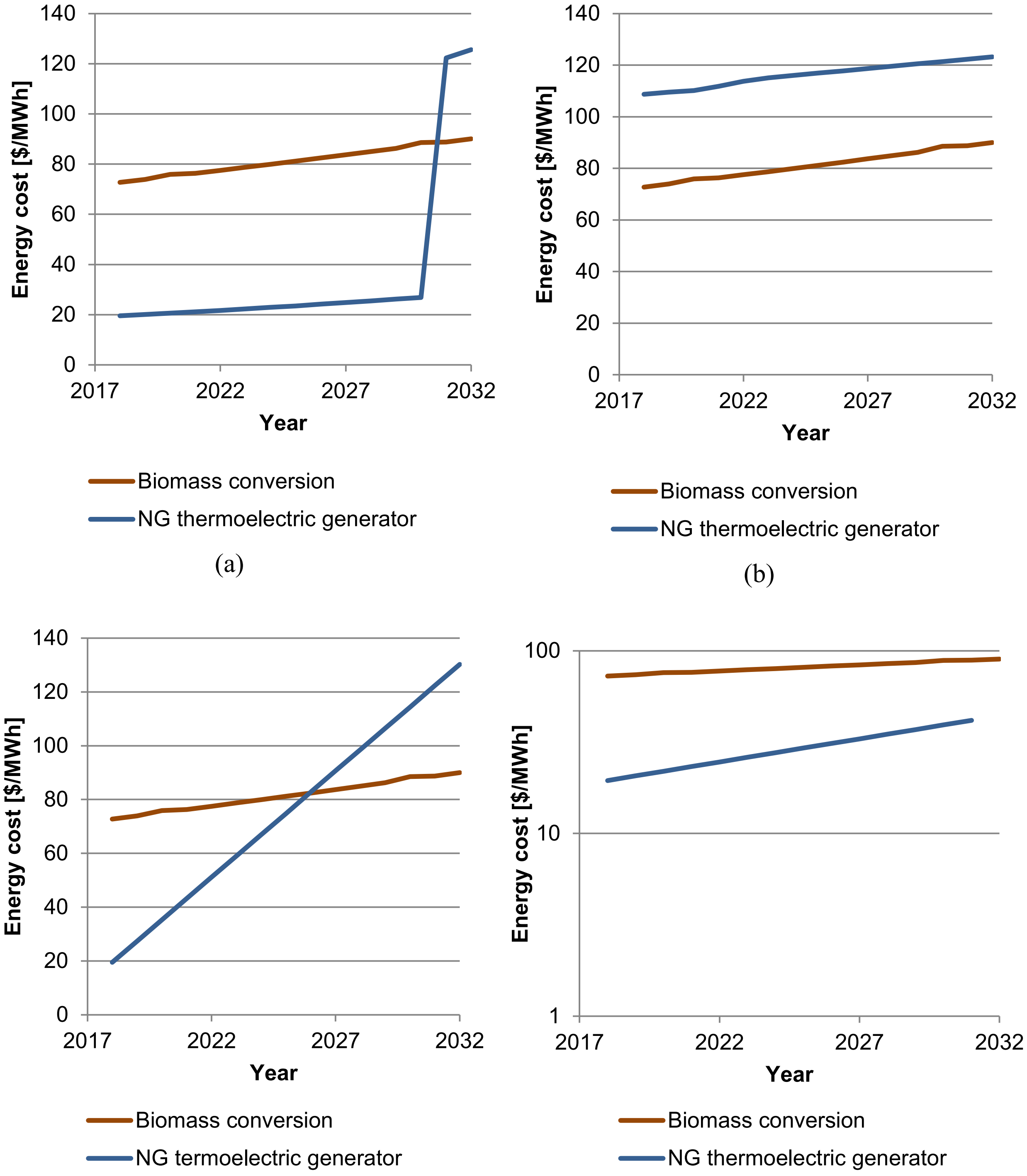
The energy cost from biomass technology is now compared with the electricity cost from natural gas-based power plants, which will vary throughout the next 14 years based on how natural gas subsidy is removed.

Scenario 1. Thermoelectric power plants continue to buy natural gas at the fixed subsidy price (1.3 $/MCF) [104] with no modification. The increase in energy cost from thermoelectric power plants is only affected by inflation only (Figure 4-24 [a]). In the first 14 years, the gap between the energy cost from biomass and natural gas generators is wide. Afterwards, however, the energy cost from thermoelectric power plants will sharply increase due to the import natural gas price. Scenario 1 has considerable social and economic impact. In this scenario, the energy cost from biomass will become competitive after 2031.

Scenario 2. The natural gas subsidy is removed immediately. The thermoelectric power generators buy natural gas at the same price as regional countries (at export price) (Figure 4-24 [b]). In this scenario, energy from biomass becomes competitive. This scenario could decrease the use of fossil fuels, which may result in natural gas savings for export or in extending its availability time. If subsidies were removed and fossil fuel prices were as high as export prices, the transition from exporting to importing would not impact final consumers.

Scenario 3. The natural gas subsidy is gradually removed from the current subsidy, 1.3 $/MCF, to the projected import price in 2031, i.e., 8.1 $/MCF (Figure 4-24 [c]). In this scenario, biomass technology will become competitive by 2027. The continuous increase in energy cost may lead to constant social dissatisfaction. However, the gradual subsidy removal may also provide an incentive to introduce other renewable sources, which could partially offset the effects of higher energy costs.

Scenario 4. The law that fixed the natural gas cost at 1.3 $/MCF is annulled. In this case, the natural gas price for thermoelectric power plants increases at the same rate as the export natural gas price. Figure 4-24 (d) shows the two electricity price lines converging, however, not enough to make biomass competitive by 2032.



(a)

(b)

(c)

(d)

Figure 4-24. Comparison between energy cost from biomass conversion and thermoelectric generators in four scenarios: (a) natural gas subsidy is maintained, (b) natural gas subsidy is removed, (c) gradual reduction of natural gas subsidy, and (d) natural gas price for thermoelectric generators increases at the same rate as the export price

The third option for making biomass a competitive source of energy is to implement policies in favor of renewable energies. The government of Bolivia has set a renewable energy target by 2020 for adding 163 MW into the power portfolio [105]; however, introducing renewable energies is still a challenge and requires concrete actions. The strategy should start by funding institutions working on renewable energies research projects in order to prove the technical and economic feasibility of promoting renewable energies in Bolivia [105]. Policies such as preferential dispatch to renewable sources, import tax exemptions, value added tax (VAT) exemptions, remuneration system incentives, discounted transmission charges, etc. can also help promote application of renewable energies.

A letter from the president of Bolivia to the Conference of the Parties (COP 14) in 2008 [106] expressed his concern about GHG emission reduction policies, particularly carbon credit mechanisms. The president argued that developed countries receive the most benefit from programs linked to climate change while they are actually the main cause due to the historic accumulation of GHG emissions. On the other hand, developing countries that produce very few GHG emissions (i.e., 0.027% from Bolivia's electricity sector [107]) are the most vulnerable and suffer greatly from the consequences of global climate change. The president believes the use of market mechanisms such as carbon credits remove responsibility without actually reducing GHG emissions. Until now, most countries have set their GHG emissions reduction targets voluntarily, and the surface average temperature was estimated to verify that it did not surpass the 2°C target [103]. However, the most responsible way should be to quantify the maximum global GHG emissions from not surpassing 1.5°C and distribute this allowance worldwide considering indexes related to historic responsibilities, ecological footprint, technology, financing capacities, and the country’s development stage. This method, based on climate justice, could develop new opportunities to support developing countries in funding and technology transfer [107].

4.5 Conclusion

Bolivia has great potential to generate electricity using biomass from unused agricultural residues. The **EN**ergy from **BIO**mas **T**echno-**E**conomic **M**odel (ENBIOTEM) was developed here to study the feasibility of collecting and transporting biomass to optimally located energy conversion facilities in Bolivia. Biomass combustion technology was considered for power generation, and two combustion systems were compared. The facility parameters and energy conversion costs were adopted from other regions (e.g., North America, Europe) and the costs of biomass collection such as harvesting and baling were estimated based on similar activities in the study area (e.g., crop harvesting, grass baling for animal feeding, etc.). The two transportation cost components (i.e., fixed and variable) were obtained through a regression analysis of data collected through personal communications with transportation companies in Bolivia. Labour cost was estimated based on employee numbers for biomass facilities and salaries for different positions at an electricity generation facility in Bolivia.

The model estimated the minimum LCOE at 111 \$/MWh; this is from fluidized bed combustion technology and an optimal plant size of 300 MW. The LCOE components were compared with a previous study, and the main difference was the high nutrient replacement cost in Bolivia, which is due to the high cost of imported fertilizers. The energy cost, which takes into account the revenues from capacity incentives and carbon credits, was estimated at 71.6 \$/MWh at the optimal case (i.e., 300 MW plant capacity and fluidized bed combustion technology). A sensitivity analysis identified the factors that most affect the energy cost. It was found that increasing capacity incentives lowers the energy cost noticeably more than an increase in carbon credits.

The energy cost (71.6 $/MWh) was then compared to the current energy cost in the country (19.5 $/MWh). This vast difference is due to the subsidized natural gas used for thermoelectric power generators, which is the main barrier towards introducing renewable energies into the Bolivian power portfolio. Considering that natural gas resources in Bolivia are available for only 14 more years and the government is planning to export electricity to neighboring countries in future, the need for new electricity generation projects becomes obvious. Some options to make biomass technology a competitive source of energy were analyzed. The first option is to export electricity generated from biomass to Argentina. That country has an increasing energy demand and is going through a power portfolio transition by removing the subsidy from fossil fuels. The second option considers removing Bolivia's natural gas subsidy. Depending on the removal rate, biomass may become competitive within the next 14 years. Lastly, supporting research studies could provide information and increase the interest of decision and policy makers. Changing the current energy revenue system, financing opportunities, and incorporating new policies in favor of renewable energies could help the energy transition. Although the introduction of renewables is still a challenge, there are options and potentials that are not yet being exploited.

References

[1] San Martin L. Determinacion del precio del gas natural para el sector electrico boliviano y su efecto en las tarifas a consumidor final 2011. http://www.gesel.ie.ufrj.br/app/webroot/files/publications/28_TDSE43_ESPANHOL.pdf. (Accessed 03.03.18).

[2] Gómez E. Evaluación rápida del sector energía en Bolivia. Programa de Energía Sostenible para Todos (SE4ALL): La Paz. 2012. https://www.seforall.org/sites/default/files/Bolivia_RAGA_ES_Released.pdf. (Accessed 04.06.18).

[3] Energy Information Administration (EIA). Cost and performance characteristics of new generating technologies, annual energy outlook 2018. 2018. https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf. (Accessed 15.02.18).

[4] Ministerio de Autonomias. Agenda patriotica 2025 Quien hace que? 2013. http://extwprlegs1.fao.org/docs/pdf/bol141864.pdf. (Accessed 03.03.18).

[5] Ministerio de Hidrocarburos y Energía (MHE). Balance energético nacional 2000-2014. 2015. http://www2.hidrocarburos.gob.bo/index.php/publicaciones/balance-energ%C3%A9tico/balance-energ%C3%A9tico-departamental/category/54-balance-energetico-nacional.html. (Accessed 12.11.16).

[6] Heras C. La hidroeléctrica que amenaza a 5,000 indígenas bolivianos. El País. 2017. https://elpais.com/elpais/2017/09/05/planeta_futuro/1504563761_414612.html. (Accessed 20.03.18).

[7] Pimienta G. El proyecto Chepete-El Bala amenaza la vocación turística Los tiempos. 2018. http://www.lostiempos.com/actualidad/economia/20180120/proyecto-chepete-bala-amenaza-vocacion-turistica. (Accessed 10.04.18).

[8] Solón P, Solon J, Suaznabar L. El plan de la energía electrica para el 2025. Funcación Solón. 2017. https://fundacionsolon.org/2017/11/01/el-plan-de-energia-electrica-para-el-2025/. (Accessed 15.03.18).

[9] British Petroleum (BP). BP Statistical review of worlds energy. Natural gas. 2017. https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review-2017/bp-statistical-review-of-world-energy-2017-natural-gas.pdf. (Accessed 20.02.18).

[10] Empresa Nacional De Electricidad (ENDE). Memoria anual 2016. 2017. http://www.ende.bo/public/memorias/memoria-2016-ende-corporacion.pdf. (Accessed 15.05.18).

[11] Instituto Nacional de Estadistica (INE). Primer censo agropecuario del Estado Plurinacional. 2013. http://censosbolivia.ine.gob.bo/webine/. (Accessed 09.03.18).

[12] Morato T, Vaezi M, Kumar A. Assessment of energy production potential from agricultural residues in Bolivia. Submitted for journal publication.

[13] Rosendahl L. Biomass combustion science, technology and engineering Preface. Woodhead Publ Ser En. 2013:9-32.

[14] Sokhansanj S, Fenton J. Cost benefit of biomass supply and pre-processing. 2006. http://www.cesarnet.ca/biocap-archive/rif/report/Sokhansanj_S.pdf. (Accessed 28.05.18).

[15] Morato T, Vaezi M, Kumar A. Developing a framework for locating BCPs to improve the biomass-based energy facilities locating procedure - A case for Bolivia. In preparation for journal publication.

[16] Kumar A, Cameron JB, Flynn PC. Biomass power cost and optimum plant size in western Canada. Biomass and Bioenergy. 2003;24:445-64.

[17] Bridgwater AV, Toft AJ, Brammer JG. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. Renewable and Sustainable Energy Reviews. 2002;6:181-246.

[18] Cameron JB, Kumar A, Flynn PC. The impact of feedstock cost on technology selection and optimum size. Biomass and Bioenergy. 2007;31:137-44.

[19] Caputo AC, Palumbo M, Pelagagge PM, Scacchia F. Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. Biomass and Bioenergy. 2005;28:35-51.

[20] Dassanayake GD. Utilization of Triticale Straw for Power Generation [Thesis]. University of Alberta; 2012.

[21] United States Nuclear Regulatory Commission (U.S. NSC). Capacity factor (net). 2017. https://www.nrc.gov/reading-rm/basic-ref/glossary/capacity-factor-net.html. (Accessed 15.03.18).

[22] Autoridad de Fiscalización y Control Social de Electricidad (AE). Anuario estadistico 2015. 2015. https://www.ae.gob.bo/aewebmobile/main?mid=1&cid=81. (Accessed 20.03.18).

[23] Latin-American Energy Organization (Organización Latinoamericana de Energía OLADE). Diagnostico de la generacion en America Latina y el Caribe: Bolivia. 2013. http://www.olade.org/wp-content/uploads/2015/08/Informe-Final-Bolivia-Diagnostico-Generacion-Distribuida.pdf. (Accessed 20.04.18).

[24] Ministerio de Hidrocarburos y Energía (MHE). Plan optimo de expansion del sistema interconectado nacional 2012-2022. 2012. https://www.cndc.bo/boletines/publicaciones.php. (Accessed 08.03.18).

[25] Renewable Energy Policy Network for the 21st Century (REN 21). Global status report. 2017. http://www.ren21.net/wp-content/uploads/2017/06/17-8399_GSR_2017_Full_Report_0621_Opt.pdf. (Accessed 18.12.17).

[26] Thakur A. Power Generation from Forest Residues [Thesis]. University of Alberta; 2011.

[27] Sultana A, Kumar A, Harfield D. Development of agri-pellet production cost and optimum size. Bioresource Technology. 2010;101:5609-21.

[28] International Renewable Energy Agency (IRENA). Renewable power generation costs in 2017. 2018. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf. (Accessed 15.03.18).

[29] IHS Markit. Costs and strategic sourcing. 2017. https://ihsmarkit.com/info/cera/ihsindexes/index.html. (Accessed 05.03.18).

[30] Banco Central de Bolivia. Indicadores de inflacion. 2017. https://www.bcb.gob.bo/?q=indicadores_inflacion. (Accessed 25.03.18).

[31] Instituto Nacional de Estadistica (INE). Bolivia: Inflacion acumulada anual, 1985 - 2016. 2016. http://medios.economiayfinanzas.gob.bo/MH/documentos/2017/indicadores/Inflacion.pdf. (Accessed 03.03.18).

[32] Maya B. Inflacion anual de 2017 llego a 2071%, la mas baja desde 2009. 2018. http://boliviamaya.com/digital/2018/01/06/inflacion-anual-de-2017-llego-a-271-la-mas-baja-desde-2009/. (Accessed 03.03.18).

[33] International Renewable Energy Agency (IRENA). Biomass for power generation 2012;1. http://www.calculator.net/inflation-calculator.html?cstartingamount1=1&cinyear1=2000&coutyear1=2017&calctype=1&x=64&y=19. (Accessed 20.04.18).

[34] Clean Development Mechanisim Executive Board (CDM-EB). Clean development mechanisim project design document form (CDM-PDD) "Guabira energia bagasse cogeneration project". 2006. https://cdm.unfccc.int/Projects/projsearch.html. (Accessed 18.05.18).

[35] Vargas JP, Calvimontes J. Evaluation of landfill biomass potential in Bolivia to produce electricity. Revista Investigación & Desarrollo. 2017;1:55-62.

[36] El País. Ofrecen mano de obra en Santa Cruz para cosecha caña. 2018. http://www.elpaisonline.com/index.php/2013-01-15-14-16-26/centrales/item/226324-ofrecen-mano-de-obra-de-santa-cruz-para-cosechar-cana. (Accessed 10.04.18).

[37] El Dia. El agro se mecaniza a paso lento en Bolivia. 2014. https://www.eldia.com.bo/index.php?cat=357&pla=3&id_articulo=139367. (Accessed 02.05.18).

[38] Bundy LG. Corn fertilization. 1998. http://www.soils.wisc.edu/extension/pubs/A3340.pdf. (Accessed 18.05.18).

[39] Sawyer J. Nutrient removal when harvesting corn stover 2007. https://crops.extension.iastate.edu/nutrient-removal-when-harvesting-corn-stover-0. (Accessed 20.03.18).

[40] Hughes JD, Coulter J. Considerations for corn residue harvest in Minnesota. 2009. https://www.extension.umn.edu/agriculture/corn/harvest/considerations-for-corn-residue-harvest/. (Accessed 15.12.17).

[41] Fixen PE. Potential biofuels influence on nutrient use and removal in the US. Better Crops. 2007;91:12-4.

[42] Instituto Nacional de Estadística (INE). Encuesta agropecuaria, 2015. Abono quimico. 2015. http://anda.ine.gob.bo/ANDA4_2/index.php/catalog/316/datafile/F9/V391. (Accessed 15.04.18).

[43] Instituto Interamericano de Cooperación para la agricultura (IICA). La situacion regional de los fertilizantes. 2009. http://repiica.iica.int/docs/B1600e/B1600e.pdf. (Accessed 01.06.18).

[44] Food and Agriculture Organization (FAO). Bolivia hacia una estrategia libre de fertilizantes. 1999. http://www.fao.org/tempref/agl/agll/docs/bolstud.pdf. (Accessed 05.06.17).

[45] Instituto de Ciencia - Economía - Educación y Salud (ICEES). Producción de fertilizantes NPK en Bolivia. 2014. http://www.icees.org.bo/2014/10/produccion-de-fertilizantes-npk-en-bolivia/. (Accessed 04.06.18).

[46] La Razon. Bolivia concreta acuerdo para exportar 335 mil toneladas de fertilizantes a Brasil. 2017. https://www.la-razon.com/economia/Bolivia-exporta-fertilizantes-Brasil-planta_0_2803519632.html. (Accessed 18.01.18).

[47] Bolivia Rural. Insumos Bolivia inicia provision de fertilizantes a pequeños productores. 2011. http://www.boliviarural.org/noticias/2011/1162-insumos-bolivia-inicia-provision-de-fertilizantes-a-pequenos-productores.html. (Accessed 04.06.18).

[48] Vargas O. Proyecto boliviano de industrializacion del litio en el salar de Uyuni. 2010. http://www.revistasbolivianas.org.bo/pdf/rmym/n7/n7a07.pdf. (Accessed 16.02.18).

[49] Mamani J. Planta de cloruro de potasio entra en operación en Agosto. Cambio. 2018. http://www.cambio.bo/?q=node/38194. (Accessed 21.03.18).

[50] German Technical Cooperation Agency (GTZ). Manejo del monte chaqueño para una ganadería sostenible. n.d. http://www.bivica.org/upload/ag_ganaderia-chaco.pdf. (Accessed 13.11.17).

[51] Agro-negocios. Mega fardos de heno, nueva opcion para la ganaderia boliviana. 2016. http://agronegocios.com.bo/mega-fardos-de-heno-nueva-opcion-para-la-ganaderia-boliviana/. (Accessed 05.11.17).

[52] Solfor. Personal communication. 2017.

[53] Ministerio de Comercio Exterior y Turismo. Guia de orientación al usuario del transporte terrestre. 2015. https://www.mincetur.gob.pe/wp-content/uploads/documentos/comercio_exterior/facilitacion_comercio_exterior/Guia_Transporte_Terrestre_13072015.pdf. (Accessed 12.05.18).

[54] Marulanda J, Ortiz A. Diseño de un sistema de costeo para las operaciones de de transporte de prakxon logistica con origen en Buena Ventura y destinos Bogota Medellin Cali Barranquilla, Cartagena, Bucaramanga, Pasto y vicerversa [Thesis]. Potificia Universidad Javeriana; 2012.

[55] Sultana A, Kumar A. Development of tortuosity factor for assessment of lignocellulosic biomass delivery cost to a biorefinery. 2014;119:288–95.

[56] United States Department of Agriculture (USDA). Grain truck and ocean rate advisory (GTOR). 4th Quarter 2017. 2017. https://www.ams.usda.gov/sites/default/files/media/GTOR4thQtr2017Quarterly.pdf. (Accessed 14.02.18).

[57] Fuller S, Yu TH, Fellin L, Lalor A, Krajewski R. Transportation developments in South America and their effect on international agricultural competitiveness. Transport Res Rec. 2003:62-8.

[58] Araujo M, Campos V, Bandeira R. An overview of road cargo transport in Brazil. 2012;4:151-60.

[59] Suarez AL. El sector del transporte. 2009;Tomo IV http://www.udape.gob.bo/portales_html/diagnosticos/documentos/TOMO%20IV%20-%20SECTOR%20TRANSPORTE.pdf. (Accessed 15.10.17).

[60] Administradora Boliviana de Carreteras (ABC). Plan estrategico institucional 2016-2020. 2016. http://www.abc.gob.bo/sites/default/files/pei_abc_2016_-_2020.pdf. (Accessed 15.10.17).

[61] Organizacion Mundial de la Salud (OMS). La seguridad vial en la región de las Américas. 2016. http://www.who.int/violence_injury_prevention/road_safety_status/2015/Road_Safety_PAHO_Spanish.pdf. (Accessed 03.06.18).

[62] Centre for Analysis and Dissemination of Demonstrated Energy Technologies (CADDET). Straw-fired biomass plants in Denmark. 1997. http://www.caddet-re.org/assets/1-97art3.pdf. (Accessed 04.06.18).

[63] Environmental Protection Agency - Combined Heat and Power Paternship (EPA-CHP). Biomass combined heat and power catalog of technologies. 2007. https://www.epa.gov/sites/production/files/2015-07/documents/biomass_combined_heat_and_power_catalog_of_technologies_v.1.1.pdf. (Accessed 16.03.18).

[64] International Finance Corporation (IFC). Converting biomass to Energy. 2017. https://www.ifc.org/wps/wcm/connect/7a1813bc-b6e8-4139-a7fc-cee8c5c61f64/BioMass_report_06+2017.pdf?MOD=AJPERES. (Accessed 19.02.18).

[65] Intergovernmental Panel on Climate Change (IPCC). Renewable energy sources and climate change mitigation. 2012. https://www.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf.

[66] Kumar A, Bhattacharya SC, Pham HL. Greenhouse gas mitigation potential of biomass energy technologies in Vietnam using the long range energy alternative planning system model. Energy. 2003;28:627-54.

[67] Missouri department of natural resources - Energize Missouri. Feasibility study for a biomass electrical power plant in the Viburnum region. 2012. http://energy.mo.gov/energy/docs/G11-SEP-RES-16VEDACFinalReport.pdf. (Accessed 15.17.17).

[68] National Renewable Energy Laboratory (NREL). Lessons learned from existing biomass power plants. 2000. https://www.nrel.gov/docs/fy00osti/26946.pdf. (Accessed 15.01.18).

[69] National Renewable Energy Laboratory (NREL). Highlights of biopower technical assessment: state of the industry and the technology. 2003. https://www.nrel.gov/docs/fy03osti/33502.pdf. (Accessed 13.02.18).

[70] National Renewable Energy Laboratory (NREL). Cost and performance data for power generation technologies. 2012. https://www.bv.com/docs/reports-studies/nrel-cost-report.pdf. (Accessed 12.01.18).

[71] Pingrey DW, Waggoner NE. Direct-combustion systems to produce power from biomass from wood, forest and agricultural crop residue. 1981:Medium: X; Size: Pages: 294.

[72] Turnbull JH. Use of biomass in electric power generation: the california experience. Biomass and Bioenergy. 1993;4:75-84.

[73] van den Broek R, Faaij A, van Wijk A. Biomass combustion for power generation. Biomass and Bioenergy. 1996;11:271-81.

[74] Ghassemi A. Firest-based biomass energy. Concepts and applications2012.

[75] Smith. Biomass conversion technologies. 2006. https://www.epa.gov/sites/production/files/2015-07/documents/biomass_combined_heat_and_power_catalog_of_technologies_5._biomass_conversion_technologies.pdf. (Accessed 15.03.18).

[76] Emberga T, Uhiara E, Nwigwe C, Amadi O. Biomass conversion technologies. 2012;4:19-24.

[77] International Renewable Energy Agency (IRENA). Renewable power generation costs in 2014. 2015. https://www.irena.org/documentdownloads/publications/irena_re_power_costs_2014_report.pdf. (Accessed 04.06.18).

[78] Energy Sector Management Assistance Program (ESMAP). Technical and economic assessment of off-grid, mini-grid and grid electrification technologies 2007. http://documents.worldbank.org/curated/en/634581468333897517/Technical-and-economic-assessment-of-off-grid-mini-grid-and-grid-electrification-technologies. (Accessed 16.02.18).

[79] Ullah M, Vaezi M, Kumar A, Bell J. Assessment of the Waste-to-Energy potential from Alberta's food processing industry. Canadian Society for Bioengineering. 2017;59.

[80] Ministerio de Economía y Finanzas Públicas. Aprobación de la escala salarial de la Empresa Nacional de Electricidad (ENDE). 2017. http://www.ende.bo/public/documentos/Reglamentacion-Escala-Salarial.pdf. (Accessed 04.06.18).

[81] Hidroelectrica Boliviana. Personal communication 2018.

[82] Comité Nacional de Despacho de Carga (CNDC). Memoria 2014 Resultados de la operacion del SIN. 2015. https://www.scribd.com/document/278385862/Memoria-anual-CNDC-2014. (Accessed 05.05.18).

[83] Guabira Energía. Personal communication 2017.

[84] Gomez M, Martinez L, Sanches A. Power generation based on agricultural residues gasification: The potential of corncobs. 2017;2017:p. 90-5.

[85] Abdelhady S, Borello D, Shaban A. Techno-economic assessment of biomass power plant fed with rice straw: Sensitivity and parametric analysis of the performance and the LCOE. Renewable Energy. 2018;115:1026-34.

[86] Kost C, Mayer J, Thomsen J, Hartmann N, Senkpiel C, Philips S, et al. Levelized cost of electricity renewable energy technologies 2013. https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/Fraunhofer-ISE_LCOE_Renewable_Energy_technologies.pdf. (Accessed 14.02.18).

[87] Open energy information (OpenEI). Levelized cost of energy 2015. https://openei.org/apps/TCDB/transparent_cost_database. (Accessed 16.03.18).

[88] Solon. El caso del Chepete y El Bala. Fundación Solón. 2017. https://fundacionsolon.org/2017/05/10/el-caso-del-chepete-y-el-bala/. (Accessed 19.04.18).

[89] Telma M. Hidroeléctrica Rositas: el proyecto que rechazan las comunidades y que amenaza a un área protegida en Bolivia Mongabay Latam. 2017. https://es.mongabay.com/2017/07/hidroelectrica-rositas-proyecto-rechazan-las-comunidades-amenaza-area-protegida-bolivia/. (Accessed 20.04.18).

[90] Latin-American Energy Organization (Organización Latinoamericana de Energía OLADE). Matriz energética en América Latina y el Caribe, situacion actual y perspectivas de las energías renovables. 2012. http://www.olade.org/sites/default/files/presentaciones-sej/8_Presentaci%C3%B3n%20OLADE%20UPADI%20201.pdf. (Accessed 20.04.18).

[91] Carrafa F. Tarifa eléctrica de Bolivia es la máas baja de Sudamérica. Cambio. 2017. http://www.cambio.bo/?q=node/28080. (Accessed 15.04.18).

[92] Ministerio de Hidrocarburos y Energía de Bolivia (MHE). Plan eléctrico del estado plurinacional de Bolivia 2025. 2014. http://globaltrends.thedialogue.org/publication/plan-electrico-del-estado-plurnacional-de-bolivia-2025/. (Accessed 12.05.18).

[93] De los cuatro países que el gobierno Boliviano baraja para exportar electricidad, tres cuentan con con sobreoferta de energía, sobre todo hidroeléctrica. Energy press. 2017. http://www.energypress.com.bo/energia-argentina-es-el-pais-mas-factible-para-exportar/.

[94] James CS. Argentina increases energy imports from neighbors. The Latin American Energy review. 2016. http://carlosstjames.com/renewable-energy/argentina-increases-energy-imports-from-neighbors/. (Accessed 16.04.18).

[95] Nolé F. Pese a la inflacion, Dujovne ratificó la eliminación de subsidios de energía y transporte. Perfil. 2018. http://www.perfil.com/noticias/economia/pese-a-la-inflacion-dujovne-ratifico-la-eliminacion-de-subsidios-de-energia-y-transporte.phtml. (Accessed 05.05.18).

[96] Compañía Administradora del Mercado Mayorista Eléctrico (CAMMESA). Informe mensual Octubre 2015. 2015. http://portalweb.cammesa.com/memnet1/Pages/descargas.aspx. (Accessed 28.04.18).

[97] Compañía Administradora del Mercado Mayorista Eléctrico (CAMESSA). Informe mensual Diciembre 2017. 2017. http://portalweb.cammesa.com/memnet1/Pages/descargas.aspx. (Accessed 28.04.18).

[98] Comisión Nacional de Energía Atómica (CNEA). Sintesis del mercado eléctrico mayorista de la República Argentina. 2017. http://www.melectrico.com.ar/web/pdfs/CNEA/SINTESIS_MEM_2017_DICIEMBRE.pdf. (Accessed 14.05.18).

[99] Lazcano M. Electricidad de termoeléctricas tendrá otro valor para la exportación La Razon - economía. 2015. http://www.la-razon.com/index.php?_url=/economia/Energia-electricidad-termoelectricas-valor-exportacion_0_2313368673.html. (Accessed 12.04.18).

[100] Fundacion de investigaciones economicas Latinoamericanas (FIEL). Argentina. 2017. https://www.oecd.org/environment/cc/g20-climate/collapsecontents/Fiel-argentina-growth-and-low-carbon-transition.pdf. (Accessed 08.05.18).

[101] Pozzo E. La energía renovable le costaría a la Argentina menos que importar combustibles. El Cronista. 2017. https://www.cronista.com/negocios/La-energia-renovable-le-costaria-a-la-Argentina-menos-que-importar-combustibles-20170802-0115.html. (Accessed 24.04.18).

[102] Ley de hidrocarburos Ley N 3058. 2005. https://www.servindi.org/pdf/Bolivia_Ley3058_hidrocarburos2005.pdf. (Accessed 04.06.18).

[103] Energy Information Administration (EIA). Annual Energy Outlook 2017 with projection to 2050. 2017. https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf. (Accessed 16.01.18).

[104] Yacimientos Petroliferos Fiscales Bolivianos (YPFB). Boletin estadistico Enero-Junio 2015. 2015. http://www.ypfb.gob.bo/es/55-ypfb-corporacion/publicaciones/79-publicaciones.html. (Accessed 21.05.18).

[105] International Renewable Energy Agency (IRENA). Renewable energy in Latin America 2015. An overview of policies. 2015. http://www.irena.org/publications/2015/Jun/Renewable-Energy-in-Latin-America-2015-An-Overview-of-Policies. (Accessed 02.05.18).

[106] Servindi. Mundo: "Salvemos al planeta del capitalismo", carta de Evo Morales sobre cambio climático. 2008. https://www.servindi.org/actualidad/5743. (Accessed 18.04.18).

[107] Ministerio de relaciones exteriores. Posición Boliviana en las Negociaciones Internacionales de la Convención Macro de Naciones Unidas sobre Cambio Climático (CMNUCC). 2016. http://www.embolivia.org.br/UserFiles/File/PDFs/emb_climatico.PDF. (Accessed 01.06.18).

Chapter: 5 Conclusions and recommendations for future research

5.1 Conclusion

In this research, we assessed the use of agricultural residues as a biomass feedstock to generate electricity in Bolivia. The country's increasing energy demand and the ambitious aim to export electricity to neighboring countries led to the need to investigate renewable energy options that have lower environmental impact than fossil fuels. Agricultural residue biomass is an unused renewable source of energy that could replace fossil fuels and ensure national energy security. In this study, we developed geographic information system (GIS)-based models for various analyses. A biomass quantification process was conducted to estimate the volume of agricultural residues that could be sustainably used for energy generation purposes. A framework was developed to strategically locate biomass collection points (BCPs). The model was applied to Bolivia, and the identified BCPs were used to site optimal locations for biomass-based facilities considering social, environmental, and economic factors. Finally, a techno-economic model was developed to estimate the cost of generating electricity using agricultural residues for a wide range of plant capacities and an optimal plant size. The conclusions reached in each section are presented here.

5.1.1 Biomass quantification in Bolivia

Agricultural residues from Bolivia's six main agricultural products (sugarcane, soybean, corn, rice, sorghum, and sunflower) were considered in the quantification process. The residue-to-product ratio (RPR) of individual crops was used to estimate a total residue generation of 9.1

Mt/yr. However, this amount cannot be used in its entirety to generate electricity. The total volume is reduced because of soil conservation and machinery capacity (23%), animal feeding (10%), losses due to handling, storage and transportation (12%), and moisture content (13%). With these losses taken into account, the final biomass volume available for energy generation purposes is an estimated 3.8 M dry t/yr. Most of the residues (i.e., 3.7 M dry t/yr) are generated in Santa Cruz, one of nine departments of Bolivia (see Figure 5-1).

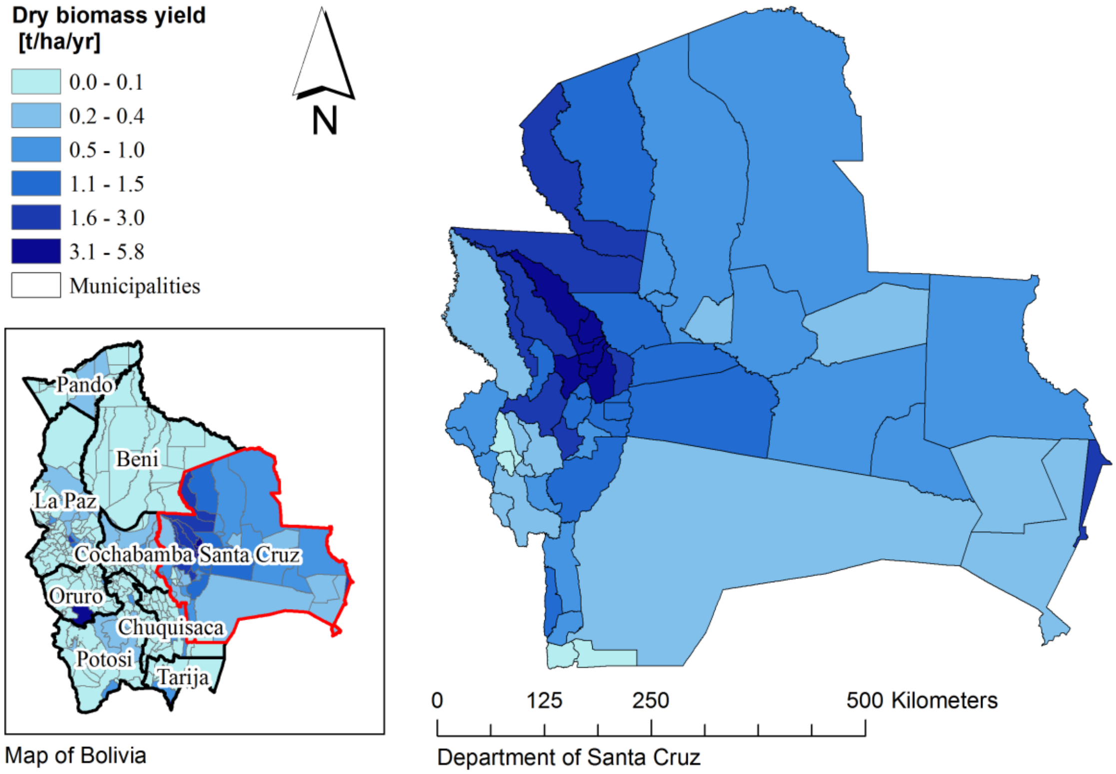


Figure 5-1: Dry biomass availability in Bolivia and enlarged in Santa Cruz

This research was, therefore, focused on the Department of Santa Cruz. The residue composition of biomass availability in Santa Cruz is 49% soybean, 22% sugarcane, 9% sorghum, 8% corn, 7% sunflower, and 5% rice. The energy potential from agricultural residues in the Department of Santa Cruz is 5.3 GWh, and ten of the 56 municipalities in Santa Cruz have an energy potential of 4.5 GWh. Moreover, these municipalities share boundaries, which is an important advantage.

These ten main residue producer municipalities are listed in Table 5-1 with corresponding biomass availability and energy potential.

Table 5-1: Ten main residue producer municipalities

Municipality	Biomass [t/yr]	Energy potential [MWh]
Warnes	146,965	218,241
Okinawa Uno	114,850	163,633
Pailón	451,368	611,777
Santa Rosa del Sara	141,670	199,749
Gral, Saavedra	135,155	202,419
Mineros	130,251	195,035
Fernández Alonso	331,109	487,503
San Pedro	663,109	948,002
San Julián	626,259	882,289
Cuatro Cañadas	471,201	642,498
Total 10 municipalities in Santa Cruz	3,211,936	4,551,146

The sensitivity analyses identified the parameters that most affect the estimation of biomass availability and energy potential. These parameters are the RPR of soybean and sugarcane and the moisture content. Therefore, properly determining these values for the study area would increase the reliability of results.

5.1.2 Location of biomass collection points and biomass-based facilities

In the biomass logistics proposed here, biomass would be compacted in bales, and then moved to biomass collection points (BCPs), which provide space and storage. Moreover, BCPs are located close to roads in order to increase the truck pick-up efficiency and provide specific collection sites along the trucking routes. Trucks would collect the bales from BCPs and transport them to the biomass-based facility. A framework was accordingly developed in a GIS environment to site BCPs by giving preference to locations with high biomass availability and close distance to roads. The model, consisting of an iterative process, was created for regions where the road network does not have a grid road pattern, fields do not have access to paved roads, and biomass availability varies greatly. The framework was applied to Santa Cruz, Bolivia, and three zones were selected in it based on biomass availability. Within these zones, 107 BCPs were sited, which together could collect 1.5 M dry t/yr.

GIS-based models were used to site optimal locations of biomass-based facilities considering social, environmental, and economic factors. The process excluded areas where the facility cannot be sited (e.g., protected areas, roads, rivers, lakes, lagoons, wetlands, urban areas, etc.) and assessed areas based on the relative location towards preference factors (e.g., agricultural areas, road network, transmission lines, land cover, property type, etc.). These preference factors were integrated based on weightage values obtained from the Analytic Hierarchy Process (AHP). The integration of exclusion and preference maps resulted in a suitability map with suitability indexes (SI); areas with high SIs were selected as candidate sites. A network analysis was then conducted using the facility candidate sites, BCPs, and actual road network. Based on the most common biomass-based facility size, i.e., 50 MW, and the total biomass volume collected at BCPs, seven facilities were located as illustrated in Figure 5-2. The biomass-based energy conversion facilities have a power capacity ranging from 23 to 82 MW

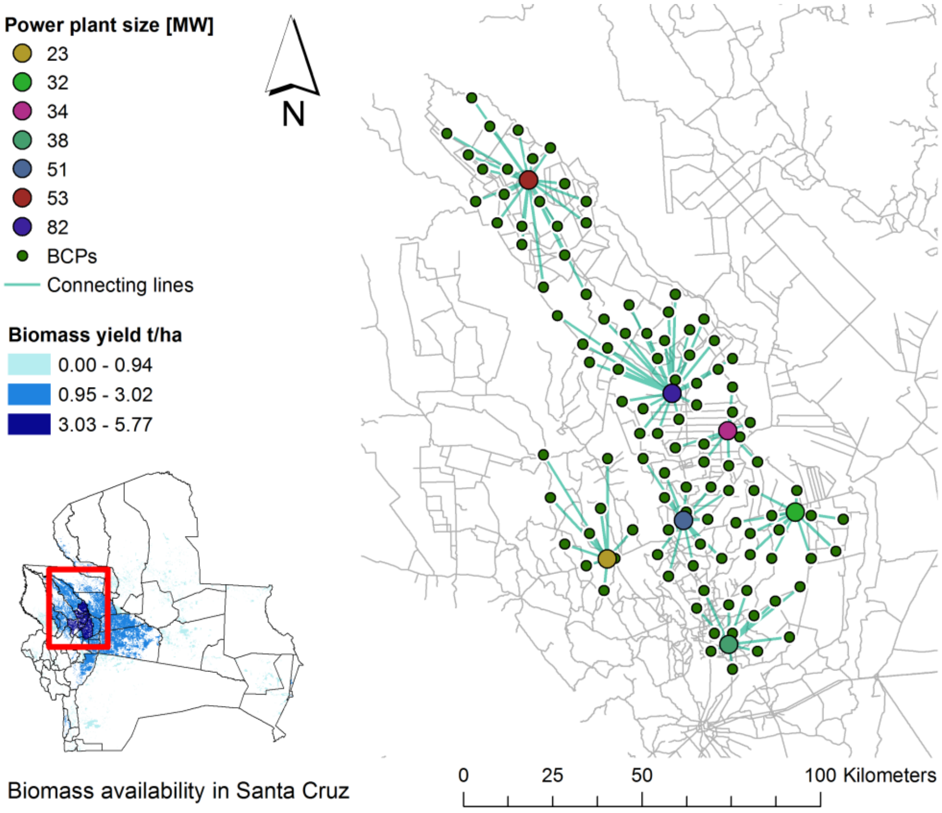


Figure 5-2: Geographic location of biomass-based energy facilities

The municipalities where each facility is located and the biomass volume assigned to corresponding facility is listed in Table 5-2.

Table 5-2: Information on biomass-based energy facilities

Number of facility	Municipality location of facility	Number of collection points for each facility	Dry biomass delivered [t/yr]	Capacity [MW]
1	Fernández Alonso	27	390,000	82
2	San Pedro	22	250,000	53
3	General Saavedra	14	240,000	51
4	Warnes	13	180,000	38
5	Okinawa Uno	12	150,000	32
6	Portachuelo	10	110,000	23
7	General Saavedra	9	160,000	34
	Total	**107**	**1,480,000**	**313**

5.1.3 Cost to generate electricity using biomass and optimal plant size

A techno-economic model was developed to estimate the cost of generating electricity using agricultural residues. The cost data was converted to US dollars and updated to 2017, the base year of this study. Costs in each stage of the biomass logistics were considered. The biomass logistic process included harvesting, baling, transportation to BCPs, storing, nutrient replacement, and transportation from BCPs to the biomass-based facility. Travel distances were obtained from a GIS network analysis. The transportation cost components, fixed and variable, were determined through personal communication with transportation companies in Bolivia and a regression analysis. The fixed and variable costs are 12.39 $/t and 0.07 $/km-t, respectively. Travel costs were estimated for a wide range of plant sizes. The biomass-to-energy conversion technology considered here is combustion, and grate-firing and fluidized bed (circulating and bubbling) combustion were compared. The capital costs of a wide range of plant capacities were collected from different sources. Through a power regression analysis, we obtained scale factors for gate firing and fluidized bed of 0.85 and 0.73, respectively, which suggests that economies of scale are more pronounced for fluidized bed than grate-firing technology.

The economic-model estimated the levelized cost of electricity (LCOE) for a wide range of plant sizes. The lowest LCOE is 111 $/MWh, corresponding to an optimal plant size of 300 MW and fluidized bed combustion technology. After 300 MW, the LCOE increases sharply because the maximum capacity of a single unit is 300 MW. For larger capacities, two same-size units are assumed. Plant sizes smaller than 300 MW slightly increase the LCOE. For example, the LCOE increases only 6% (relative to the lowest LCOE) if the plant size decreases to 200 MW. At 300 MW, the cost is composed of biomass collection, transportation, and energy conversion (at facility), and the percentages of each are 34%, 11% and 54%, respectively. The energy cost was estimated to be 71.7 $/MWh in the first year the facility generates electricity. This cost is higher than the current energy cost, which is considerably low, compared to neighboring regions, because of the subsidized natural gas for thermos-electrics. If the subsidy is removed, the energy from biomass conversion could be a competitive source of energy.

5.2 Recommendations for future work

The following research recommendations could expand and improve the use of biomass as a source of electricity generation in Bolivia:

1. The biomass quantification considered only the agricultural residues of the six main crops, sugarcane, soybean, corn, rice, sorghum, and sunflower. However, biomass includes forest residues, municipality solid waste, food processing residues, etc. These could be equally well used to generate energy. A research study on estimating the potential of these other biomass sources could increase the interest in the use of biomass to generate electricity.
2. The biomass quantification used several factors taken from the literature, but using actual factors for the study area would improve the biomass availability estimate. Since the sensitivity analysis identified moisture content and the residue-to-product ratio of soybean and sugarcane as the main factors affecting the biomass availability estimate, studies should be conducted to determine their actual values in order to increase accuracy in biomass quantification.
3. The location analysis of BCPs and biomass-based facilities used the most updated maps available. However, the results of this analysis are subject to change with changes in geographic features, such as expansion in urban areas, increased road network, new

facilities, etc. Also, regulations should be reviewed in case new provisions are incorporated. If there are changes, the model should be updated.

4. In this study, the conversion technology focused on combustion, specifically two types, grate-firing and fluidized bed; however, there is a wide variety of conversion technologies using biomass (e.g., gasification, pyrolysis, anaerobic digestion, composting, and landfill gas), along with other biofuels (e.g., ethanol, biodiesel, biogas, and syngas)) that can be assessed for the study area.
5. Biomass utilization technology is not currently economically feasible due to the high energy cost. The natural gas subsidy for thermoelectric power plants is the greatest barrier towards increasing the competitiveness of renewable energy. Studies should be conducted to look for alternatives to support the use of biomass to generate energy in order to motivate and increase the interest of decision makers.

Bibliography

Abdelhady S, Borello D, Shaban A. Techno-economic assessment of biomass power plant fed with rice straw: Sensitivity and parametric analysis of the performance and the LCOE. Renewable Energy. 2018;115:1026-34.

Administradora Boliviana de Carreteras (ABC). Plan estrategico institucional 2016-2020. 2016. http://www.abc.gob.bo/sites/default/files/pei_abc_2016_-_2020.pdf. (Accessed 15.10.17).

Agencia Nacional de Hidrocarburos (ANH). IV Reglamento para la construccion y operacion de plantas de destribucion de gas licuado de petroleo (GLP) en garrafas. http://www.anh.gob.bo/InsideFiles/Documentos/Documentos_Id-62-140311-26.pdf. (Accessed (27.04.17)).

Agenda Patriótica 2025: Los trece pilares de la Bolivia digna y soberana,. 2013. http://www.bolivia.de/fileadmin/Dokumente/DestacadosEmpfehlenswertes_Footer/4AgendaPatriotica2025-%2013%20pilares.pdf. (Accessed 10.01.17).

Agro-negocios. Mega fardos de heno, nueva opcion para la ganaderia boliviana. 2016. http://agronegocios.com.bo/mega-fardos-de-heno-nueva-opcion-para-la-ganaderia-boliviana/. (Accessed 05.11.17).

Araujo M, Campos V, Bandeira R. An overview of road cargo transport in Brazil. 2012;4:151-60.

Autoridad de Fiscalizacion y Control Social de Electricidad (AE). Anuario estadístico 2015. 2016. https://www.ae.gob.bo/aewebmobile/main?mid=1&cid=81. (Accessed 15.04.18).

Ayamga EA, Kemausuor F, Addo A. Technical analysis of crop residue biomass energy in an agricultural region of Ghana. Resources, Conservation and Recycling. 2015;96:51-60.

Babu S, Rana D, Yadav G, Singh R, Yadav S. A review on recycling of sunflower residue for sustaining soil health. International Journal of Agronomy. 2014. https://www.hindawi.com/journals/ija/2014/601049/abs/. (Accessed 18.06.18).

Ballivian H, Suarez T, Martínez L, Montero C, Careaga G, Cardozo D, et al. Decreto Ley N 2978, 14 de febrero de 1952. 1952:7. http://www.lexivox.org/norms/BO-DL-2978.xhtml. (Accessed 27.04.17).

Banco Central de Bolivia. Indicadores de inflacion. 2017. https://www.bcb.gob.bo/?q=indicadores_inflacion. (Accessed 25.03.18).

Bolivia Rural. Insumos Bolivia inicia provision de fertilizantes a pequeños productores. 2011. http://www.boliviarural.org/noticias/2011/1162-insumos-bolivia-inicia-provision-de-fertilizantes-a-pequenos-productores.html. (Accessed 04.06.18).

Bolivia: sector industrial deberá pagar por el agua que se utiliza de manera directa. La Razon. 2010. https://www.americaeconomia.com/economia-mercados/bolivia-sector-industrial-debera-pagar-por-el-agua-que-se-utiliza-de-manera-direct.

Bridgwater AV, Toft AJ, Brammer JG. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. Renewable and Sustainable Energy Reviews. 2002;6:181-246.

British Petroleum (BP). BP Statistical review of worlds energy. Natural gas. 2017. https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review-2017/bp-statistical-review-of-world-energy-2017-natural-gas.pdf. (Accessed 20.02.18).

British Petroleum (BP). Statistical Review of World Energy. 2016. https://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2016/bp-statistical-review-of-world-energy-2016-full-report.pdf. (Accessed 04.05.17).

Bundy LG. Corn fertilization. 1998. http://www.soils.wisc.edu/extension/pubs/A3340.pdf. (Accessed 18.05.18).

Cameron JB, Kumar A, Flynn PC. The impact of feedstock cost on technology selection and optimum size. Biomass and Bioenergy. 2007;31:137-44.

Campos M. Guabirá prevé generar 45MW de energía. El Dia. 2013. https://www.eldia.com.bo/index.php?cat=357&pla=3&id_articulo=117356. (Accessed 10.09.16).

Caputo AC, Palumbo M, Pelagagge PM, Scacchia F. Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. Biomass and Bioenergy. 2005;28:35-51.

Carrafa F. Tarifa eléctrica de Bolivia es la máas baja de Sudamérica. Cambio. 2017. http://www.cambio.bo/?q=node/28080. (Accessed 15.04.18).

Carrasco N, Zamora M, Melin A. Sorghum Manual. 2011. http://inta.gob.ar/sites/default/files/inta_manual_de_sorgo_renglon_191.pdf. (Accessed 18.10.16).

Central Intelligence Agency (CIA). South America: Bolivia. 2016. https://www.cia.gov/library/publications/the-world-factbook/geos/bl.html. (Accessed 12.01.17).

Centre for Analysis and Dissemination of Demonstrated Energy Technologies (CADDET). Straw-fired biomass plants in Denmark. 1997. http://www.caddet-re.org/assets/1-97art3.pdf. (Accessed 04.06.18).

Chávez-Rodríguez MF, Garaffa R, Andrade G, Cárdenas G, Szklo A, Lucena AF. Can Bolivia keep its role as a major natural gas exporter in South America? Journal of Natural Gas Science and Engineering. 2016;33:717-30.

Clarke S, Preto F. Biomass burn characteristics. 2015. http://www.omafra.gov.on.ca/english/engineer/facts/11-033.htm. (Accessed 26.11.16).

Clean Development Mechanisim Executive Board (CDM-EB). Clean development mechanisim project design document form (CDM-PDD) "Guabira energia bagasse cogeneration project". 2006. https://cdm.unfccc.int/Projects/projsearch.html. (Accessed 18.05.18).

Comisión Nacional de Energía Atómica (CNEA). Sintesis del mercado eléctrico mayorista de la República Argentina. 2017. http://www.melectrico.com.ar/web/pdfs/CNEA/SINTESIS_MEM_2017_DICIEMBRE.pdf. (Accessed 14.05.18).

Comité Nacional de Despacho de Carga (CNDC). Memoria 2014 Resultados de la operacion del SIN. 2015. https://www.scribd.com/document/278385862/Memoria-anual-CNDC-2014. (Accessed 05.05.18).

Compañía Administradora del Mercado Mayorista Eléctrico (CAMESSA). Informe mensual Diciembre 2017. 2017. http://portalweb.cammesa.com/memnet1/Pages/descargas.aspx. (Accessed 28.04.18).

Cooperativa rural de electrificacion (CRE). Manual del Consumidor http://www.cre.com.bo/webcre/hogar/pdf/Manual%20del%20Consumidor.PDF. (Accessed 19.05.18).

Dassanayake GD. Utilization of Triticale Straw for Power Generation [Thesis]. University of Alberta; 2012.

De los cuatro países que el gobierno Boliviano baraja para exportar electricidad, tres cuentan con con sobreoferta de energía, sobre todo hidroeléctrica. Energy press. 2017. http://www.energypress.com.bo/energia-argentina-es-el-pais-mas-factible-para-exportar/.

Duke, A. J. CRC handbook of alternative cash crops: Boca Raton: CRC Press; 1993.

El Dia. El agro se mecaniza a paso lento en Bolivia. 2014. https://www.eldia.com.bo/index.php?cat=357&pla=3&id_articulo=139367. (Accessed 02.05.18).

El País. Ofrecen mano de obra en Santa Cruz para cosecha caña. 2018. http://www.elpaisonline.com/index.php/2013-01-15-14-16-26/centrales/item/226324-ofrecen-mano-de-obra-de-santa-cruz-para-cosechar-cana. (Accessed 10.04.18).

Emberga T, Uhiara E, Nwigwe C, Amadi O. Biomass conversion technologies. 2012;4:19-24.

Empresa de luz y fuerza electrica Cochabamba (ELFEC). Norma de distancias de seguridad en lineas de distribucion http://www.elfec.com/sites/default/files/normas.pdf. (Accessed 27.04.17).

Empresa Nacional de Electricidad (ENDE). Memoria anual, 2015. 2016. http://www.ende.bo/public/memorias/memoria-2015-10-final.pdf. (Accessed 15.10.16).

Empresa Nacional De Electricidad (ENDE). Memoria anual 2016. 2017. http://www.ende.bo/public/memorias/memoria-2016-ende-corporacion.pdf. (Accessed 15.05.18).

Energy Information Administration (EIA). Annual Energy Outlook 2017 with projection to 2050. 2017. https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf. (Accessed 16.01.18).

Energy Information Administration (EIA). Cost and performance characteristics of new generating technologies, annual energy outlook 2018. 2018. https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf. (Accessed 15.02.18).

Energy Information Administration (EIA). International energy outlook 2017 2017. https://www.eia.gov/outlooks/ieo/pdf/0484(2017).pdf. (Accessed 09.06.18).

Energy Sector Management Assistance Program (ESMAP). Technical and economic assessment of off-grid, mini-grid and grid electrification technologies 2007. http://documents.worldbank.org/curated/en/634581468333897517/Technical-and-economic-assessment-of-off-grid-mini-grid-and-grid-electrification-technologies. (Accessed 16.02.18).

Environmental Protection Agency - Combined Heat and Power Paternship (EPA-CHP). Biomass combined heat and power catalog of technologies. 2007. https://www.epa.gov/sites/production/files/2015-07/documents/biomass_combined_heat_and_power_catalog_of_technologies_v.1.1.pdf. (Accessed 16.03.18).

Environmental Systems Research Institute (ESRI). Location-allocation analysis. 2017. http://desktop.arcgis.com/en/arcmap/latest/extensions/network-analyst/location-allocation.htm#GUID-A1F63AFF-8333-42A1-A540-6C49E7D717F4. (Accessed 19.05.18).

Esri. Mapping without limits. 2017. http://www.arcgis.com/features/index.html. (Accessed 22.01.17).

Fernandez M. Estimacion del Potencial de Introduction de Energias Renovables Energetica. 2010;11:1-5.

Fixen PE. Potential biofuels influence on nutrient use and removal in the US. Better Crops. 2007;91:12-4.

Food and Agriculture Organization (FAO). Bolivia hacia una estrategia libre de fertilizantes. 1999. http://www.fao.org/tempref/agl/agll/docs/bolstud.pdf. (Accessed 05.06.17).

Forster-Carneiro T, Berni MD, Dorileo IL, Rostagno MA. Biorefinery study of availability of agriculture residues and wastes for integrated biorefineries in Brazil. Resources, Conservation and Recycling. 2013;77:78-88.

Fuller S, Yu TH, Fellin L, Lalor A, Krajewski R. Transportation developments in South America and their effect on international agricultural competitiveness. Transport Res Rec. 2003:62-8.

Fundacion de investigaciones economicas Latinoamericanas (FIEL). Argentina. 2017. https://www.oecd.org/environment/cc/g20-climate/collapsecontents/Fiel-argentina-growth-and-low-carbon-transition.pdf. (Accessed 08.05.18).

German Technical Cooperation Agency (GTZ). Manejo del monte chaqueño para una ganadería sostenible. n.d. http://www.bivica.org/upload/ag_ganaderia-chaco.pdf. (Accessed 13.11.17).

Ghassemi A. Firest-based biomass energy. Concepts and applications2012.

Gómez E. Evaluación rápida del sector energía en Bolivia. Programa de Energía Sostenible para Todos (SE4ALL): La Paz. 2012. https://www.seforall.org/sites/default/files/Bolivia_RAGA_ES_Released.pdf. (Accessed 04.06.18).

Gomez M, Martinez L, Sanches A. Power generation based on agricultural residues gasification: The potential of corncobs. 2017;2017:p. 90-5.

Graham RL, English BC, Noon CE. A geographic information system-based modeling system for evaluating the cost of delivered energy crop feedstock. Biomass and bioenergy. 2000;18:309-29.

Guabira Energía. Personal communication 2017.

Guabirá. Guabirá energía S.A. 2014. http://www.guabira.com/guabira/guabira-energia-sa.html. (Accessed 09.04.18).

Guabirá. Guabirá energía S.A. 2014. http://www.guabira.com/guabira/guabira-energia-sa.html. (Accessed 09.04.18).

Helwig T, Jannasch R, Samson R, DeMaio A, Caumartin D. Agricultural biomass residue inventories and conversion systems for energy production in Eastern Canada. Prepared for Natural Resources-Canada. 2002;23348. http://agrienvarchive.ca/bioenergy/download/REAP_NRCAN-inventory-final.pdf. (Accessed 09.06.18).

Heras C. La hidroeléctrica que amenaza a 5,000 indígenas bolivianos. El País. 2017. https://elpais.com/elpais/2017/09/05/planeta_futuro/1504563761_414612.html. (Accessed 20.03.18).

Hidroelectrica Boliviana. Personal communication 2018.

Holtzhausen JP, Vosloo WL. High voltage engineering Practice and theory.

Hoskinson RL, Karlen DL, Birrell SJ, Radtke CW, Wilhelm W. Engineering, nutrient removal, and feedstock conversion evaluations of four corn stover harvest scenarios. Biomass and Bioenergy. 2007;31:126-36.

Hughes JD, Coulter J. Considerations for corn residue harvest in Minnesota. 2009. https://www.extension.umn.edu/agriculture/corn/harvest/considerations-for-corn-residue-harvest/. (Accessed 15.12.17).

IHS Markit. Costs and strategic sourcing. 2017. https://ihsmarkit.com/info/cera/ihsindexes/index.html. (Accessed 05.03.18).

Instituto de Ciencia - Economía - Educación y Salud (ICEES). Producción de fertilizantes NPK en Bolivia. 2014. http://www.icees.org.bo/2014/10/produccion-de-fertilizantes-npk-en-bolivia/. (Accessed 04.06.18).

Instituto Interamericano de Cooperación para la agricultura (IICA). La situacion regional de los fertilizantes. 2009. http://repiica.iica.int/docs/B1600e/B1600e.pdf. (Accessed 01.06.18).

Instituto Nacional de Estadistica (INE). Bolivia: Inflacion acumulada anual, 1985 - 2016. 2016. http://medios.economiayfinanzas.gob.bo/MH/documentos/2017/indicadores/Inflacion.pdf . (Accessed 03.03.18).

Instituto Nacional de Estadistica (INE). Electric Power Coverage in Bolivia. 2012. http://www.ine.gob.bo/pdf/boletin/NP_2013_32.pdf. (Accessed 05.10.16).

Instituto Nacional de Estadística (INE). Encuesta agropecuaria, 2015. Abono quimico. 2015. http://anda.ine.gob.bo/ANDA4_2/index.php/catalog/316/datafile/F9/V391. (Accessed 15.04.18).

Instituto Nacional de Estadística (INE). http://www.ine.gob.bo/. (Accessed 18.11.16).

Instituto Nacional de Estadistica (INE). Primer censo agropecuario del Estado Plurinacional. 2013. http://censosbolivia.ine.gob.bo/webine/. (Accessed 09.03.18).

Instituto Nacional de Reforma Agraria (INRA). Normas tecnicas para el saneamiento de la propiedad agraria, conformacion del catastro y registro predial 2008. http://www.inra.gob.bo/InraPb/upload/Norma_Tecnica_VERSION_FINAL_AGUA_%20aprobada%20-%20REVISADA.pdf.

Instituto Nacional de Reforma Agraria (INRA). Tipos de propiedad 2012. http://www.inra.gob.bo/InraPb/paginaController?cmd=contenido&id=6650. (Accessed 15.04.18).

Intended Nationally Determined Contribution from the Plurinational State of Bolivia (INDC). 2015. http://www4.unfccc.int/submissions/INDC/Published%20Documents/Bolivia/1/INDC-Bolivia-english.pdf. (Accessed 10.11.16).

Intergovernmental Panel on Climate Change (IPCC). Renewable energy sources and climate change mitigation. 2012. https://www.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf.

International Energy Agency (IEA). Energy and Climate Change. 2015. https://www.iea.org/publications/freepublications/publication/WEO2015SpecialReportonEnergyandClimateChange.pdf. (Accessed 17.10.16).

International Energy Agency (IEA). World Energy Outlook 2016. https://www.iea.org/publications/freepublications/publication/WorldEnergyOutlook2016ExecutiveSummaryEnglish.pdf. (Accessed 07.01.17).

International Energy Agency (IEA). World Energy Outlook 2017. 2017. https://www.iea.org/Textbase/npsum/weo2017SUM.pdf. (Accessed 09.06.18).

International Finance Corporation (IFC). Converting biomass to Energy. 2017. https://www.ifc.org/wps/wcm/connect/7a1813bc-b6e8-4139-a7fc-cee8c5c61f64/BioMass_report_06+2017.pdf?MOD=AJPERES. (Accessed 19.02.18).

International Renewable Energy Agency (IRENA). Biomass for power generation. 2012;1. https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-BIOMASS.pdf. (Accessed 05.05.17).

International Renewable Energy Agency (IRENA). Renewable energy in Latin America 2015. An overview of policies. 2015. http://www.irena.org/publications/2015/Jun/Renewable-Energy-in-Latin-America-2015-An-Overview-of-Policies. (Accessed 02.05.18).

International Renewable Energy Agency (IRENA). Renewable power generation costs in 2017. 2018. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf. (Accessed 15.03.18).

International Renewable Energy Agency (IRENA). Renewable power generation costs in 2014. 2015. https://www.irena.org/documentdownloads/publications/irena_re_power_costs_2014_report.pdf. (Accessed 04.06.18).

James CS. Argentina increases energy imports from neighbors. The Latin American Energy review. 2016. http://carlosstjames.com/renewable-energy/argentina-increases-energy-imports-from-neighbors/. (Accessed 16.04.18).

Kevin C, Mari C, Michael K, Matthew V. Biomass supply chain management in North Carolina (part 2): biomass feedstock logistical optimization. AIMS Energy, Vol 4, Iss 2, Pp 280-299 (2016). 2016:280.

Khan M. Development of a Decision Making Framework for Solid Waste Management Using GIS-based Site Selection and an Economic Comparison [Thesis]. University of Alberta; 2015.

Khan MMU, Vaezi M, Kumar A. Optimal siting of solid waste-to-value-added facilities through a GIS-based assessment. Science of the Total Environment. 2018;610:1065-75.

Kludze H, Deen B, Weersink A, Acker A, Acker R, Janovicek K, et al. Assessment of the availability of agricultural biomass for heat and energy production in Ontario. 2010. https://www.uoguelph.ca/plant/research/agronomy/publications/pdf/Ontario_Biomass_Availability_Project_Final_Report_2011.01.27.pdf. (Accessed 10.02.17).

Kost C, Mayer J, Thomsen J, Hartmann N, Senkpiel C, Philips S, et al. Levelized cost of electricity renewable energy technologies 2013. https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/Fraunhofer-ISE_LCOE_Renewable_Energy_technologies.pdf. (Accessed 14.02.18).

Kumar A, Bhattacharya SC, Pham HL. Greenhouse gas mitigation potential of biomass energy technologies in Vietnam using the long range energy alternative planning system model. Energy. 2003;28:627-54.

Kumar A, Cameron JB, Flynn PC. Biomass power cost and optimum plant size in western Canada. Biomass and Bioenergy. 2003;24:445-64.

Kumar A, Sokhansanj S, Flynn PC. Development of a multicriteria assessment model for ranking biomass feedstock collection and transportation systems. Applied Biochemistry and Biotechnology. 2006;129:71-87.

La Razon. Bolivia concreta acuerdo para exportar 335 mil toneladas de fertilizantes a Brasil. 2017. https://www.la-razon.com/economia/Bolivia-exporta-fertilizantes-Brasil-planta_0_2803519632.html. (Accessed 18.01.18).

Laclette JP, Zuñiga P. Diagnóstico del agua en las Américas 2012.

Lal R. World crop residues production and implications of its use as a biofuel. Environment International. 2005;31:575-84.

Latin-American Energy Organization (Organización Latinoamericana de Energía OLADE). Diagnostico de la generacion en America Latina y el Caribe: Bolivia. 2013. http://www.olade.org/wp-content/uploads/2015/08/Informe-Final-Bolivia-Diagnostico-Generacion-Distribuida.pdf. (Accessed 20.04.18).

Latin-American Energy Organization (Organización Latinoamericana de Energía OLADE). Matriz energética en América Latina y el Caribe, situacion actual y perspectivas de las energías renovables. 2012. http://www.olade.org/sites/default/files/presentaciones-sej/8_Presentaci%C3%B3n%20OLADE%20UPADI%20201.pdf. (Accessed 20.04.18).

Lazcano M. Electricidad de termoeléctricas tendrá otro valor para la exportación La Razon - economía. 2015. http://www.la-razon.com/index.php?_url=/economia/Energia-electricidad-termoelectricas-valor-exportacion_0_2313368673.html. (Accessed 12.04.18).

Leal MR, Galdos MV, Scarpare FV, Seabra J, Walter A, Oliveira COF. Sugarcane straw availability, quality, recovery and energy use: A literature review. Biomass and Bioenergy. 2013;53:11-9.

Legislativo P. Ley del servicio nacional de reformas agrarias (1715). 1996. https://bolivia.infoleyes.com/norma/1274/ley-del-servicio-nacional-de-reforma-agraria-1715. (Accessed 28.05.18).

Ley de hidrocarburos Ley N 3058. 2005. https://www.servindi.org/pdf/Bolivia_Ley3058_hidrocarburos2005.pdf. (Accessed 04.06.18).

Liu E. Straw procurement business case. 2008. https://www.gov.mb.ca/agriculture/innovation-and-research/pubs/straw-procurement-final-report.pdf. (Accessed 18.06.18).

Mamani J. Planta de cloruro de potasio entra en operación en Agosto. Cambio. 2018. http://www.cambio.bo/?q=node/38194. (Accessed 21.03.18).

Marulanda J, Ortiz A. Diseño de un sistema de costeo para las operaciones de de transporte de prakxon logistica con origen en Buena Ventura y destinos Bogota Medellin Cali Barranquilla, Cartagena, Bucaramanga, Pasto y vicerversa [Thesis]. Potificia Universidad Javeriana; 2012.

Maya B. Inflacion anual de 2017 llego a 2071%, la mas baja desde 2009. 2018. http://boliviamaya.com/digital/2018/01/06/inflacion-anual-de-2017-llego-a-271-la-mas-baja-desde-2009/. (Accessed 03.03.18).

Mcdonald RI, Forman RT, Kareiva P, Neugarten R, Salzer D, Fisher J. Urban effects, distance, and protected areas in an urbanizing world. Landscape and Urban Planning. 2009;93:63-75.

McIntire J, Reed JD, Tedla A, Jutzi S, Kebede Y. Evaluating sorghum cultivars for grain and straw yield. Red. 1988;2:53.6.

Ministerio de Autonomias. Agenda patriotica 2025 Quien hace que? 2013. http://extwprlegs1.fao.org/docs/pdf/bol141864.pdf. (Accessed 03.03.18).

Ministerio de Comercio Exterior y Turismo. Guia de orientación al usuario del transporte terrestre. 2015. https://www.mincetur.gob.pe/wp-content/uploads/documentos/comercio_exterior/facilitacion_comercio_exterior/Guia_Transporte_Terrestre_13072015.pdf. (Accessed 12.05.18).

Ministerio de Economía y Finanzas Públicas. Aprobación de la escala salarial de la Empresa Nacional de Electricidad (ENDE). 2017. http://www.ende.bo/public/documentos/Reglamentacion-Escala-Salarial.pdf. (Accessed 04.06.18).

Ministerio de Hidrcarburos y Energía (MHE). Plan de Desarrollo Energetico. Analisis de Escenarios: 2008-2027 2009. http://www2.hidrocarburos.gob.bo/phocadownload/PLAN%20DE%20DESARROLLO%20ENERG%C3%89TICO.pdf. (Accessed 22.10.16).

Ministerio de Hidrocarburos y Energía (MHE). Balance energético nacional 2000-2014. 2015. http://www2.hidrocarburos.gob.bo/index.php/publicaciones/balance-energ%C3%A9tico/balance-energ%C3%A9tico-departamental/category/54-balance-energetico-nacional.html. (Accessed 12.11.16).

Ministerio de Hidrocarburos y Energía (MHE). Plan optimo de expansion del sistema interconectado nacional 2012-2022. 2012. https://www.cndc.bo/boletines/publicaciones.php. (Accessed 08.03.18).

Ministerio de Hidrocarburos y Energía (MHE). Plan para el desarrollo de las energías alternativas, 2025. 2014. http://www.bivica.org/upload/energias-alternativas-plan.pdf. (Accessed 17.10.16).

Ministerio de Hidrocarburos y Energía de Bolivia (MHE). Plan eléctrico del estado plurinacional de Bolivia 2025. 2014. http://globaltrends.thedialogue.org/publication/plan-electrico-del-estado-plurnacional-de-bolivia-2025/. (Accessed 12.05.18).

Ministerio de relaciones exteriores. Posición Boliviana en las Negociaciones Internacionales de la Convención Macro de Naciones Unidas sobre Cambio Climático (CMNUCC). 2016. http://www.embolivia.org.br/UserFiles/File/PDFs/emb_climatico.PDF. (Accessed 01.06.18).

Missouri department of natural resources - Energize Missouri. Feasibility study for a biomass electrical power plant in the Viburnum region. 2012. http://energy.mo.gov/energy/docs/G11-SEP-RES-16VEDACFinalReport.pdf. (Accessed 15.17.17).

Molburg JC, Kavicky JA, Picel KC. The design, construction, and operation of long-distance high-voltage electricity transmission technologies 2007. http://solareis.anl.gov/documents/docs/APT_61117_EVS_TM_08_4.pdf.

Montross M, Crofcheck C. Effect of stover fraction and storage method on glucose production during enzymatic hydrolysis. Bioresource technology. 2004;92:269-74.

Morato T, Kumar A, Vaezi M. Assessment of potential energy from agricultural residues in Bolivia. Manuscript submitted for publication.

Morato T, Vaezi M, Kumar A. Assessment of energy production potential from agricultural residues in Bolivia. Submitted for journal publication.

Morato T, Vaezi M, Kumar A. Developing a framework for locating BCPs to improve the biomass-based energy facilities locating procedure - A case for Bolivia. In preparation for journal publication.

National Renewable Energy Laboratory (NREL). Cost and performance data for power generation technologies. 2012. https://www.bv.com/docs/reports-studies/nrel-cost-report.pdf. (Accessed 12.01.18).

National Renewable Energy Laboratory (NREL). Highlights of biopower technical assessment: state of the industry and the technology. 2003. https://www.nrel.gov/docs/fy03osti/33502.pdf. (Accessed 13.02.18).

National Renewable Energy Laboratory (NREL). Lessons learned from existing biomass power plants. 2000. https://www.nrel.gov/docs/fy00osti/26946.pdf. (Accessed 15.01.18).

Nolé F. Pese a la inflacion, Dujovne ratificó la eliminación de subsidios de energía y transporte. Perfil. 2018. http://www.perfil.com/noticias/economia/pese-a-la-inflacion-dujovne-ratifico-la-eliminacion-de-subsidios-de-energia-y-transporte.phtml. (Accessed 05.05.18).

Open energy information (OpenEI). Levelized cost of energy 2015. https://openei.org/apps/TCDB/transparent_cost_database. (Accessed 16.03.18).

Organizacion Mundial de la Salud (OMS). La seguridad vial en la región de las Américas. 2016. http://www.who.int/violence_injury_prevention/road_safety_status/2015/Road_Safety_PAHO_Spanish.pdf. (Accessed 03.06.18).

Organo Legislativo. Ley de Minería y Metalúrgia (535). 2014. https://bolivia.infoleyes.com/norma/4984/ley-de-miner%C3%ADa-y-metal%C3%BArgia-535. (Accessed 27.04.17).

Oursbourn C, Lacewell R, LePori W, Patton W. Energy potential from agricultural residues in Texas. Southern Journal of Agricultural Economics. 1978:73-80.

Overend RP. The average haul distance and transportation work factors for biomass delivered to a central plant. Biomass. 1982;2:75-9.

Perlack R.D, Turhollow A.F. Assessment of option for the collection handling and transport of corn stover. 2002. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.562.267&rep=rep1&type=pdf. (Accessed 18.06.18).

Perlack RD, Wright LL, Turhollow AF, Graham RL, Stokes BJ, Erbach DC. Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. 2005. https://www1.eere.energy.gov/bioenergy/pdfs/final_billionton_vision_report2.pdf. (Accessed 18.06.18).

Perpina C, Alfonso D, Pérez-Navarro A, Penalvo E, Vargas C, Cárdenas R. Methodology based on Geographic Information Systems for biomass logistics and transport optimisation. Renewable Energy. 2009;34:555-65.

Pimienta G. El proyecto Chepete-El Bala amenaza la vocación turística Los tiempos. 2018. http://www.lostiempos.com/actualidad/economia/20180120/proyecto-chepete-bala-amenaza-vocacion-turistica. (Accessed 10.04.18).

Pingrey DW, Waggoner NE. Direct-combustion systems to produce power from biomass from wood, forest and agricultural crop residue. 1981:Medium: X; Size: Pages: 294.

Poder Ejecutivo. Reglamento de aguas (s/n de 08/09/1879). 1906. https://bolivia.infoleyes.com/norma/2442/reglamento-de-aguas-s-n-de-08-09-1879. (Accessed 27.04.17).

Pozzo E. La energía renovable le costaría a la Argentina menos que importar combustibles. El Cronista. 2017. https://www.cronista.com/negocios/La-energia-renovable-le-costaria-a-la-Argentina-menos-que-importar-combustibles-20170802-0115.html. (Accessed 24.04.18).

Prihar S, Stewart B. Sorghum harvest index in relation to plant size, environment, and cultivar. Agronomy Journal. 1991;83:603-8.

Programa de electricidad para vivir con dignidad (PEVD). Programa de electricidad para vivir con dignidad. 2014. http://www.pevd.gob.bo/pevd/nosotros/que-es-el-programa-electricidad-para-vivir-con-dignidad-pevd. (Accessed 5.11.16).

Rehman K, Jawaid M, Rashid U. Biomass and Bioenergy: Processing and Properties: Springer International Publishing; 2014.

Renewable Energy Policy Network for the 21st Century (REN 21). Global status report. 2017. http://www.ren21.net/wp-content/uploads/2017/06/17-8399_GSR_2017_Full_Report_0621_Opt.pdf. (Accessed 18.12.17).

Roberts JJ, Cassula AM, Prado PO, Dias RA, Balestieri JAP. Assessment of dry residual biomass potential for use as alternative energy source in the party of General Pueyrredón, Argentina. Renewable and Sustainable Energy Reviews. 2015;41:568-83.

Rosendahl L. Biomass combustion science, technology and engineering Preface. Woodhead Publ Ser En. 2013:9-32.

Saaty TL. Fundamentals of decision making and priority theory with the analytic hierarchy process: Rws Publications; 2000.

San Martin L. Determinacion del precio del gas natural para el sector electrico boliviano y su efecto en las tarifas a consumidor final 2011. http://www.gesel.ie.ufrj.br/app/webroot/files/publications/28_TDSE43_ESPANHOL.pdf. (Accessed 03.03.18).

Sanchez G, Aranibar A, Sánchez C, Otasevic J, Guillermo J, Oswaldo R, et al. Reglamento Ambiental para el sector de Hidrocarburos (RASH). Decreto Supremo N 24335 de 19/07/1996. 1996. http://extwprlegs1.fao.org/docs/pdf/bol146679.pdf. (Accessed 27.04.17).

Sanchez MC. Las quemas reducen el rendimiento de plantaciones de caña en Bermejo. Periodico digital de investigacion sobre Bolivia. 2014. http://www.pieb.com.bo/sipieb_nota.php?idn=8950. (Accessed 20.01.17).

Sawyer J. Nutrient removal when harvesting corn stover 2007. https://crops.extension.iastate.edu/nutrient-removal-when-harvesting-corn-stover-0. (Accessed 20.03.18).

Scarlat N, Martinov M, Dallemand JF. Assessment of the availability of agricultural crop residues in the European Union: potential and limitations for bioenergy use. Waste management (New York, NY). 2010;30:1889-97.

Servicio Nacional de Areas Protegidas (SERNAP). Las zonas externas de amortiguamiento. http://www.bivica.org/upload/zonas-externas-amortiguacion.pdf. (Accessed 28.05.18).

Servindi. Mundo: "Salvemos al planeta del capitalismo", carta de Evo Morales sobre cambio climático. 2008. https://www.servindi.org/actualidad/5743. (Accessed 18.04.18).

Sharma B, Ingalls RG, Jones CL, Huhnke RL, Khanchi A. Scenario optimization modeling approach for design and management of biomass-to-biorefinery supply chain system. Bioresource Technology. 2013;150:163-71.

Sigua GC, Stone KC, Hunt PG, Cantrell KB, Novak JM. Increasing biomass of winter wheat using sorghum biochars. Agronomy for Sustainable Development. 2015;35:739-48.

Singh J, Panesar B, Sharma S. Energy potential through agricultural biomass using geographical information system—A case study of Punjab. Biomass and Bioenergy. 2008;32:301-7.

Smith. Biomass conversion technologies. 2006. https://www.epa.gov/sites/production/files/2015-07/documents/biomass_combined_heat_and_power_catalog_of_technologies_5._biomass_conversion_technologies.pdf. (Accessed 15.03.18).

Sokhansanj S, F. Turhollow A. Baseline cost for corn stover collection. Applied Engineering in Agriculture. 2002;18:525.

Sokhansanj S, Fenton J. Cost benefit of biomass supply and pre-processing. BIOCAP Canada 2006. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.546.5141&rep=rep1&type=pdf. (Accessed 20.04.18).

Solfor. Personal communication. 2017.

Solón P, Solon J, Suaznabar L. El plan de la energía electrica para el 2025. Funcación Solón. 2017. https://fundacionsolon.org/2017/11/01/el-plan-de-energia-electrica-para-el-2025/. (Accessed 15.03.18).

Solón. El caso del Chepete y El Bala. Fundación Solón. 2017. https://fundacionsolon.org/2017/05/10/el-caso-del-chepete-y-el-bala/. (Accessed 15.05.18).

Spaeth SC, Randall HC, Sinclair TR, Vendeland JS. Stability of Soybean Harvest Index1. Agronomy Journal. 1984;76:482-6.

Statistics Canada: Agricultural Division. Livestock Feed Requirements Study. 2003. http://www.statcan.gc.ca/pub/23-501-x/23-501-x2003001-eng.pdf. (Accessed 12.09.16).

Stumborg M, Townley-Smith L, Coxworth E. Sustainability and economic issues for cereal crop residue export. Canadian journal of plant science. 1996;76:669-73.

Suarez AL. El sector del transporte. 2009;Tomo IV http://www.udape.gob.bo/portales_html/diagnosticos/documentos/TOMO%20IV%20-%20SECTOR%20TRANSPORTE.pdf. (Accessed 15.10.17).

Sultana A, Kumar A, Harfield D. Development of agri-pellet production cost and optimum size. Bioresource Technology. 2010;101:5609-21.

Sultana A, Kumar A. Development of tortuosity factor for assessment of lignocellulosic biomass delivery cost to a biorefinery. 2014;119:288–95.

Sultana A, Kumar A. Optimal siting and size of bioenergy facilities using geographic information system. Applied Energy. 2012;94:192-201.

Tan Z, Liu S, Bliss N, Tieszen LL. Current and potential sustainable corn stover feedstock for biofuel production in the United States. Biomass and bioenergy. 2012;47:372-86.

Telma M. Hidroeléctrica Rositas: el proyecto que rechazan las comunidades y que amenaza a un área protegida en Bolivia Mongabay Latam. 2017. https://es.mongabay.com/2017/07/hidroelectrica-rositas-proyecto-rechazan-las-comunidades-amenaza-area-protegida-bolivia/. (Accessed 20.04.18).

Thakur A. Power Generation from Forest Residues [Thesis]. University of Alberta; 2011.

The dialogue - Leadership for the Americas. Can Latin America transition to low carbon energy? 2016. http://www.thedialogue.org/wp-content/uploads/2016/10/WCEE-Presentation_10.17.16-1.pdf. (Accessed 05.06.18).

Turnbull JH. Use of biomass in electric power generation: the california experience. Biomass and Bioenergy. 1993;4:75-84.

Ullah M, Vaezi M, Kumar A, Bell J. Assessment of the Waste-to-Energy potential from Alberta's food processing industry. Canadian Society for Bioengineering. 2017;59.

Ullah M. Techno-economic assessment of utilization of food processing waste for production of energy and chemicals [Thesis]. University of Alberta; 2017.

United States Department of Agriculture (USDA). Grain truck and ocean rate advisory (GTOR). 4th Quarter 2017. 2017. https://www.ams.usda.gov/sites/default/files/media/GTOR4thQtr2017Quarterly.pdf. (Accessed 14.02.18).

United States Nuclear Regulatory Commission (U.S. NSC). Capacity factor (net). 2017. https://www.nrc.gov/reading-rm/basic-ref/glossary/capacity-factor-net.html. (Accessed 15.03.18).

Urquiola M, Andersen L, Antelo E, Luis Evia J, Nina O. Geography and Development in Bolivia2018.

van den Broek R, Faaij A, van Wijk A. Biomass combustion for power generation. Biomass and Bioenergy. 1996;11:271-81.

Vargas JP, Calvimontes J. Evaluation of landfill biomass potential in Bolivia to produce electricity. Revista Investigación & Desarrollo. 2017;1:55-62.

Vargas O. Proyecto boliviano de industrializacion del litio en el salar de Uyuni. 2010. http://www.revistasbolivianas.org.bo/pdf/rmym/n7/n7a07.pdf. (Accessed 16.02.18).

Vasquez W. Eleven energy plants will produce 420 MW by 2020. La Razon. 2015;La Razon http://www.la-razon.com/economia/Once-energias-alternas-produciran-MW_0_2315168462.html. (Accessed 05.11.16).

Velázquez-Martí B, Annevelink E. GIS application to define biomass collection points as sources for linear programming of delivery networks. Transactions of the ASAE (American Society of Agricultural Engineers). 2009;52:1069.

Viana H, Cohen WB, Lopes D, Aranha J. Assessment of forest biomass for use as energy. GIS-based analysis of geographical availability and locations of wood-fired power plants in Portugal. Applied Energy. 2010;87:2551-60.

Vicepresidencia del Estado Plurinacional de Bolivia. Información Geográfica de Bolivia, GeoBolivia. http://geo.gob.bo/portal/. (Accessed 04.05.17).

Voivontas D, Assimacopoulos D, Koukios E. Assessment of biomass potential for power production: a GIS based method. Biomass and bioenergy. 2001;20:101-12.

Wekesa AN. Using GIS to assess the potential of crop residues for energy generation in Kenya [Thesis]. University of Canterbury; 2013.

World Heritage Encyclopedia. Plurinational State of Bolivia. http://self.gutenberg.org/articles/eng/Plurinational_State_of_Bolivia#cite_note-52. (Accessed 25.01.17).

Yacimientos Petroliferos Fiscales Bolivianos (YPFB). Boletin estadistico Enero-Junio 2015. 2015. http://www.ypfb.gob.bo/es/55-ypfb-corporacion/publicaciones/79-publicaciones.html. (Accessed 21.05.18).