



# **A climate, land-use, energy and water nexus assessment of Bolivia**

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## **Abstract**

Land, energy and water are the foundational resources of a country, and have a number of complex interactions with a changing climate. Their exploitation can have significant impacts on climate change, which in turn can affect the future availability of these resources. Thus it is important to properly manage these resources, to ensure that they can continue to provide long into the future. This thesis aims to assess the climate, land-use, energy and water systems (CLEWs) nexus in Bolivia, to determine critical points of interactions, and to produce recommendations for policy actions. This includes both mitigation and adaptation actions. The results show that Bolivia's projected demand increases are certainly manageable, and with the investments as outlined, they can easily be satisfied, while reducing emissions and increasing climate resilience. An important result is that municipal and thermal water demand don't appear to be limiting constraints, and so water management efforts should focus on agricultural and hydropower use.

Recommended future work is to increase the scope and detail of the water and land model, so that all of the planned hydropower projects are included, and so that agriculture and irrigation demands and impacts can be more accurately predicted.

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## List of Abbreviations

BAU	Business as usual
CLEWs	Climate, Land, Energy and Water systems
FAO	Food and Agriculture Organisation of the United Nations
GAEZ	Global Agro-Ecological Zones
GDP	Gross Domestic Product
GHG	Greenhouse gas
GIS	Geographical Information Systems
GLPK	GNU Linear Programming Kit
HDI	Human Development Index
IIASA	International Institute for Applied Systems Analysis
KTH-dESA	The Division for Energy Systems Analysis at the Royal Institute of Technology
LCOE	Levelised cost of electricity
LHV	Lower heating value
LULUCF	Land use, land-use change and forestry
MoManI	Model Management Infrastructure for OSeMOSYS
ONSSET	Open Source Spatial Electrification Toolkit
OSeMOSYS	Open Source Energy Modeling System
O&M	Operation and maintenance
PP	Power plant
PV	Photovoltaic
RES	Reference energy system
SDG	Sustainable Development Goal
UN DESA	United Nations Department of Economic and Social Affairs
VBA	Visual Basic for Applications
WEAP	Water Evaluation and Planning

# 1 Introduction

## 1.1 Background

With increasing standards of living and populations, the world places increasing stresses on its key resources. Competition for water resources, access to quality land, and affordable energy availability are at the core of this issue. And as the use and misuse of these resources contributes to climate change, so the changing climate makes their continued use more unpredictable and prone to instability. These issues are particularly pressing in developing countries, which have less developed infrastructure, and the systems are more vulnerable and less able to adapt. On top of this, global electricity access levels remain low, water access is often rudimentary and land and malnourishment issues persist. Thus the effective management of land, energy and water systems is becoming increasingly important. Tackling these as separate issues has led to discord and inefficiency in policy design. The Climate, Land, Energy and Water systems (CLEWs) approach aims to integrate these resource assessments into one framework. This methodology was created by the Division for Energy Systems Analysis at the Royal Institute of Technology (KTH-dESA) and is being developed along with a number of international organisations.

Bolivia has the lowest Human Development Index in South America, and its unique geography make it vulnerable to changes in land and water conditions. Although almost 90% of the population has access to electricity, the per capita electricity usage is still extremely low, and will need to increase in the coming years if Bolivia is to develop [1]. It has a 24% undernourishment rate, which contributes to the highest regional incidence of infant mortality. All of these are getting better, but their continued improvement will place increasing demands on the country's resources [2].

The interconnections between these resources are many and complex. Agriculture makes up 92% of water withdrawals in Bolivia [3] while LULUCF is responsible for 52% of the country's climate impact [4]. Bolivia's dramatic electrification targets (including an eight-fold increase in capacity in the next fifteen years [5]) would greatly increase its demand on water and land. The effects of climate change have already been felt, with a delayed rainy season, disappearing glaciers, and higher and more unpredictable rainfall and temperatures in certain areas [6, 7, 8].

An important part of this project is to contribute to achieving the UN's Sustainable Development Goals (SDGs) [9]. Within this framework, the relevant goals are Goal 6 (water availability), Goal 7 (energy availability) and Goal 13 (climate change). Bolivia is ahead of global averages for most of the indicators, but lags South America in many.

## 1.2 Objectives

The primary objectives of this thesis are as follows:

- Create models for spatial electrification, energy systems, water and land-use
- Integrate these models with each other and with the effects of climate change

- Determine the pressure points between resources

Additionally, some extra objectives are included that do not form a core part of the discussion of this thesis, but are contributions to the work being carried out by KTH-dESA:

- Improve the ONSSET methodology and create a Python implementation of it
- Conduct testing and help with improvements on the Momani interface for OSeMOSYS

## 2 The CLEWs nexus in Bolivia

The CLEWs framework acknowledges that land, energy and water resources are deeply integrated, and need to be approached as such. This novel approach was developed by KTH-dESA in partnership with UN DESA. It combines a number of modelling techniques under one umbrella, highlighting the need to create feedbacks and connections between resource categories. Instead of modelling climate, land, energy and water each in separate silos, they are combined and approached as one problem.

These tools include:

- Open Source Spatial Electrification Toolkit (ONSSET):  
A methodology developed by dESA (see [10]) to quantify the technology and investment pathways to achieve complete electrification, based on GIS data and levelised costs of electrification.
- Open Source Energy Modeling System (OSeMOSYS):  
The open source model created by dESA (see [11]) for long-term energy planning, using linear programming to optimise technology selection.
- Water Evaluation and Planning (WEAP):  
A software tool for water resource assessment and planning, developed by the Stockholm Environmental Institute (see [12]). It is based on water balance accounting, using basins and inputs and water demand sites as basic elements.
- Global Agro-Ecological Zones (GAEZ):  
A land and agriculture database developed by the Food and Agriculture Organisation of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) (see [13]).

### 2.1 The Bolivian context

Bolivia has a population of more than 10.8 million spread over an area of just under 1.1 million square kilometres [14]. It has the lowest GDP per capita in South America, at 3125 USD [15]. The annual population growth is 1.6% and the average economic growth

for the last ten years was 4.9% [15]. The urbanised population in 2030 is expected to increase from the current 68.1% to 75.2% [16].

It is a landlocked country with a unique and varied geography. There are three broadly defined geographic zones: the high-altitude Altiplano in the west, the humid slopes of the Yungas valleys, and the temperate to tropical lowlands in the east and north. Each of these areas has a drastically different climate, with additional variations within each zone. Each area has different challenges, along with different potentials for farming, energy and water.

With reference to the Sustainable Development Goals, a number of comparisons are made in Table 1.

**Table 1:** Comparison of SDG indicators [1, 15]

Indicator	Description	Global	Bolivia
7.1.1	Electricity access	83%	88%
7.1.2	Access to clean fuels	59%	76%
7.2.1	Renewable energy share of consumption	18%	28%
7.3.1	Energy intensity of economy	5.8 MJ/USD	6 MJ/USD
6.1.1	Access to safely managed drinking water	86%	90%
6.3.1	Percentage wastewater safely treated	72%	50%

### 2.1.1 Climate impacts and projections

Most of the Altiplano experiences a desert-polar climate, with low rainfall and higher solar radiation. This region includes some of Bolivia's largest population areas, and they are dependent on the mountain glaciers for river flow and water in the long dry season [8]. These glaciers are retreating at an increasing rate, and the nearly-extinct glacier Chacaltaya (near the administrative capital La Paz), has been a highly publicised example of things to come [7]. There are also indications of a delayed or weaker rainy season, which would exacerbate these problems [6].

In the Amazon basin, there has been increased rainfall in some areas, resulting in more floods [8]. Already farmers have reported that rainfall, hail and frost have become less predictable and more extreme [17]. Although the uncertainty is still very high, one model has suggested that climate change will result in reduced yields, especially in smallholder farms [18].

At the other end, Bolivia is only responsible for 0.05% of the world's GHG emissions, while making up 0.15% of its population [19].

### 2.1.2 Land use and food production

Agriculture contributes about 9% of Bolivia's GDP, and makes up 40% of its labour, although these have been decreasing in the last twenty years. Cultivated land makes up 4% of the total area, and has grown in size by 50% since the nineties. Cereals and potatoes are the biggest products for domestic consumption, while soybeans, nuts and coffee are the

most important exports [2]. Forest cover has been decreasing by about half a percent per year over the past twenty years.

The majority of the large, commercial farms are in the eastern lowlands, and have access to modern technology and mechanisation, improved irrigation, and financing sources. However, 94% of the agricultural units in the country belong to smallholder producers of mostly staple crops. Most of these are around the high Altiplano and Yungas valleys. These land parcels are family-owned *minifundios* — sometimes as small as 500 m<sup>2</sup> — which are facing higher demands and diminishing yields [20]. According to the Ministry of Rural Development and Land, 89% of the municipalities are classified with medium to high vulnerability to food insecurity [21].

### 2.1.3 The energy system

Although Bolivia has the second lowest electrification rate in Latin America, it is still quite high in a global context, at 96% and 73% for urban and rural populations, respectively [1]. The national grid currently reaches most of the large cities, but about five cities with more than 20 000 inhabitants remain separate, along with one of the nine departments<sup>1</sup> [22]. The grid, population and road network are shown in Figure 1a.

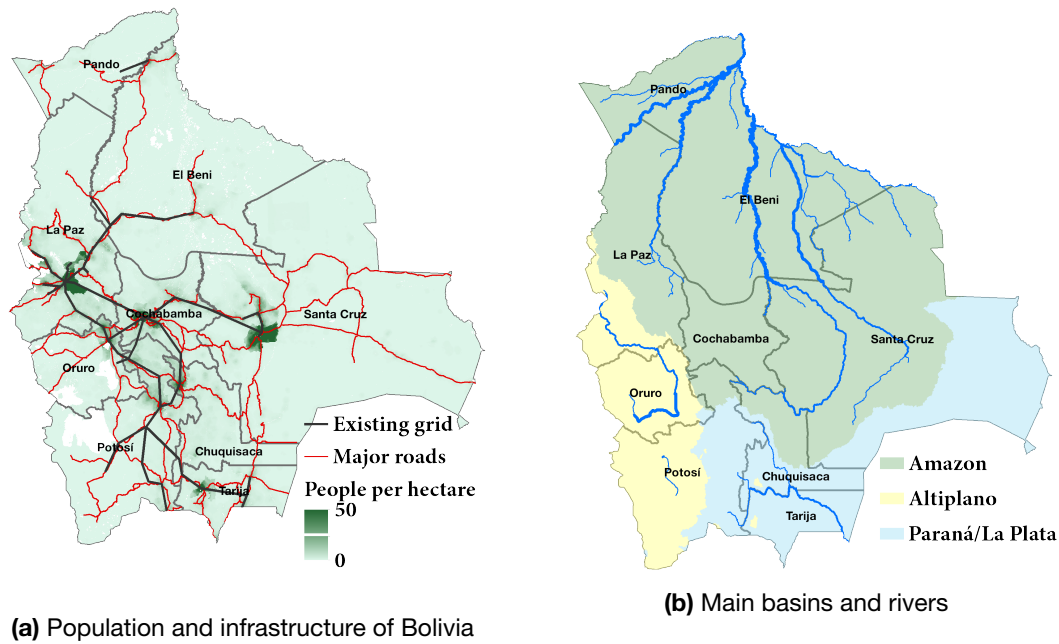
Electricity represents less than 10% of Bolivia's total final energy supply, while 75% is from direct use of oil and natural gas, and the remaining 10% is from biofuels. Industry represents 25% of energy demand, transport is 40%, residential is 19% and agriculture and forestry are 11%. As for electricity, 66% is from natural gas, 31% from hydropower, and the remainder from a small amount of oil and biofuels, with a tiny contribution from wind and PV power. [23].

Bolivia is completely self-sufficient for crude oil and natural gas, but does import some refined oil products. The majority of the oil and 70% of the natural gas is extracted in the southern department of Tarija [24, 25, 26]. Currently there are two natural gas pipelines, one to Brazil and one to Argentina, and Bolivia exports more than 80% of its natural gas production [23]. Local natural gas prices are set by the government [27]. Estimates of oil and gas proven reserves have fallen in recent years, with oil standing at 210 million barrels (the lowest in South America apart from Paraguay and Uruguay) and natural gas at 280 billion m<sup>3</sup>, behind the big natural gas countries in South America [26].

Bolivia has a complicated history of privatisation and unbundling of energy companies. In 1994, the government separated the state-owned electricity company into separate companies for generation, transmission and distribution [27], and made such vertical unbundling a requirement for any company connected to the main national grid. As a result of this, there are currently fourteen generation companies [28], three transmission companies [29] and eight distribution companies [30]. Bolivia's natural gas ownership has changed between private and government a few times over the last hundred years, but it was finally nationalised again in 2006, with the government taking an 82% share in the largest two fields, and 60% of the smaller ones [31].

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<sup>1</sup>Departments are the primary geopolitical subdivisions of Bolivia



**Figure 1:** Basic geopolitical overview of Bolivia

#### 2.1.4 Water resources

Bolivia has three main drainage basins: the Amazon, Paraná/La Plata and a number of endorheic (no outflow) basins terminating in the Altiplano. The Amazon basin makes up about 70% of Bolivia's area, the entire northern and central parts of the country. It drains the Andes to the east and north, and includes most of the high rainfall regions of Bolivia, as well as the vast majority of the population. The Paraná basin drains the southern and eastern section of Bolivia into Argentina and Paraguay, and experiences less rainfall on average. The endorheic basins are in the furthest west sections, and drain into a number of salt flats and shallow lakes. These basins are shown along with the main rivers in [Figure 1b](#).

The average rainfall is 1146 mm, but this ranges in different regions from less than 100 mm in parts of the Altiplano up to more than 2200 mm in some areas of the Amazonas basin [13, 32]. The rain is concentrated to a few months around December and January, which can cause serious flooding, while the long dry seasons pose a risk for droughts. Like most countries in the region, Bolivian weather is strongly affected by the El Niño cycle. [32]

Agriculture accounts for 92% of water withdrawals, while municipal and industrial are 6.5% and 1.5%, respectively. Currently, only 6.5% of cultivated land is irrigated, and 93% of this is by surface irrigation [3]. Lake Titicaca near La Paz is the largest lake in South America, and provides water for a large area of the Altiplano through controlled release into a drainage river.

As of 2015, 97% of the urban and 76% of the rural population have access to safe drinking water [3]. In the last two decades, water issues have been brought to the fore in alarming ways. The Cochabamba protests in 2000, over the privatisation of the municipal water company, showed the importance placed on affordable water by the public, and smaller incidents in other areas have shown that water access issues need to be taken seriously [33].

## 3 Methodology

### 3.1 Overview

The primary steps are as follows:

- Conduct a continuous literature study, to find indicators for pressure points, government plans and policies, critical issues in Bolivia and existing models.
- Collect and manage data for climate, land, energy and water through online databases and Bolivian government as required. This needs to be organised and managed to make it useable in the various tools.
- Create models for the various parts of the nexus, apply feedback and interactions where appropriate, and create scenarios.
- Combine quantitative modelling outputs with qualitative research outputs to draw conclusions and recommendations for Bolivian policy makers.

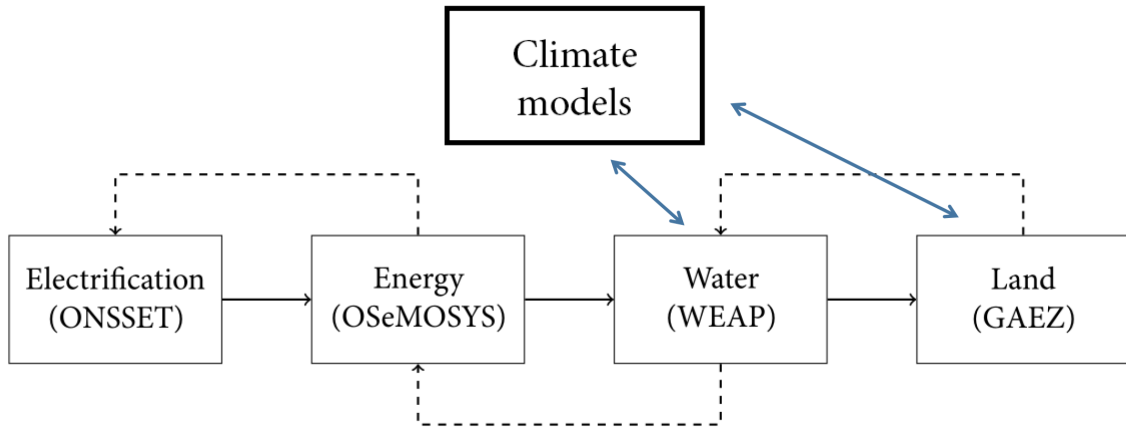
This analysis of Bolivia requires a complex and interconnected set of approaches. These are described here, along with data sources, modelling techniques, assumptions and scenarios. Emphasis is also placed on the points of interconnection between the approaches. The analysis begins with a pre-analysis of all four approaches, in order to determine the pressure points in the Bolivian nexus that deserve the most attention. The four main steps are shown in [Figure 2](#).

The first procedure is to create an optimised spatial electrification plan for Bolivia, in order to achieve 100% electrification by 2030. This will be done using the ONSSET methodology, based on detailed geographical (GIS) data and technology costs specific to Bolivia. Most solutions should involve minigrids and standalone solutions.

The next section of the analysis is to create an energy optimisation model of Bolivia, using OSeMOSYS. There is the potential for feedback from the energy model into the electrification model. For example, if the energy optimisation creates a solution involving lots of wind power, this could extend the grid to certain areas and alter the parameters for electrification in those areas. However, as Bolivia already has a very high grid penetration, it is not expected that any electrification plan will include drastic changes to the electricity network.

With the energy and electrification models complete, a water resource model is created in WEAP. This will focus on a few sub-basins, chosen for data availability and their potential for limiting interconnections with the energy and food systems. This water model will include hydro- and thermal-power stations, as well as their water requirements, and could thus limit the production capacity for the energy modelling.

Finally, land-use parameters from GAEZ will be considered based on the outcomes from the previous steps. A set of consistent scenarios will be created for the scenarios, that can be applied through each step of the methodology. These will be based on business as usual, on projections and plans from the Bolivian government, and on requirements for certain climate and development targets.



**Figure 2:** Methodological sequence and feedbacks

### 3.2 Pre-nexus assessment

A pre-nexus assessment was performed to identify pressure points and critical pathways in Bolivian resource use.

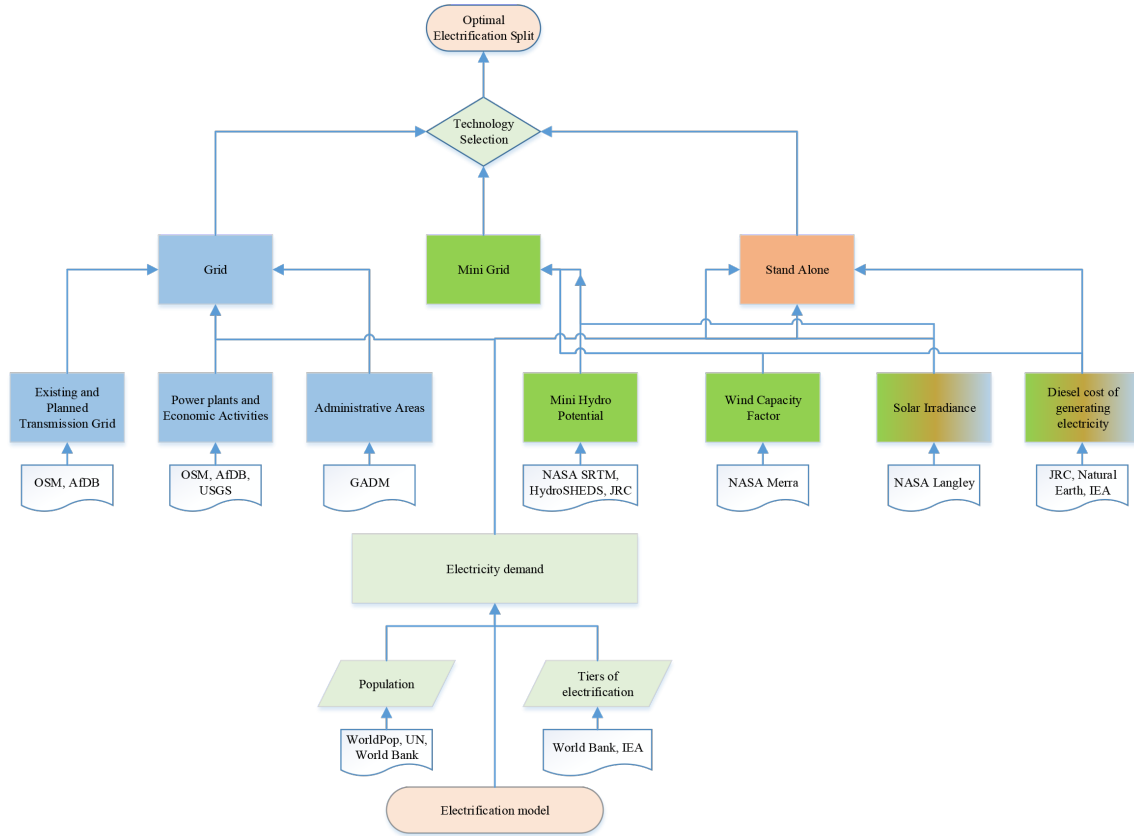
- The La Paz region faces water shortages as glaciers melt and agricultural waterways are diverted for hydropower.
- The Beni department contains extensive and growing pasture lands, and will face continued deforestation if left unchecked.
- Santa Cruz is the fastest growing region, with extensive and rapid agricultural and industrial expansions, along with a number of hydropower and thermal power plants planned.
- Finally, Tarija province is the source of most of Bolivia's oil and gas, which still has lots of room for expansion.

### 3.3 Spatial electrification

This paper will primarily follow the methodology used in a previous case-study on Nigeria by KTH-dESA [10], which built on previous work by Szabó et al. [34]. The basic steps of this methodology are shown in Figure 3.

This analysis is based on equally sized settlements of 100 km<sup>2</sup> spread across the country. Each one has a certain location, population, elevation etc. The primary goal is to determine for each settlement whether it is cheapest to connect to the grid, operated as a mini-grid, or if stand-alone power solutions should be provided to each household. Additionally, it determines the cheapest technology for each settlement, choosing between diesel, solar, wind and hydro-power (for non-grid connected settlements).

The target of 100% electrification by 2025 – 2030 is from published Bolivian government material [35].



**Figure 3: ONSSET methodology [36]**

### 3.3.1 Data gathering and processing

The main geographical layers used in the ONSSET procedure are shown in Table 2. The required output from the geospatial processing is a table of equally-sized settlements with the attributes of each settlement:

- population, current and future
- urban/rural classification
- distance from the existing and planned grid network
- global horizontal irradiation
- travel time from nearest city
- average wind velocity
- small- and mini-hydropower potential
- settlement coordinates in latitude and longitude

To achieve this, a script was created in the Python programming language [37] to extract this data from the required files and export it as a table. To do this, it requires a desired

settlement size to be specified. Then it extracts the population values to individual points, and assigns the data from the remaining GIS layers to those points. This python code is shown in [Appendix A](#).

**Table 2:** Data used in ONSSET with sources

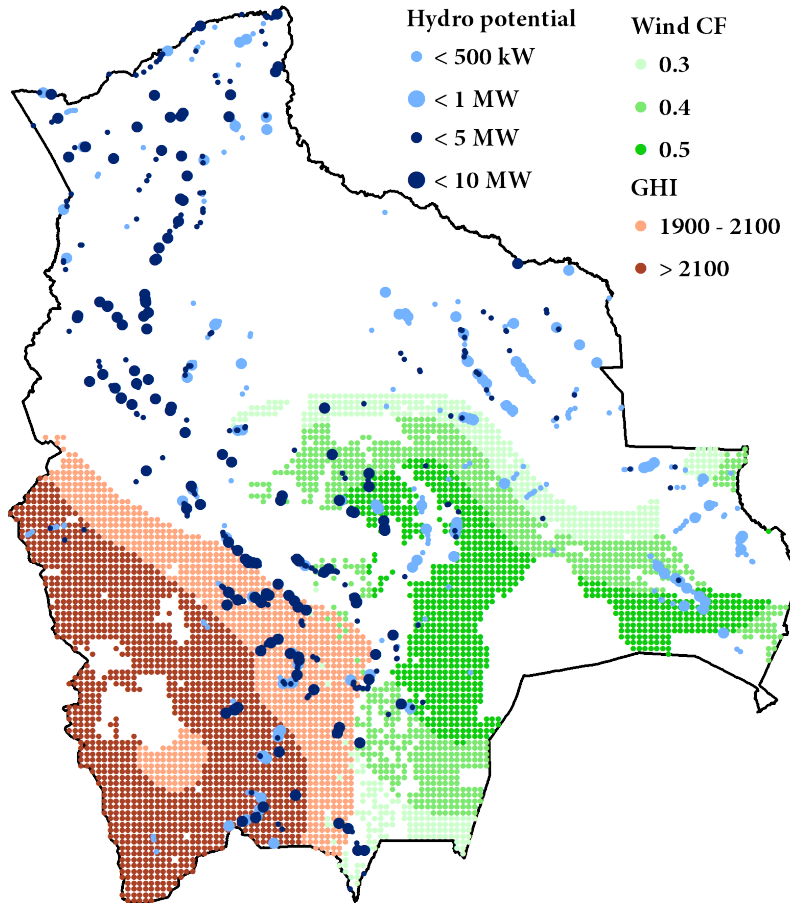
Description	Use	Source
Administrative boundaries	Used to delineate other layers	[38]
Population density	Population per settlement	[39]
Population forecast	Calculate 2030 population	[16]
GHI	Calculate solar potential	[40]
Wind velocity	Determine wind capacity factor	[41]
Elevation	Calculate flow direction, flow accumulation, slope angle and head potential for hydropower	[42]
Protected areas	Used to exclude certain areas from analysis	[43]
Water bodies	Exclude certain areas from analysis	[44]
Travel time	Determine diesel cost in remote areas	[45]
Electrical grid	Determine distance from grid	[22]
Streamflow	Calculate the potential discharge for an area	[46]
River network	Calculate hydropower potential	[47]
Mine locations	Determine potential grid extensions	[24]
Urban extents	Differentiate urban/rural split	[48]
Night light intensity	Determine electrification status	[49]

Some specific procedures were used to prepare the different resource categories:

- The urban/rural split for each settlement is based on population and the urban extents GIS layer, and is calibrated to match national urban percentage of 68% [14]
- The capacity factor for wind is calculated according to an internally developed algorithm, using a Rayleigh probability distribution. Additionally, any sites with a slope of more than 18 ° and an elevation of more than 2000 m (a significant percentage of Bolivia) were excluded, along with protected and built-up land.
- The hydropower potential for each site is calculated according to an internally developed algorithm, which was created as a Python script for this project (see [Appendix B](#)). It takes the river network, runoff layers and elevation map to estimate mini-hydro (100 kW – 1 MW) and small-hydro (1 MW – 10 MW) potential. These are then restricted based on distance from urban areas, land-use, head, discharge and stream order.
- The diesel cost is based on the travel time to major cities, following a methodology used for African electrification [34], using prices and properties relevant to Bolivia [50, 51].
- The cost for solar PV installations is based on a simple linear interpolation using historical GHI-price relationships.

- The grid was extended to connect to three high-production mines that are near to existing grid infrastructure. These mines are collectively responsible for over half of antimony production, more than 90% of lead production and more than a third of gold output. It is assumed that these extensions will be made by 2030.

The primary sources of off-grid energy, apart from diesel, are displayed in [Figure 4](#).



**Figure 4:** Renewable energy potential

### 3.3.2 Electrification and technology costs

In order to choose between electrification approaches — grid, mini-grid and stand-alone — and separate technologies, it is necessary to determine the levelised cost of electricity (LCOE) for each option. This is based on generic capital and O&M (operation and maintenance) data for each technology category, as summarised in [Table 3](#). Using general time-value-of-money and economic parameters, with a discount rate of 8%, non-site-specific LCOEs are generated for each technology.

However, the cost for a technology is dependent on three additional factors: population, energy access target, and additional grid length required. With higher population and

**Table 3:** Sources for various technology costs

Description	Investment cost	Life (years)	Source
Diesel generators	721 USD/kW	15	[52]
Hydropower	5000 USD/kW	30	[53]
Wind power	2500 USD/kW	20	[54]
Photovoltaic power	5500 USD/kW	15	[55]
Transmission HV (>69 kV)	28 000 USD/km	30	[56]
Transmission MV (33 kV)	9000 USD/km	30	[56]
Distribution LV (0.2 kV)	5000 USD/km	30	[56]

energy access targets, the grid and mini-grid solutions are preferable, as they benefit from higher economies of scale than stand-alone solutions. The grid length required determines the cost of extending the grid line, and is limited to 50 km from existing lines.

The United Nations has initiated a program called Sustainable Energy for All, aimed primarily at achieving universal energy access. Part of this program is the Global Tracking Framework [57], which introduced a multi-tier framework for measuring tracking access. It combines a number of factors, most importantly annual electrical consumption, to create five tiers of electricity access.

The energy access target is the desired energy access per household in kWh/year. This is calculated using the average Bolivian household size of four people [58]. The residential demand projections are from previous internal work in KTH-dESA [59]. This gives a demand per household of 1907 kWh/household/year, which matches closely with Tier 4 (the second highest) of the Global Tracking Framework.

The next step is to take the settlements that are within the limit of 50 km from the existing grid, and to determine which ones can economically be connected to the grid. As no geographical data exists for electricity access, an initial estimate must be made for the settlements that currently have electricity access. This is based on their distance to the existing grid, population, distance from major roads and the intensity of lights on at night. This is then calibrated with the known electrification rate of Bolivia, currently at 88% [1], and with the known electrification rates of each municipality [35].

This initial estimate is then projected forward to 2030, by accounting for proposed and potential grid additions, as well as population increases. An algorithm is then applied to determine the economic feasibility of electrifying settlements, based on their population and distance from already electrified settlements. This is performed recursively, so that once a settlement is electrified, settlements near it can benefit from the closer proximity of the grid.

Part of this thesis was to improve the entire electrification methodology. The existing routine depended on an algorithm written in Visual Basic for Applications [60]. This took an extremely long time to process, so a new Python script was created (see [Appendix C](#)) that cut the time to about a tenth.

The final step is to combine the spatial, financial and electrification data to determine the optimum electrification split. This is done by calculating the LCOE for each approach and

technology, and then choosing the cheapest option for each site. A separate investment cost is also calculated, which is the total capital expenditure for each site.

### 3.4 Energy system optimisation

The next step in the CLEWs framework is to use OSeMOSYS to determine the optimum energy mix for the grid connected generation. This model uses the GLPK (GNU Linear Programming Kit) to find the optimal mix, based on technologies and fuels entered by the user. For this project, the Model Management Interface (MoManI) will be used to create the models. This is a web interface that is being created within KTH-dESA to make using the OSeMOSYS modelling technique much easier and available to anyone with an internet connection.

The purpose of this model is to determine the optimum energy system investments until the year 2040. Of particular interest is the interconnections with water usage. Thus the primary stages of the system (fuel extraction and refining) are modelled very simply, with more emphasis placed on accurately capturing temporal characteristics, especially for water-intensive thermal- and hydro-power generation. The range of technologies is also restricted, with unlikely technologies excluded from the mix (notably nuclear and coal power, as Bolivia has no concrete nuclear plans, and no significant coal reserves).

Finally, the model was limited to grid-connected production and demand, as it is assumed that the previous electrification methodology will handle the off-grid characterisation better.

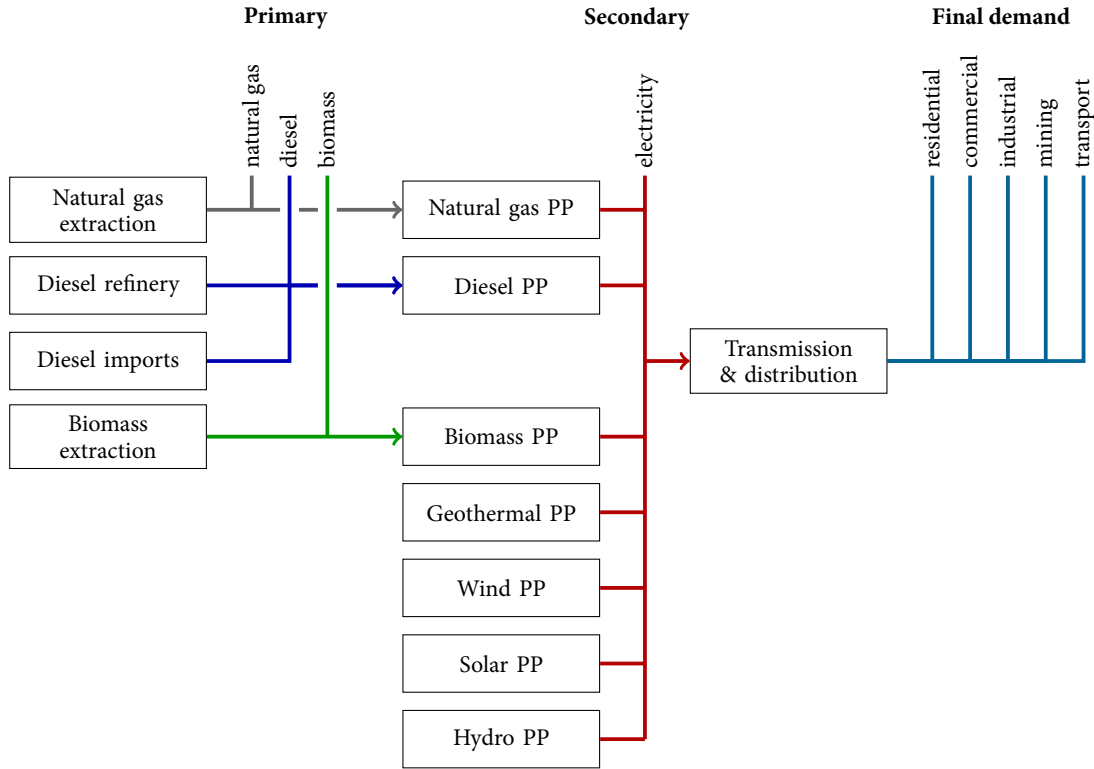
#### 3.4.1 Reference energy system

Before creating the model, it is necessary to decide which fuels and technologies will be included. To this end, a simplified reference energy system (RES) is shown in [Figure 5](#). As the supply-side is not of particular interest for this analysis, the separate stages of resource extraction and conversion are not modelled, and are simply created as sources with fuels ready to be used by the power plants. A number of simplifying assumptions are made for the various fuel sources:

- Natural gas will only be extracted and not imported, as Bolivia is projected to have more than enough reserves for domestic needs, assuming exports and power exports aren't prioritised over domestic use [25].
- Diesel can either be refined from domestic oil production, or imported.
- Biomass will only be locally grown and produced.
- All renewable sources are modelled without any input fuel. They will be manually limited if their production needs to be constrained.

In the diagram, PP stands for power plant. These are grouped by fuel use to simplify the diagram. Thus natural gas plants include conventional as well as combined cycle, and hydro

plants cover a range of sizes, types and capacity factors. Transmission and distribution are lumped, but distribution actually consists of five technologies, matching each of the five final demands.



**Figure 5:** Reference energy system

### 3.4.2 Data sources

The primary data sources are shown in Table 4. All values for energy production come from Bolivia's Comité Nacional de Despacho de Carga [61]. This has hourly production values for all of the existing power plants connected to Bolivia's grid. From this, a daily demand curve is generated, as well as capacity factors for each power plant. Ideally, each hour and each day could be modelled separately, to accurately capture all variations in demand and availability. However, this would be computationally impractical, and wouldn't make a significant impact. Thus it is important to choose 'slices' that will be modelled, to capture as much variation as possible.

The power source with the most significant seasonal variation is hydropower, which can have much lower capacity factors during dry seasons. By analysing the generation curves for the existing 23 grid-connected hydropower plants, it was decided that six seasonal slices would be sufficient, each representing two months of the year. There is on average less than 10% variation between demands for weekdays and weekends, and so this difference was not modelled. Finally, the day was divided into four slices of unequal length. This is based on the daily demand curve, as well as the fact that solar power only produces electricity during the day. This resulted in 24 slices, accounting for all seasonal and hourly variations. The

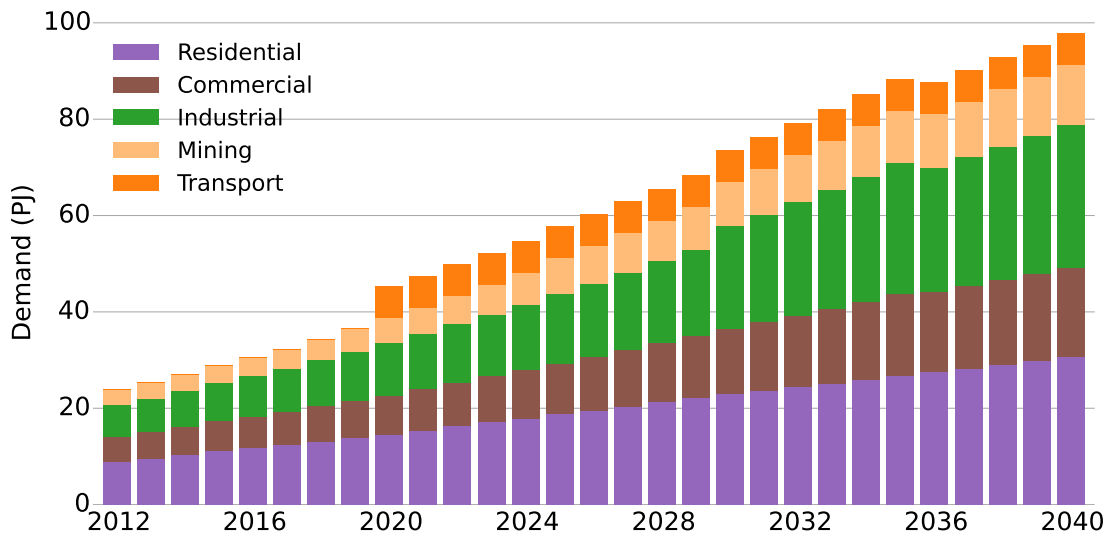
**Table 4:** Data sources for OSeMOSYS model

Description	Source
Capacity, efficiency and economics of existing plants	[62]
Generation curves for existing plants	[61]
Geographical information on plants	[63, 64]
Planned future installations	[62]
Renewable energy financial and efficiency information	[55, 53, 54]

capacity factors for all existing hydropower plants were calculated for each seasonal time slice, to show their seasonal variations. To reduce computational complexity, the plants are grouped by capacity factor and seasonality.

### 3.4.3 Electricity demand and emissions

Projected annual demand values until 2035 are from a forthcoming paper, and were further extrapolated to 2040 using linear regression [59]. Using the daily demand curve, the demand is then divided proportionally between the different time slices, to capture seasonal and hourly variations in demand. The baseline demand projection is shown in Figure 6. The electricity demand for transport is based on specific projects, and so doesn't experience annual growth like the other demand categories.

**Figure 6:** Electricity demand forecast

Greenhouse gas emissions were modelled for natural gas, diesel and biomass, using average values from the IPCC and including carbon dioxide, methane and nitrous oxide [65, 66].

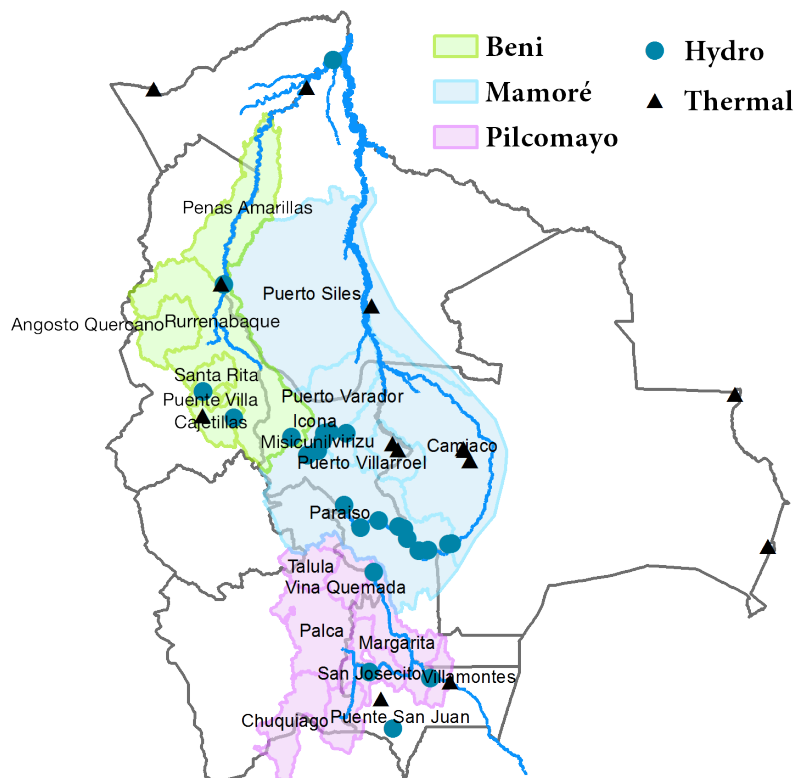
### 3.5 Water resources and land use

The final component of this CLEWs analysis is to model a few key water basins, and to determine how the water and land use is connected to the energy system already created. This is done using the WEAP water modelling system. This software is capable of highly detailed analysis on specific water basins, including water quality and advanced runoff and evapotranspiration modelling. However, as this is geographically a very large model that will cover basins totalling 430 000 km<sup>2</sup> (40% of Bolivia's surface area, along with a small part of northern Argentina), a very simplified approach will be used.

The primary aim is to accurately capture the water potential and demands, and how these will impact or be impacted by energy and agricultural land-use expansions. With this goal it is not necessary to model in extremely fine detail, and large areas covering multiple cities can be modelled as single demand sites. Additionally, the modelling requires stream gauge data for calibration, and the level of confidence possible is limited by this data availability.

#### 3.5.1 Basin delineation

The analysis will focus on the three basins identified in the pre-nexus assessment. These are the Beni and Mamoré basins, which are tributaries of the Amazon, and the Pilcomayo basin, ultimately discharging into the Río de la Plata. These three basins, shown in [Figure 7](#), account for about 73% of Bolivia's population, and all of its major cities. They also cover all of the existing hydropower plants, and most of those planned.



**Figure 7:** Primary basins used in WEAP analysis, with planned power plants

The first step in this modelling process is to define the sub-basins that will be analysed. These can be seen in [Figure 7](#), as the smaller outlines within each coloured area. This is based on availability of streamgauge data, as well as existing and planned dams. Sub-basins are defined for each stream-gauge and dam, so that the flows and water levels calculated in the model can be calibrated against actual data. These basins are calculated using an elevation map and the exact location of each gauge/dam. This procedure results in an accurate spatial representation of each basin.

Each sub-basin is given its own catchment characteristics (land-use, precipitation, etc), as well as demand sites. The catchment runoff was modelled using the rainfall runoff simplified coefficient method. The main elements are summarised in [Table 5](#). All existing and planned dam and run-of-river hydropower installations are included. Run-of-river sites do not have dedicated catchment areas, as they don't have a surface level that can be calibrated against. All planned and existing thermal plants (natural gas, oil and biomass) are included. In addition to these, each sub-basin has a rural and urban demand specified.

**Table 5:** Main elements in water model

Basins	Rivers	Gauges	Hydropower	Thermal plants
<b>Beni</b>	· Beni · Zongo · Miguillas	· Peñas Amarillas · Rurrenabaque · Angosto · Aranjuez · Cajetillas · Puente Villas · Tamampaya	· Bala · Zongo · Miguillas · Chojlla · Yanacachi	· Huaricana · El Alto · Kenko · Buenaventura
<b>Mamoré</b>	· Mamoré · Grande	· Puerto Siles · Puerto Varador · Camiaco · Paraiso · Puerto Villaroel	· Rositas · Corani · Ivirizu · Banda Azul · Ambrosia · Santa Isabel · Icona	· Trinidad · Moxos · Valle Hermoso · Guabira · Bulo Bulu · Carrasco · Entre Rios · Santa Cruz · Guaracachi · Warnes
<b>Pilcomayo</b>	· Pilcomayo	· Villamontes · Vina Quemada · Talula · Chuquiago · Puente San Juan · San Josecito · Palca	· Margarita · Icla · Carrizal · Kilpani	· Karachipampa · Aranjuez · Villamontes · Defensores

In order to define the characteristics and features of each sub-basin and demand site, a number of additional data layers were used, as detailed in [Table 6](#). These are used with GIS processing to calculate average physical characteristics for each sub-basin, which are used

by WEAP to calculate the amount of water available to flow into groundwater and river systems. The demographics and demand characteristics are used to specify how much water is withdrawn for residential, commercial and industrial use. Finally, the thermal power stations are individually specified with all of their capacity and generation details. As no data was available for water use for each plant, generic values were used, with the assumption that all cooling (for single cycle and combined cycle) is once-through cooling. The most important plant type for the future is combined cycle natural gas, which is modelled with a withdrawal of 34.1 l/kWh and a consumption of only 0.2%.

The dams and run-of-river stations require details about volume and head. For planned plants, this information has sometimes not yet been determined, so assumptions were made based on the relief of the area and discharge of the river. This followed the technique used in a previous KTH-dESA analysis [67].

**Table 6:** Data layers used in water system modelling

Description	Description	Source
Hydrology	Determine watershed sizes	[42]
Stream gauges	Calibrate modelled flow	[68, 69]
Precipitation	Input rainfall per basin	[68]
Evapo-transpiration	runoff	[13, 70]
Land-use	Input different land-use classes	[71]
Irrigation	Irrigated area and water use	[3]
Water demand	Per capita water demand	[3]
Energy	Location and characteristics of plants	[64, 61, 72, 73, 27, 74, 63]

### 3.5.2 Assumptions and limitations

The population and projections are based on the same source as above, disaggregated only for rural and urban differences. The urban/rural split is based on the spatial electrification analysis. The population distribution GIS layer is used to specify what percentage of the urban and rural populations fall within each sub-basin.

Residential and industrial water use rates were based on national averages from FAO [3]. Power plant water withdrawals are based on generic data from [75, 76, 77], which required some assumptions to be made about the cooling type being used, when not specified. Precipitation for each basin was based on Senamhi (Bolivia's National Service of Meteorology and Hydrology) gauges [68], averaged out over the geographical area of each basin.

Evapo-transpiration data from [13] was used as a base, as it is available as a global geospatial layer. However, it lacks seasonal variation, so this was created using FAO values where available [70]. No detailed information on underground aquifers was available, so large assumptions had to be made for groundwater. For simplicity's sake, one aquifer was modelled for each of the three basin groups, and the percentage of precipitation for each catchment going into groundwater is then calibrated using streamflow gauges and historical hydropower production values.

WEAP was setup using the rainfall runoff – simplified coefficient method. This method of determining runoff from precipitation has the lowest data requirements, and was chosen as the most suitable method for a model covering such a large geographical area.

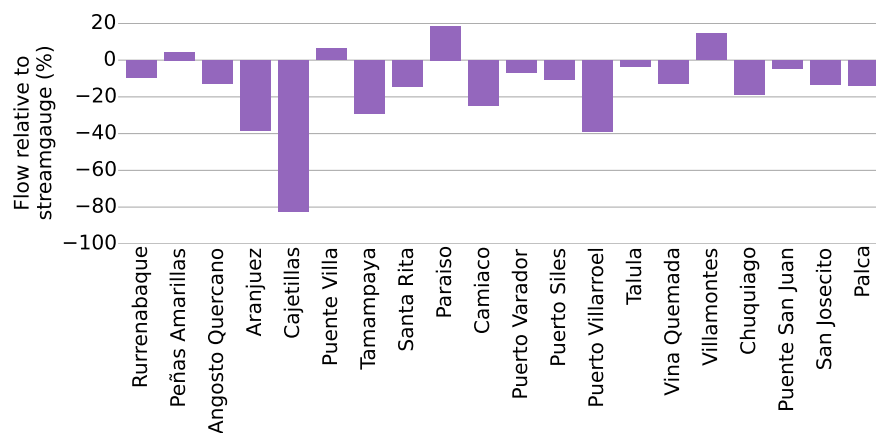
### 3.5.3 Catchments, land-use and demand sites

Due to data limitations, the level of detail in land-use modelling is quite limited. The land-use categories used were forest, general agriculture and irrigated land. There was no data available for land-use and irrigation coverage for each area, so the national statistics were used, along with assumptions based on low resolution geospatial land-use data [71]. The national FAO statistics [3] suggest that 0.3% of the Bolivia's land area is currently irrigated (about 3000 km<sup>2</sup>). It is assumed that 90% of this irrigated land falls within the area of the analysis (the remaining areas being mostly desert, forest or pasture), so that the average based on this smaller area then becomes 0.7% irrigated. This is applied to all the catchment areas, as no better data is available. To include a more realistic projection in the model, a 4% annual growth in irrigated area is added, resulting in a doubled irrigated area by 2030 (compared to the INDC target of triple).

For the same reason, the actual land cover was limited to two categories: forest and grain. This impacts the evapotranspiration, which won't be accurately captured by incorrect land use. This will, however, be easier to rectify in the future with improved land-use data.

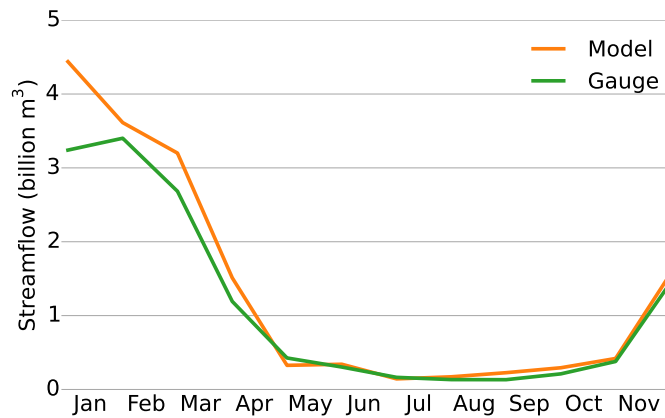
### 3.5.4 Model calibration

The model was calibrated against streamgauge data [68], which ran from the year 2004 until 2012. This was done by modifying the effective precipitation (the percentage of precipitation available for evapotranspiration) as well as the percentage of runoff going to ground-water and not streamflow. By adjusting these parameters, all streamflows for the base year were calibrated to have a maximum of 40% deviation from the streamgauges. Most of the streamgauges had up to 50% variation between different years, so it was deemed necessary to aim for a closer match than this. The results of this process are indicated in Figure 8.



**Figure 8:** Results of WEAP calibration

In addition, and where streamgauges were not available, hydropower output from reservoirs and run-of-river plants could be calibrated with historical production data [61]. If there is over- or under-production, this would indicate that the streamflow is incorrect. Hydropower generation data was used for the base modelling year (2012) to calibrate the flow. The monthly generation was compared, and refined until it matched the recorded data to within 30%. A single example of modelled flow compared to streamgauge flow data is given in Figure 9.



**Figure 9:** Calibration example for Rio Grande at the site of planned Rositas hydropower project

### 3.6 Scenarios

With the entire modelling framework complete, a number of scenarios can be developed to determine the impact of different assumptions and actions. Because of the complex nature of the interlinked models, this study will be limited to four scenarios, based on the intersections of two categories: demand projection and climate change.

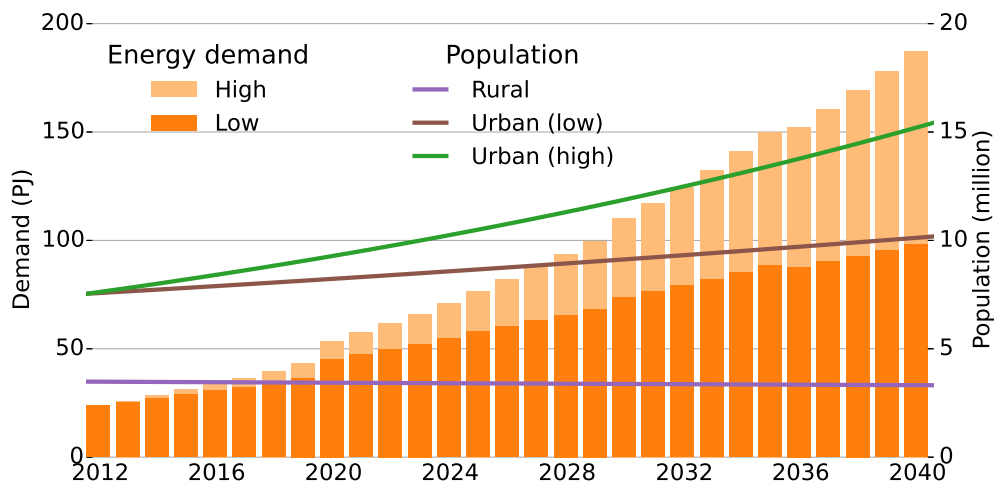
#### 3.6.1 Demand projections

With low-growth as the baseline, a high-growth scenario will be created by increasing the population projections and demand growth. This will increase population and densities, growth rates and overall demand for energy, water and agriculture.

The baseline scenario has been based on a population of 13.4 million in the year 2030, an average 1.3% growth rate from 2015. This was disaggregated into an urban growth rate of 1.954% and a rural growth rate of  $-0.314\%$  [16]. Separately from population, electricity demand projections taken from [59] give a demand growth from 8024 GWh in 2015, to 20 629 GWh in 2030, an average growth rate of 6.5% per year.

In order to test the impact of higher than expected population and energy demand growth, an additional scenario is created. For this, the negative rural growth will be kept the same, but the urban growth rate is increased to 2.5%, to indicate both higher population growth, as well as higher levels of urbanisation. Additionally, the electricity demand in 2030 is

increased by 50%, which is more in line with some of Bolivia's proposals for capacity expansion [5]. These changes are shown in Figure 10.



**Figure 10:** Different demand projections for population and energy demand

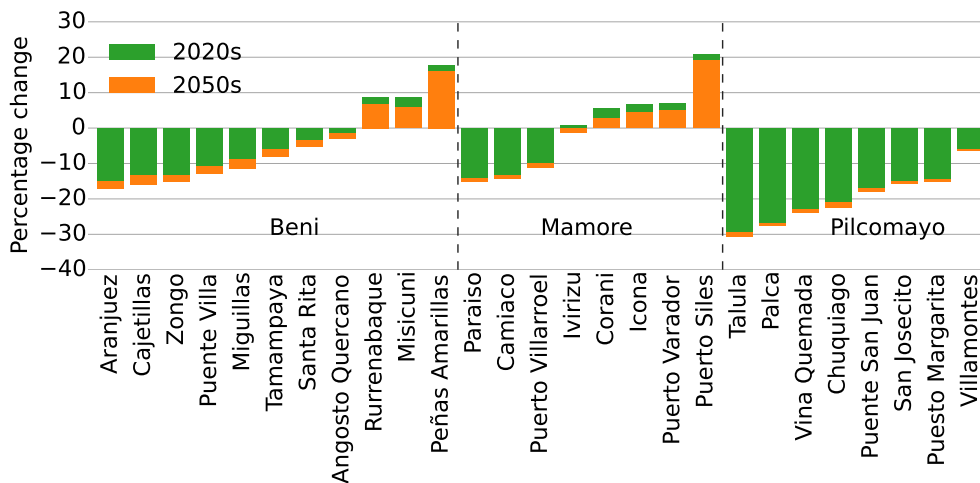
### 3.6.2 Climate change

The baseline scenario will ignore the impact of climate change, and use only business-as-usual plans for climate mitigation. The additional climate change scenario will include the projected impacts of climate change on temperature, water availability and land-use potential, as well as more aggressive government responses to climate change, through altered energy and water use policies.

The baseline scenario ignores any projected changes to Bolivia's climate and weather systems. Thus rainfall and runoff will remain unchanged in future years, and will continue to follow their historical quantities and seasonal patterns. On the response side, the baseline scenario will include only energy, land and water projects that are considered to be very likely to be pursued, mostly those that are already under tender, or that have clear government policies supporting them. This means that most of the more ambitious plans and targets are excluded.

As a crucial element of a CLEWs analysis, climate feedback and interactions should be included in the overall model. This means that the impacts of the scenario on climate change should be quantified, that climate mitigation plans should be included, and that projected changes in weather patterns should have an impact. This is achieved by setting a 70% renewable energy target for 2030, in accordance with Bolivia's INDC [5]. A CO<sub>2</sub> tax of 20 USD/ton is added. This increase is implemented in the electrification mode with a simple 28% increase in diesel price in the year 2030. Additional models should explore the impact of more complex taxing schemes (such as progressive increases in successive stages).

Finally, precipitation forecasts from the model CSIRO Mk2 with IPCC scenario B2 [78, 79] were used to predict future rainfall patterns. This model assumes moderate global



**Figure 11:** Projected rainfall changes per basin, relative to year average of 2000s

population growth (10 billion by 2100) and temperature increase (3 °C by 2100). This did not include projections of seasonal changes. These changes are shown in [Figure 11](#). This figure doesn't tell the full story, however, as the sub-basins vary vastly in size and thus impact. So although the majority of the basins are projected to have decreased rainfall, some of the largest are expected to have increased rainfall. Thus the total water falling on the two Amazon basins is actually increased, as seen in [Table 7](#), as is the total rainfall in the modelled area. The Pilcomayo basin sees a decrease in water, as all of its sub-basins are projected to have decreased rainfall.

**Table 7:** Total change in annual water availability with climate change model CSIRO Mk2 B2

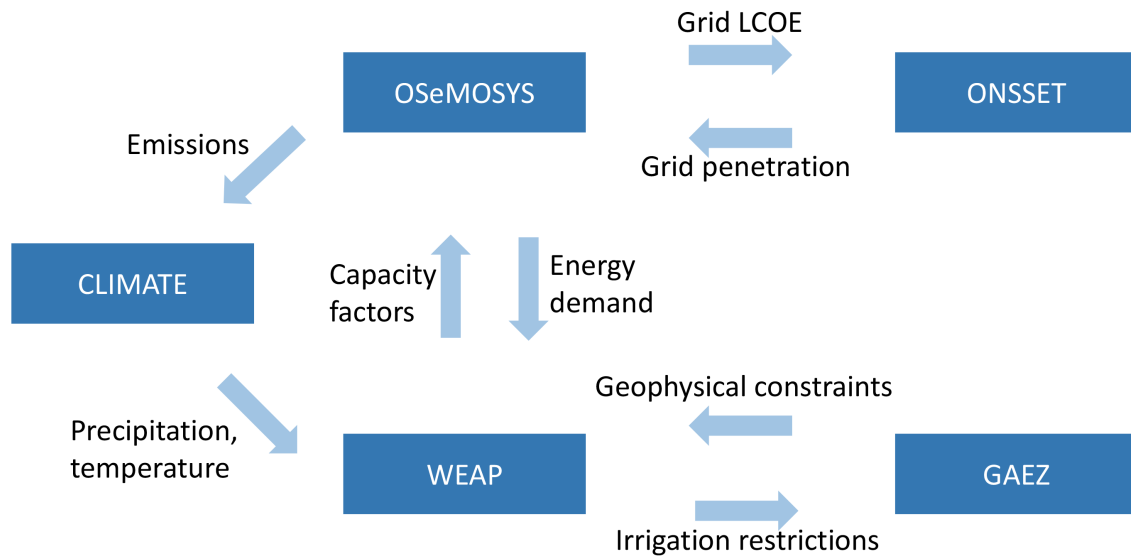
Basin	Change (billion m <sup>3</sup> )
Beni	+ 8.39
Mamoré	+ 4.51
Pilcomayo	– 11.90
Total	+ 1.04

### 3.7 Model integration and interconnections

The final procedure in the overall methodology is to link the three models together. As each model has a completely different structure and methodology, it must be determined which specific parameters will be shared between them, and in which direction the data will flow. These links are shown in [Figure 12](#).

The final procedure to integrate the models is as follows. This procedure is iterated until convergence is achieved between the models.

1. Run the OSeMOSYS model to obtain an LCOE value for the electrical grid



**Figure 12:** Model links and feedbacks

2. Use this value in the ONSSET model and determine an optimum spatial electrification
3. Use these results to modify the demand used in OSeMOSYS and re-calculate the LCOE
4. If necessary, rerun ONSSET with the new LCOE
5. Use the demand projections from OSeMOSYS in WEAP to determine future water needs
6. Take the modelled capacity factors from WEAP and re-run OSeMOSYS using these new values

## 4 Results

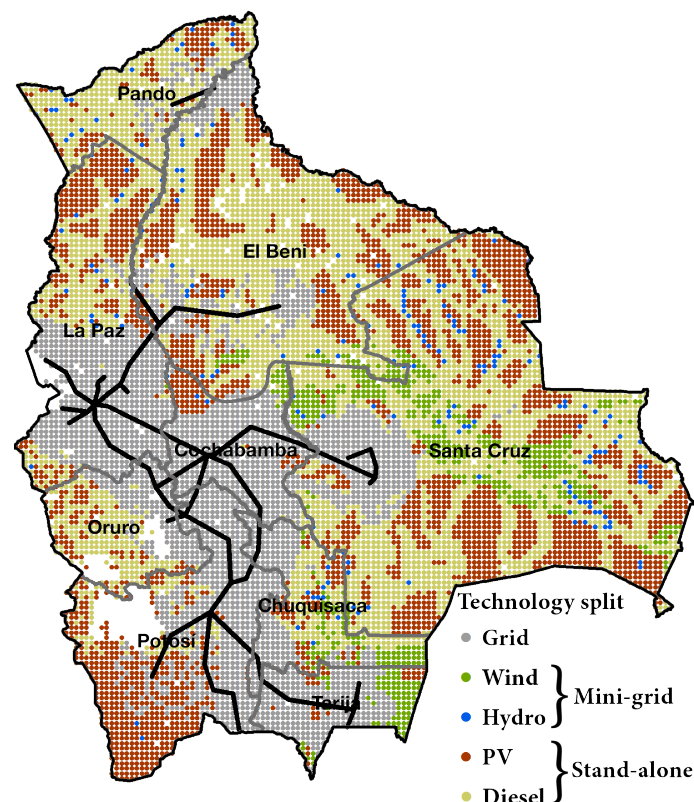
This section provides an overview of the results from each of the different models, as well as comparisons between scenarios and indications of pinch-points between resource categories.

### 4.1 Spatial electrification results

The most important factor connecting the electrification and energy mix models is the LCOE for grid-supplied electricity. After iteration, this was found to be 4.4 US¢/kWh in the year 2030, for the baseline scenario. The higher this value, the less favourable grid extensions will be, and the more mini-grid and stand-alone solutions will be necessary. The results for the baseline are explained here in the most detail, followed by the most pertinent differences found between scenarios.

The calculated geospatial split by technology is shown in Figure 13, which clearly shows the main trends. About 91% of the population is grid connected, while 1% and 8% are mini-grid and stand-alone, respectively. The grid-connected percentage is only slightly increased from the current value, with most of the new connections coming from grid extensions in the south-west and far north.

For non-grid connections, diesel stand-alone dominates everywhere where the travel distance to cities is low enough. This could be strongly impacted by assumptions of diesel price, which could vary largely in the future. The different results from the climate scenarios is discussed below, where the diesel pump price is increased by 28% to reflect an aggressive carbon tax. Although the map of renewable energy sources indicates that wind energy is theoretically preferable over much of lowland eastern and northern Bolivia, solar PV still takes preference due to the very low population density in most areas. Mini-grid wind installations require more infrastructure and demand to be feasible. Where the population is higher, wind energy mini-grids become more effective, as shown in the eastern corridor and the southern border with Argentina.



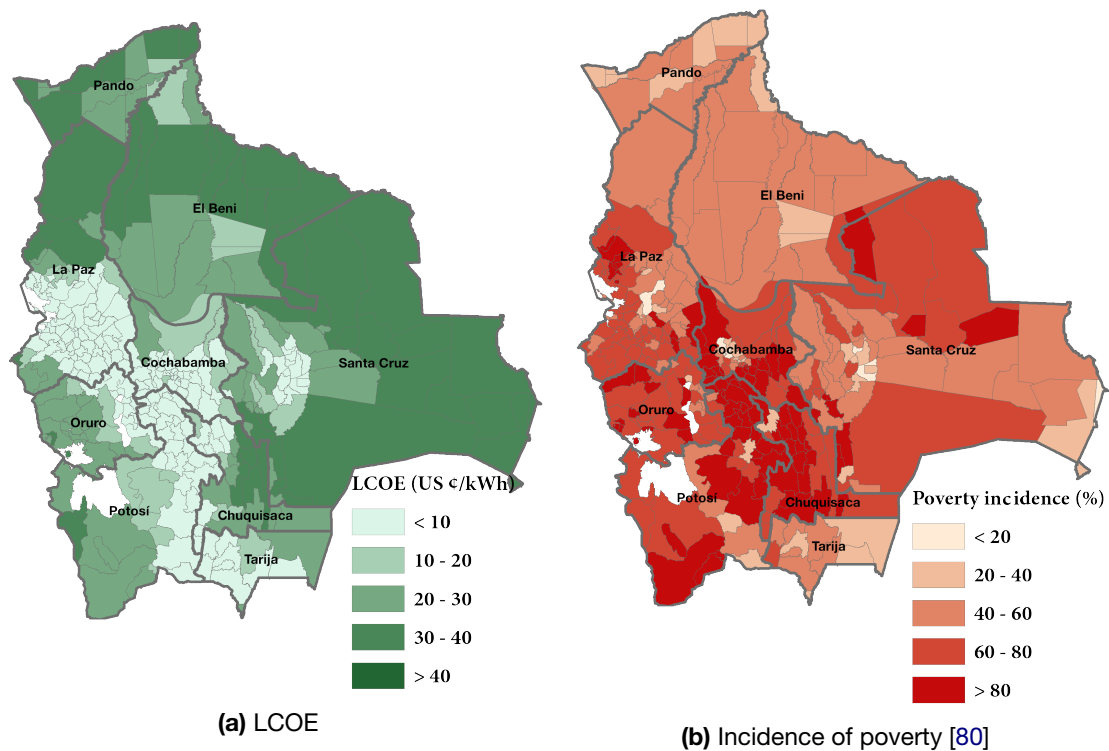
**Figure 13:** Geospatial technology split

Stand-alone solar PV is also the most economic solution in most of the highlands away from the high population zones, helped by the low population density and extremely high solar irradiation. Mini-grid hydropower solutions are scattered around the country. Where the potential exists and populations are high enough, hydropower is far cheaper than the other renewable options. This part of the analysis needs further work, as currently only

mini-grid hydropower solutions are considered, while stand-alone hydropower could also have considerable potential. The model is currently also limited in its ability to distinguish economically between different sizes of hydropower potential, and everything between 500 kW and 10 MW is treated the same.

Following from the technology split, the spatial LCOE is shown in [Figure 14](#), alongside a map of incidence of extreme poverty. The grid connected areas simply have the cost of grid energy, as calculated in the energy mix model. The cheapest non-grid solution is still nearly four times more expensive, and is limited to areas with close road access to cities (for diesel) or extremely high solar radiation. The majority of non-grid areas are paying at least 30 US¢/kWh.

The areas paying the highest levelised cost are the stand-alone solar installations in the eastern and northern lowlands. The highest cost, at 44 US¢/kWh, is ten times as expensive as the grid. For the baseline scenario, with an assumed household consumption of 1907 kWh/HH/year, these households could pay as much as 760 USD per year for electricity, which could be a significant fraction of rural household income. This data can be used to guide government policy-making in providing energy and electrification subsidies, as many families would presumably be unable to afford the cost of electricity at this rate.



**Figure 14:** Levelised cost of electricity and incidence of extreme poverty by municipality

With the basic layout explained, the results from the different scenarios can be explored. The percentages (by population) for each electrification category are shown in [Table 8](#). There are two easily identifiable trends. The higher demand scenarios have an increased average demand of 2693 kWh/HH/year, which makes grid connections slightly more favourable, increasing the number of people connected to the grid by about 100 000. For the same reason, higher demand makes mini-grid relatively more favourable compared to stand-alone

solutions, as the higher investment costs pay off for a lower overall LCOE. Secondly, the climate scenarios have higher proportions of mini-grid over stand-alone. This is mostly driven by the increased diesel price, and will be discussed below with reference to the different technologies.

Although the grid connected population is only slightly increased from the current value in all scenarios, it represents about three million new connections, in order to keep up with growing population and demand.

The technology splits can now be discussed, with reference to [Table 8](#). The most obvious change, as touched on above, is the change in diesel penetration with the climate scenarios. The increase in cost for diesel fuel causes the model to drastically favour solar PV for stand-alone installations. This also causes the overall levelised cost for stand-alone solutions to increase, so mini-grid solutions become more feasible. Thus there is a significantly increased percentage of wind installations.

**Table 8:** Technology choice for different scenarios

		Low demand		High demand	
Technology		Standard	Climate	Standard	Climate
Grid		90.7%	90.7%	91.5%	91.5%
Mini-grid	Wind	0.96%	1.70%	1.53%	1.84%
	Solar PV	0.00%	0.00%	0.00%	0.07%
	Hydro	0.31%	0.35%	0.33%	0.33%
Stand-alone	Diesel	5.64%	2.64%	4.51%	2.24%
	Solar PV	2.40%	4.60%	2.13%	4.03%

Finally, the total investment costs for electrification for each scenario are shown in [Table 9](#). The capital outlay for HV grid extensions is a small part of the total capital cost, but this is based on large assumptions about where future grid extensions will be made. If the main grid is connected to the Pando grid area in the north, and if any grid extensions are made into neighbouring countries, this could be increased significantly. Finally, this cost only includes physically extending the grid to areas which currently aren't served by HV grid lines. It doesn't include the cost of increasing grid capacity, which will be covered in the following section.

As expected, the investment cost for local distribution network extensions is the dominant cost for all scenarios, as this is the method responsible for the largest number of newly electrified households. Between the two different demand scenarios, there is no change in the character of the capital outlay, but the higher demand requires uniformly high investments.

The most interesting observation is the change in cost brought about by the climate change scenarios. Due mostly to the increased diesel price, the climate scenarios recommend higher amount of solar PV, wind and hydropower, which all have significantly higher up-front capital costs than diesel generators. This change makes the electrification strategies for the climate scenarios between 12% and 14% more capital intensive.

In terms of the link between models, the most important output from the electrification model is the percentage of households that are connected to the national grid. This value

**Table 9:** Total investment costs

Item	Cost (billion USD 2013)			
	Low demand		High demand	
	Standard	Climate	Standard	Climate
HV and MV grid extensions	0.04	0.04	0.04	0.04
LV distribution lines	4.84	4.84	6.39	6.39
Mini-grid systems	0.43	0.68	0.79	0.94
Stand-alone systems	1.07	1.71	1.39	2.23
<b>Total</b>	<b>6.37</b>	<b>7.27</b>	<b>8.61</b>	<b>9.60</b>

(around 91% for all scenarios) is used to modify the residential demand in OSeMOSYS, as the remaining 9% of residential demand is not connected to the grid and doesn't need to be served by the national energy mix.

Additionally, the investments calculated for grid extensions must be carefully taken into account in the energy grid model, to ensure that the cost of increasing grid capacity isn't double counted by both models.

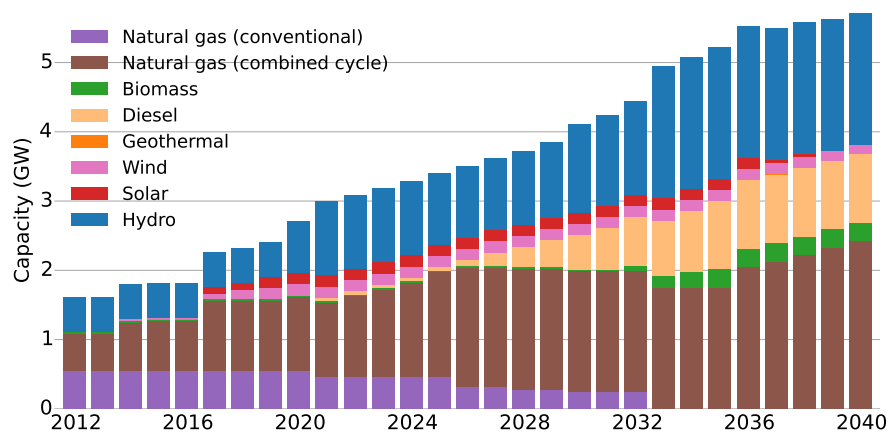
## 4.2 Energy optimisation results

With the spatial electrification complete, it is possible to move on to the results for the national energy grid. The model for the energy system is focused on the electricity system, and especially on understanding the interconnections with water and land. Thus extraneous parts of the system (such as detailed modelling of primary energy systems) and technologies deemed unlikely (such as nuclear and coal power) are excluded from the model. The results for the baseline scenario are presented, followed by comparisons for the additional scenarios.

One of the most important interconnections for the CLEWs analysis is the potential capacity factor for thermal plants and hydropower, based on water availability. The initial run of the model is made using capacity factor assumptions based on dam type and location, and subsequently the results and demand are iterated with the water model to find the actual capacity factor that is possible for each plant. This iteration was performed twice, after which the capacity factors did not change significantly.

The optimised energy mix calculated with OSeMOSYS for the baseline scenario is shown in [Figure 15](#). This demonstrates an increase in total generating capacity from the current 1600 MW to about 4160 MW in 2030. This is significantly below the target of 13 387 MW from the INDC [5]. However, in the high demand climate scenario, this increases to 7850 MW in 2030 and 13 357 MW in 2040. An important note is that the high capacity targets from the INDC is linked to plans for electricity exports, which weren't included in this model.

The majority of the capacity is covered by hydropower and combined cycle natural gas plants, although the hydropower plants have a lower capacity factor and thus lower pro-

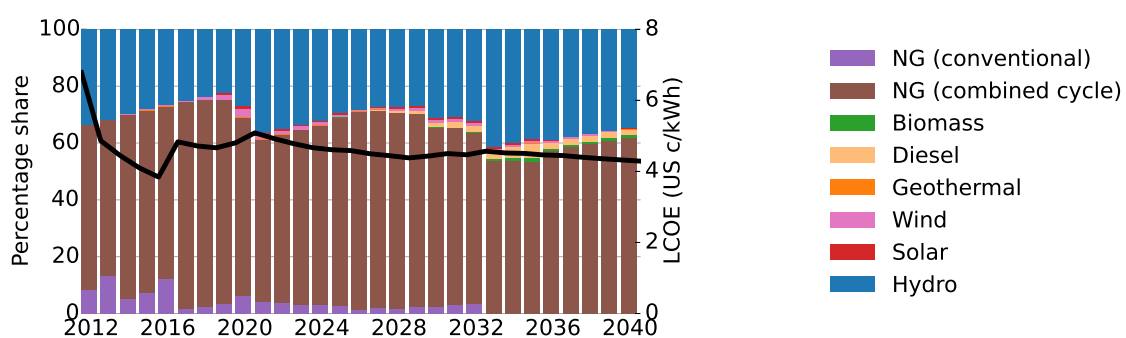


**Figure 15:** Optimal energy capacity mix for baseline

duction. The conventional natural gas plants that make up most of the current fleet are completely phased out by 2032, being replaced by combined cycle plants.

There is a significant amount of diesel capacity installed in later years, but this is subject to a number of assumptions. This build-out of diesel power is mostly due to the fact that the model is limited to planned natural gas plants until 2025, and after that there is a restriction on the pace of installations. The diesel is thus a backstop technology, and shows the extra capacity required that won't be met by existing plans. There is a small amount of solar, wind and biomass power in the results, but this is mostly accounted for by plants that are already in the planning stage, and not necessarily chosen by the model's algorithm.

The difference in actual output between natural gas and hydropower is made more clear in Figure 16, where hydropower is responsible on average for only about 30% of electricity generation. This makes it clear that natural gas will still be responsible for the vast majority of Bolivia's electricity production well into the future, under baseline assumptions.

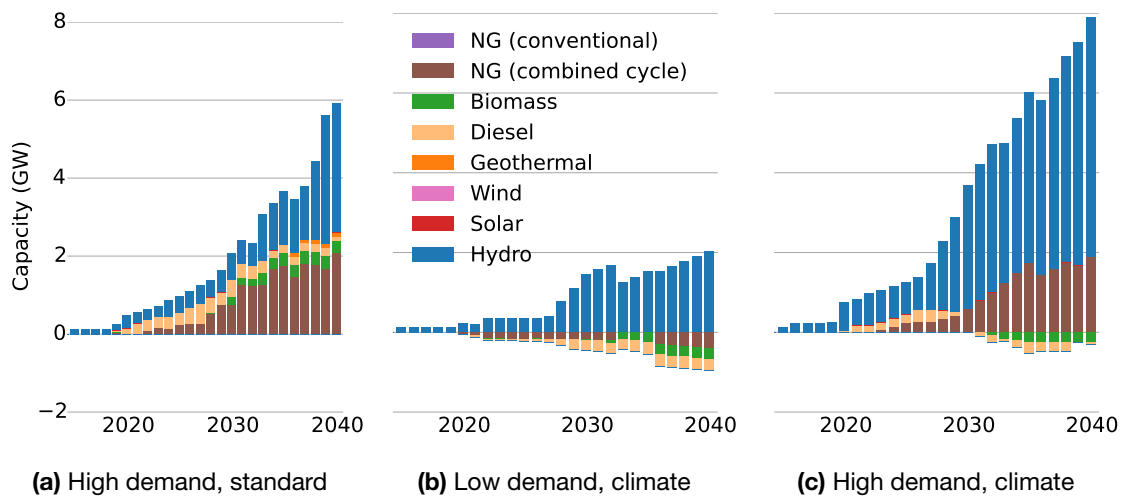


**Figure 16:** LCOE and production percentage by source

The LCOE curve (black line) shows the cumulative LCOE for each year. There is strong variation at the beginning of the investment period as new investments are made, but the value steadies by about 2020. Past this period, the generation mix doesn't change significantly, and since the costs were modelled without future increases, there is little reason for the levelised cost to change.

The different scenarios completely change the character of the generation mix. The changes in installed capacity are in Figure 17, shown relative to the baseline scenario. Firstly, the high demand scenario (Figure 17a) shows a change that is mostly in magnitude, as expected. The relative proportions of generating technologies does not change significantly, but the total capacity increases to keep pace with the increased demand.

When the climate scenario is introduced (Figure 17b), diesel and biofuel are dropped significantly, and hydropower is installed to a much greater degree. This is because of the carbon tax, as well as the 70% minimum requirement for renewable technologies. For the high demand climate scenario, in Figure 17c, the amount of new natural gas is still increased, as it is still more economical than hydropower to keep up with the much increased demand.



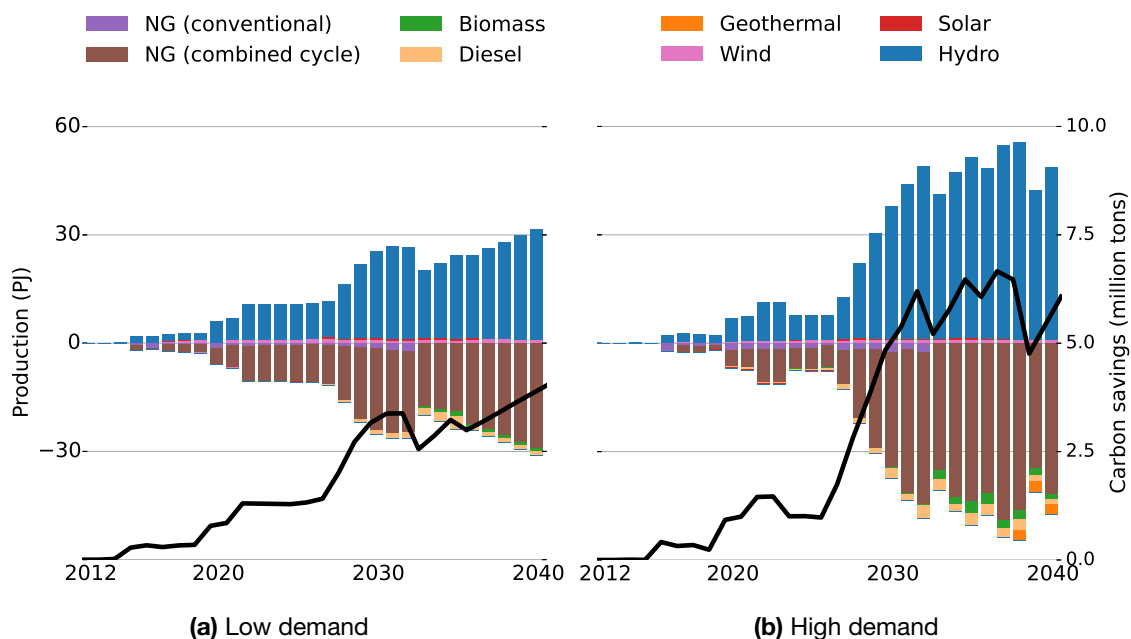
**Figure 17:** Energy capacity installations relative to baseline

The two most important goals of analysing a climate scenario are to show what reductions in emissions can be achieved with realistic assumptions, and to understand what impact future changes might have on Bolivia's ability to produce electricity. The first of these is shown graphically in Figure 18. This shows the reductions in CO<sub>2</sub> emissions (black line) alongside the changes in electricity generation. As the total demand is unchanged for the climate scenarios, the graphs are symmetrical about the x-axis, as every PJ not produced by one source is replaced with a PJ from another source.

In both cases the emissions savings are significant, with cumulative reductions of 35% for the low demand, and 37% for high demand, over the 29 year modelling period. As the energy system makes up 20% of Bolivia's emissions [4], this will contribute to a significant reduction in overall emissions for the country.

One potential issue with these results is the reduction of biomass production in the climate scenarios. This is because the biomass emissions were entered only for 'end-of-the-pipe' emissions, and possible carbon sinks from the complete life-cycle were not considered. There was insufficient data to calculate a proper life-cycle value, so this simplification was used, but the actual value for carbon emissions from biomass is probably significantly lower.

A comparison of LCOEs and total investment costs is given in Table 10. Overall, the high demand scenarios increase the total investments costs by more than double, for a 50% in-



**Figure 18:** Yearly greenhouse gas emissions and electricity production, relative to non-climate scenarios

crease in capacity. This is joined by an increase of about 30% in levelised cost, caused by the necessary inclusion of more expensive power sources, as well as higher grid investments.

Moving from the standard to climate scenarios causes an increase in levelised cost of about 10% for both demand cases. This comes almost entirely from the shift to more expensive hydro plants instead of natural gas. This shift to hydropower adds 3.54 billion USD and 5.32 billion USD to the low and high demand cases, respectively.

The increased demand scenario causes the grid investments to double. However, there is little variation in grid cost within demand scenarios, as the total demand is unchanged. Note that this cost is in addition to the 4 – 6 billion USD calculated in the electrification analysis.

The climate scenarios include a carbon tax, which comes to a cumulative total of 2.02 and 2.94 billion USD for low and high demand, respectively.

**Table 10:** Financial breakdown of different scenarios

	Low demand		High demand	
	Standard	Climate	Standard	Climate
LCOE (US ¢/kWh)	4.38	4.90	5.74	6.30
Capacity investments (billion USD)	8.92	12.46	20.45	25.77
Grid investments (billion USD)	6.09	6.11	13.56	13.56
<b>Total investments (billion USD)</b>	<b>15.01</b>	<b>18.57</b>	<b>34.01</b>	<b>39.32</b>

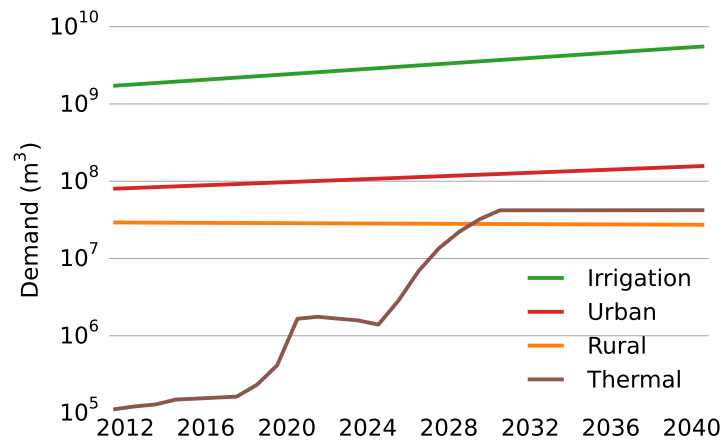
For this analysis, only very loose restrictions were placed on the amount of diesel, natural gas and biomass that could be produced within Bolivia. Thus no model had any reason to

resort to more expensive imports. This is an oversimplification, as although local oil production is sufficient for domestic needs, about 30% of refined oil products are imported [23], as local refining capacity is limited. This doesn't apply to natural gas, which needs minimal processing. Under the high demand scenario, the energy system will be consuming about 5.5 billion m<sup>3</sup> of natural gas per year by 2040, which represents just over 11% of current production [81]. Currently, electricity plants consume about 7% of the gas production [23]. Future natural gas reserves will be the biggest deciding factor, but it is possible that larger increases in domestic use could have a significant impact on Bolivia's ability to earn from natural gas exports.

### 4.3 Water modelling results

With the water model fully set up and calibrated, the yearly energy demands for each scenario are entered from the energy models. This creates a demand for each plant that the model will try to meet, and shortfalls can be inserted back into the energy model as reduced capacity factors.

The projected baseline water demand from the four main sectors is shown in Figure 19, with a logarithmic y-axis. This compares with the national statistics of 1.92 billion m<sup>3</sup> for irrigation and 0.168 billion m<sup>3</sup> for all other uses. By the end of the model period, non-agricultural water use accounts for only 4% of total water withdrawals in the region. This is slightly higher for the higher demand scenarios, with more thermal plants and higher municipal water demands, but the trend is unchanged.



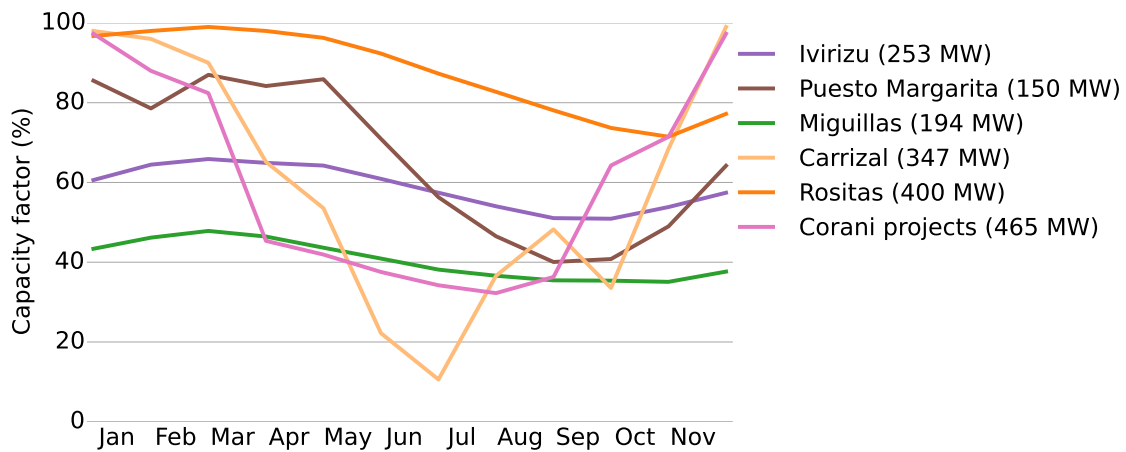
**Figure 19:** Water demand by sector

Agriculture is by far the most important water user in Bolivia, and with the high water availability in most of the country, municipal and thermal water use are unlikely to play a major role. There are smaller regions with water stress, especially the dry Altiplano, but a detailed analysis is outside the scope of this study.

An important caveat to note is that three important planned hydropower projects were excluded from the water model, that were however included in the energy model. These are the Rio Grande, Cachuela Esperanza and Bionacional Madeira projects, totalling 5500 MW.

The first was excluded due to a lack of data on location and characteristics, while the second two fell outside the analysed region. These three projects provide a considerable percentage of electricity generation in all but the baseline scenario (from 5% to 30%). For this analysis, they are given the same capacity factors as the Rositas project, which is the most similar in terms of size, type and location.

Capacity factors for selected planned hydropower projects are shown in Figure 20. The values shown are for the high demand scenario without climate change impacts, for the final year of the simulation, after being fully iterated with the energy model. The 'Corani projects' are three planned hydropower plants on the same river that have nearly the same capacity factor curve. One project was left out: Misicuni in the Beni basin. It was not possible to get the modelled capacity factor higher than a few percent, indicating that either the available data on head is incorrect, or the location/catchment size was incorrectly calculated.



**Figure 20:** Monthly capacity factor for selected hydropower plants

While calibrating the catchment areas against streamgauge data, it became evident that the model tends to underpredict dry season flow (May – August), and overpredict wet season flow (September – April). It is important to keep this in mind, as some of these projects are at locations that allowed little model calibration. Thus although most of the plants shown clearly follow the wet/dry seasonal cycle, it is possible that the variation will be less extreme once further calibration is done.

Of note is the high capacity factor of the Rositas project, as the remaining Rio Grande projects will be built on the same river and probably have similar capacity factors. Three of the projects have visibly smoothed curves, due to their larger reservoirs allowing some buffer. The run-of-river projects are completely at the whim of changing water availability.

The changes in capacity factor over the modelling period, with climate projections included, are shown in Table 11. So the general trend is negative, but only very slightly. However, this is only one climate model, and more would need to be included to make any confident forecasts. It will be instructive for future work to model the excluded projects, as these receive a large portion of run-off from areas projected to have increased rainfall, and could have significantly increased capacity factors.

**Table 11:** Change in hydropower capacity factors with climate impacts

Basin	Change (%)
Ivirizu	– 0.7
Puesto Maragarita	– 1.9
Miguillas	– 3.0
Carrizal	– 1.0
Rositas	– 0.8
Corani projects	+ 0.9

## 5 Conclusions

Management of energy, water and land resources will be paramount to letting Bolivia make meaningful contributions to the Sustainable Development Goals. The Bolivian government plans show a high commitment to increasing the penetration of electricity access as well as renewable energy, with the added intention of becoming an important player in a regional electricity network. At the same time, natural gas extraction and exports are vital to the country's economy, and there are plans to greatly increase this capacity. Underneath these grand ambitions, Bolivia has a delicate relationship with its natural resources, and faces major potential upsets through climate change and its impacts, as well as land degradation and deforestation.

This thesis has brought together some of the most crucial areas for planning and investment, and given a first analysis in indicating where pinch points and resource competition could become an issue. The electrification and energy system models indicate that it will take about 21 billion USD in investments to achieve complete electrification and keep up with increasing demand in the baseline scenario. However, if the massive hydropower potential in the country is leveraged, it could give a huge increase to the amount of electricity available to the country, or serve as an important source of foreign income. These plans for electricity export haven't been included in the current model. Using only plans already in the pipeline, the high demand scenario calls for 7600 MW of hydropower, and it is likely that this could be increased.

The water modelling showed that climate change is unlikely to adversely impact hydropower potential, in terms of gross output. This is because the majority of the eastern and northern lowlands are predicted to have increased rainfall in the future. More climate models need to be incorporated, and more direct comparisons need to be made, but the first indication is that none of the major projects will have reduced output. However, the significantly diminished rainfall in the highlands, and especially in the highly populated region around La Paz, could have bad effects on vulnerable agriculture in that region, especially when combined with glaciers melting and extended dry seasons. Unfortunately, I did not get access to detailed land-use data in time, so it isn't possible at this stage to make more accurate predictions on the potential impacts on agriculture. However, the basic analysis showed that municipal and thermal uses of water are nearly insignificant compared to agriculture, and so all further work should focus in that area.

For this analysis, four complete scenarios were created, so that the qualitative differences

between them could be compared. However, in order to quantify the potential impacts of different assumptions and scenarios, it will be useful to perform the analysis with some variables controlled. This will allow the direct impacts of climate change, with and without a government response, to be measured. In addition, many more climate models and scenarios should be included, as this project included only one. This will show a much wider range of possible positive and negative impacts, and allow the problem to be more fully understood. Nevertheless, the results show that even with a high demand scenario, and climate change included, Bolivia can achieve most of its INDC goals, decrease its dependence on carbon, and have more electricity and natural gas available to export.

## 6 Discussion

Apart from the analysis of Bolivia, this thesis has served as a case study of an extended CLEWs methodology. The energy-water nexus is a topic gaining increasing attention as the importance of these interactions are realised. Here the nexus is extended to include climate change, land-use, as well as electricity access, with all potential connections mapped out.

The results indicate that this extended framework is indeed worth the effort. All of the different categories have important links with each other, and by modelling them together it is possible to understand the extent to which these links alter the results. However, some of the links are relatively minor, and it is easy to predict their influence without complete modelling (such as the percentage grid connected, fed from ONSSET into OSeMOSYS). The most important connections are the levelised cost of electricity, the hydropower demand projections, the hydropower capacity factors, the water available to agriculture, and of course, the impacts of climate change on all of these.

Nonetheless, there are significant limitations in this project, imposed by intrinsic model limitations, data access as well as time. The primary limitation of the electricity access model is that it has no temporal aspect, and assumed overnight investments for an outcome state in 2030. Additionally, the lack of some data (most importantly detailed current electricity access data) meant that significant assumptions had to be made. The energy optimisation model made large simplifying assumptions, and didn't consider limitations in regional interconnects, nor did it model primary energy sources in any detail. Most importantly, the water model did not cover the entire country, and excluded two very large hydropower projects, as well as huge areas of agricultural and pasture land. Finally, the land-use and aquifers were modelled very simply, which means that the calculated runoff can't have complete confidence.

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## Appendix A Python code: ONSSET data extraction

```
def createSettlements(settlements, pop, popPer, size):
    # clip and project

    # resample to the chosen size
    Resample_management(pop, 'temp', size, 'BILINEAR')
    # and create the new point layer
    RasterToPoint_conversion('temp', settlements)
    # add x and y points
    AddXY_management(settlements)

    # add the new values for the points, using the ratio of the new cells to the
    # ↪ original
    AddField_management(settlements, 'Population', 'LONG')
    CalculateField_management(settlements, 'Population', '!grid_code!*_*' + str(
        # ↪ size*size/popPer), 'PYTHON_9.3')

    # rename and clean up
    # done this way (as opposed to AlterField) so that the field type can be
    # ↪ specified
    AddField_management(settlements, 'X', 'LONG')
    CalculateField_management(settlements, 'X', '!POINT_X!', 'PYTHON_9.3')
    DeleteField_management(settlements, 'POINT_X')
    AddField_management(settlements, 'Y', 'LONG')
    CalculateField_management(settlements, 'Y', '!POINT_Y!', 'PYTHON_9.3')
    DeleteField_management(settlements, 'POINT_Y')
    DeleteField_management(settlements, 'pointid;_grid_code')
# end createSettlements

def isUrban(settlements, targetPercent):
    calculated = 1.0 # variable used to store calculated urban fraction
    target = targetPercent/100 # target fraction
    urbanCutoff = 1000.0 # starting guess for urban cutoff density
    cont = True
    AddField_management(settlements, 'temp_urban', 'LONG')

    while cont:

        # sum the total population
        total = 0.0
        with da.SearchCursor(settlements, 'Population') as cursor:
            for row in cursor:
                total += row[0]

        # use the current cutoff and insert populations for every urban settlement
        codeblock = """def getClass(population):
            if population > """ + str(urbanCutoff) + """:
                return population
            else:
                return 0"""
        CalculateField_management(settlements, 'temp_urban', 'getClass(!Population
            # ↪ !)', 'PYTHON_9.3', codeblock)

        # sum the urban population
```

```

urbanTotal = 0.0
with da.SearchCursor(settlements, "temp_urban") as cursor:
    for row in cursor:
        urbanTotal += row[0]

calculated = urbanTotal/total

if abs(target - calculated) < 0.001:
    # if the calculated is within 0.5 percentage points then it's good
    ↪ enough
    cont = False # so we quite the loop
else:
    # otherwise nudge the cutoff a bit in the right direction
    if calculated > target:
        urbanCutoff += urbanCutoff * 2 * abs(1 - calculated/target)
    else:
        urbanCutoff -= urbanCutoff * 2 * abs(1 - calculated/target)
# end while

# create the new field and specifiy the cutoff value used
AddField_management(settlements, 'IsUrban_' + str(int(urbanCutoff)), 'SHORT')
codeblock = """def getClass(population):
    if population > """ + str(urbanCutoff) + """:
        return 1
    else:
        return 0"""
CalculateField_management(settlements, 'IsUrban_' + str(int(urbanCutoff)), '
    ↪ getClass(! Population!) ', 'PYTHON_9.3 ', codeblock)

# clean up
DeleteField_management(settlements, 'temp_urban')
# end isUrban

def getPV(settlements, ghi, size):
    # import from csv
    # clip and project

    # create a raster for the solar data using the specified cell size
    spline = sa.Spline(ghi, 'Ann', size)
    spline.save('temp')
    # and insert into settlements
    sa.ExtractMultiValuesToPoints(settlements, [['temp', 'ghi_day']])

    # calculate the yearly value by multiplying by 365
    AddField_management(settlements, 'GHI_annual', 'LONG')
    CalculateField_management(settlements, 'GHI_annual', '!ghi_day!*365', '
    ↪ PYTHON_9.3 ')

    # clean up
    DeleteField_management(settlements, 'ghi_day')

    # calculate the PV cost based on GHI, by interpolating from the following two
    ↪ points from Szabo2013
    # 1800 kWh/m2/year - 0.24 USD/kWh
    # 2600 kWh/m2/year - 0.21 USD/kWh

```

```

c1 = 0.24
c2 = 0.21
g1 = 1800.0
g2 = 2600.0
m = (c2-c1)/(g2-g1)
# C = m(G-g1) + c1

AddField_management(settlements, 'PV_cost', 'FLOAT')
CalculateField_management(settlements, 'PV_cost', str(m)+'*(!GHI_annual!- '+str(
    ↪ g1)+')'+str(c1), 'PYTHON_9.3')
# end getPV

def getCF(settlements, wind, size):
    import math
    from math import *

    # import from NetCDF and average
    # clip and project

    # calculate CF
    Prated = 600.0
    Umean = 6.0
    k = 2.0
    mu = 0.97
    T = 365.25 * 24

    Uarr = range(1,26)
    P = [0.0, 0.0, 25.0, 80.0, 130.0, 205.0, 290.0, 375.0, 450.0, 510.0, 555.0,
    ↪ 580.0, 595.0, 597.0, 600.0, 600.0, 600.0, 600.0, 600.0, 600.0, 600.0,
    ↪ 600.0, 600.0, 600.0, 600.0]

    AddField_management(wind, 'CF', "FLOAT")
    with da.UpdateCursor(wind, ['Ann', 'CF']) as cursor:
        for row in cursor:
            Umean = row[0]
            f = []
            for u in Uarr:
                f.append( (pi/2.0) * (u/Umean**2.0) * exp( (-pi/4.0) * (u/Umean)**k
                ↪ ) )

            E = 0.0
            for i in range(len(Uarr)):
                E += mu * T * P[i] * f[i]

            row[1] = E/(Prated * T)
            cursor.updateRow(row)

    # create a raster for the cf data using the specified cell size
    # we only categorize it after, otherwise the categories get destroyed by the
    ↪ spline
    spline = sa.Spline(wind, 'CF', size)
    spline.save('temp')
    # and insert into settlements
    sa.ExtractMultiValuesToPoints(settlements, [['temp', 'CF_uncat']])

    AddField_management(settlements, 'CF', 'FLOAT')

```

```

with da.UpdateCursor(settlements, ['CF_uncat','CF']) as cursor:
    for row in cursor:
        CF_uncat = row[0]
        if CF_uncat < 0.15:
            row[1] = 0.0
        elif CF_uncat >= 0.15 and CF_uncat < 0.25:
            row[1] = 0.2
        elif CF_uncat >= 0.25 and CF_uncat < 0.35:
            row[1] = 0.3
        elif CF_uncat >= 0.35 and CF_uncat < 0.45:
            row[1] = 0.4
        else:
            row[1] = 0.5
        cursor.updateRow(row)

# clean up
DeleteField_management(settlements, 'CF_uncat')
# end getCF

def createSlope(elevation):
    outSlope = sa.Slope(elevation, 'DEGREE')
    outSlope.save('elev_slope')
    return 'elev_slope'
# end createSlope

def filterCF(settlements, elevation, slope, protected, water, isUrbanName):
    isUrbanName = 'IsUrban_2576'

    sa.ExtractMultiValuesToPoints(settlements, [[elevation, 'temp_elevation']])
    sa.ExtractMultiValuesToPoints(settlements, [[slope, 'temp_slope']])

    with da.UpdateCursor(settlements, [isUrbanName, 'temp_elevation', 'temp_slope',
    ↪ 'CF']) as cursor:
        for row in cursor:
            if row[0] == 1 or row[1] > 2000 or row[2] > 18:
                row[3] = 0.0
                cursor.updateRow(row)

# clean up
DeleteField_management(settlements, 'temp_elevation;_temp_slope')

# find areas covered by protected land
Intersect_analysis([protected, settlements], 'temp', 'ONLY_FID', '0.1')
fid_name = Describe(settlements).OIDFieldName

# where there is a match between the ID and the ID create by Intersect_analysis
↪ , set CF to 0
with da.SearchCursor('temp', ['FID_' + settlements]) as search_cursor:
    for rowProtected in search_cursor:
        with da.UpdateCursor(settlements, [fid_name, 'CF']) as update_cursor:
            for rowSettlements in update_cursor:
                if rowSettlements[0] == rowProtected[0]:
                    rowSettlements[1] = 0.0
                    update_cursor.updateRow(rowSettlements)
                    break

```

```

# find areas covered by inland water bodies
Intersect_analysis([water, settlements], 'temp', 'ONLY_FID', '0.1')

# where there is a match between the ID and the ID create by Intersect_analysis
    ↪ , set CF to 0
with da.SearchCursor('temp', ['FID_' + settlements]) as search_cursor:
    for rowProtected in search_cursor:
        with da.UpdateCursor(settlements, [fid_name, 'CF']) as update_cursor:
            for rowSettlements in update_cursor:
                if rowSettlements[0] == rowProtected[0]:
                    rowSettlements[1] = 0.0
                    update_cursor.updateRow(rowSettlements)
                break

# end filterCF

def getDiesel(settlements, travel, size):
    # clip and project

    # resample up to correct size
    Resample_management(travel, 'temp', size, 'BILINEAR')
    # insert values
    sa.ExtractMultiValuesToPoints(settlements, [['temp', 'travel_minutes']])

    # calculate value in hours by dividing by 60
    AddField_management(settlements, 'Travel_hours', "LONG")
    CalculateField_management(settlements, 'Travel_hours', '!travel_minutes!/_/_60',
        ↪ 'PYTHON_9.3')

    # clean up
    DeleteField_management(settlements, 'travel_minutes')

    # calculate the diesel cost based on the travel time and other variables
    # from Mentis2015:
    #  $P_p = (P_d + 2 * P_d * c * t / V) * (1 / \mu) * (1 / LHV_d) + P_{om}$ 
    Pd = '0.54' # (USD/l) national diesel price: WorldBank2014
    c = '12.0' # (l/h) truck consumption per hour: Szabo2013
    # t (h) is travel time from layer
    V = '300.0' # (l) volume of truck: Szabo2013
    mu = '0.286' # (kWhth/kWhel) gen efficiency: Szabo2013
    LHVd = '9.9445485' # (kWh/l) lower heating value: Boundy2011
    Pom = '2.7777' # (USD/kWh) operation, maintenance and amortization: Torrero2003
        ↪ (need better source)

    # calculate value in hours by dividing by 60
    AddField_management(settlements, 'Diesel_cost', "FLOAT")
    CalculateField_management(settlements, 'Diesel_cost', '(!+Pd+!+2*!+Pd+!*!+c+*!
        ↪ Travel_hours!/!+V+)*(1/!+mu+)*(1/!+LHVd+)+!+Pom, 'PYTHON_9.3')
# end getDiesel

def getGridDistance(settlements, gridExisting, gridPlanned):
    # each point's distance from the existing grid
    Near_analysis(settlements, gridExisting)

    # done this way (as opposed to AlterField) so that the field type can be
        ↪ specified
    AddField_management(settlements, 'Grid_distance_existing', 'LONG')

```

```

CalculateField_management(settlements, 'Grid_distance_existing', '!!NEAR_DIST!',
    ↪ 'PYTHON_9.3')

#clean up
DeleteField_management(settlements, 'NEAR_DIST;_NEAR_FID')

# each point's distance from either grid
Near_analysis(settlements, [gridExisting, gridPlanned])

# done this way (as opposed to AlterField) so that the field type can be
    ↪ specified
AddField_management(settlements, 'Grid_distance_planned', 'LONG')
CalculateField_management(settlements, 'Grid_distance_planned', '!!NEAR_DIST!',
    ↪ 'PYTHON_9.3')

# clean up
DeleteField_management(settlements, 'NEAR_DIST;_NEAR_FID;_NEAR_FC')
# end getGridDistance

```

## Appendix B Python code: determine hydro potential

```
desc = Describe(rivers)
CreateFeatureclass_management(geodb, points, geometry_type='POINT', spatial_reference=
    ↪ desc.spatialReference)
fid_name = 'river_ID'
AddField_management(points, fid_name, 'LONG')

with da.SearchCursor(rivers, ['SHAPE@', desc.OIDFieldName]) as search_cursor:
    with da.InsertCursor(points, ['SHAPE@', fid_name]) as insert_cursor:
        for row in search_cursor:
            line = row[0]

            if line:
                cur_length = interval
                max_position = line.length
                insert_cursor.insertRow([line.firstPoint, row[1]])
                while cur_length < max_position:
                    insert_cursor.insertRow([line.positionAlongLine(cur_length,
                        ↪ False), row[1]])
                    cur_length += interval

sa.ExtractMultiValuesToPoints(points, [[elevation, 'elev']])

AddField_management(points, 'head', 'FLOAT')
with da.UpdateCursor(points, [fid_name, 'elev', 'head']) as cursor:
    prevFid = 0
    prevElev = 0

    for row in cursor:
        if row[1]: #check to make sure an elevation entry exists
            currentFid = row[0]
            currentElev = row[1]

            if (currentFid == prevFid) and ((prevElev - currentElev) > 0):
                row[2] = prevElev - currentElev
            else:
                row[2] = 0

            cursor.updateRow(row)
            prevFid = currentFid
            prevElev = currentElev
        else:
            row[2] = 0
            prevFid = row[0]
            prevElev = 0

sa.ExtractMultiValuesToPoints(points, [[discharge, 'discharge_second']])
rho = '1000' # density
g= '9.81' # gravity
nt = '0.88' # turbine efficiency
ng = '0.96' # generator efficiency
conv = '0.6' # conversion factor for environmental flow deduction
AddField_management(points, 'power', 'FLOAT')
CalculateField_management(points, 'power', rho+'*' +g+'*' +nt+'*' +ng+'*' +conv+'*_'!)
```

⇒ `discharge_second!_*_!head! ', 'PYTHON_9.3 ')`

## Appendix C Python code: determining grid connections

```
conDis = zcon[0] # distance
conPop = con[1] # population
result = elec
gridLength = np.zeros(len(result), dtype=int)

unelectrified = []
electrified = []
for index, row in enumerate(gis):
    if row[3] == 1: electrified.append(index)
    else: unelectrified.append(index)

while True:
    changes = []
    for unelec in unelectrified:
        for elec in electrified:
            if abs(gis[elec][0] - gis[unelec][0]) < conDis and abs(gis[elec][1] -
↪ gis[unelec][1]) < conDis:
                if gis[unelec][2] > conPop + conDis*(15.702*(gridLength[elec]+7006)
↪ /1000-110)/4400 and gridLength[elec] < 50000:
                    changes.append(unelec)
                    gridLength[unelec] = gridLength[elec] + conDis
                    break

    if len(changes) > 0:
        electrified = changes[:]
        for row in changes:
            unelectrified.remove(row)
            result[row] = 1
    else: break
```