Integrated analysis of land-use, energy and water systems for ethanol production from sugarcane in Bolivia

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9 Supplementary Materials

9.1 Spatial Zonation

Two zonation schemes were combined to divide the territory of Bolivia into a manageable number of regions aiming to capture similar hydrological, climatic, physiographic and agricultural activity characteristics. The first scheme corresponds to the watershed delineation of the HydroBASINS project (Lehner et al. 2013) which is a subset of the HydroSHEDS hydrographic database (Hydrological data and maps based on SHuttle Elevation Derivatives, (Lehner et al. 2008)). The HydroBASINS polygon layers (7 levels with increased sub-basin breakdown) provide a sub-basin delineation consistently sized and nested, allowing for analysis of watershed topology such as upstream and downstream connectivity (Lehner et al. 2008).

The HydroBASINS delineation was adopted by the Ministry of Environment and Water to develop the national Water Balance of Bolivia, WBB, (Ministerio de Medio Ambiente y Agua (MMAyA) 2017). In the WBB, 96 hydrographical units (resulting from a combination of levels 6,7 and 8) contributing to the renewable water resource in Bolivia were modelled (see **Figure A.1.a**). For the WBB, other shared catchments outside the territory of Bolivia were considered. At national level, three large freshwater river-basins divide Bolivia in three macro-basins (level 4 HydroBASINS), each with contrasting hydro-climatic characteristics: the Amazon, La Plata and the Altiplano as it is shown in **Figure A.1.a**.

The second scheme corresponds to the agro-productive areas from the National Irrigation Plan of Bolivia, which divide the country into 19 regions with similar weather, geography, physiography and agricultural activity (see **Figure A.1.a**) (Ministerio del Agua 2007). Both zonation schemes are currently used for official water and agriculture planning (Ministerio de Medio Ambiente y Agua (MMAyA) 2017; Ministerio del Agua 2007). To combine these schemes, the 19 agro-productive areas were divided by overlaying with the watersheds belonging to the three macro-basins and to selected watersheds tributary to large-scale hydropower projects; resulting in 27 regions as it is shown in **Figure A.1.b**. The regions not suitable for sugarcane production were excluded from the analysis.

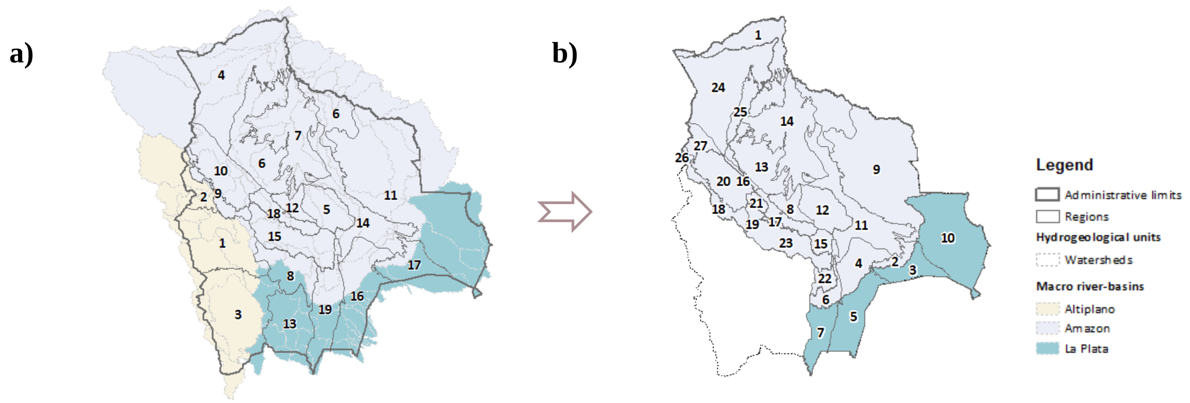

Figure A.1. a) map of the 96 watersheds overlaying with the 19 agro-productive zones. (GeoBolivia 2012b; 2016)**. b) Map of the harmonized zonation scheme with 27 regions. Note that the regions with no sugarcane crop potential were removed from the study.**

9.2 Spatial and non-spatial datasets

Several GIS and non-GIS datasets were collected for the model as illustrated in **Figure A.2**. **Table-A. 1** provides a detailed description and sources of each dataset. All GIS-data was processed to obtain averaged data for each of the 27 regions modelled. For the land-use model (detailed in **Section 2.5.2**), GIS-data of land-cover, forest land and protected areas were combined to classify land-use in nine land-use classes: cropland, forest, protected forest, grasslands, protected grasslands, cultivated pastures, barren, settlements, and water bodies. The cropland area for sugarcane and other crops was adjusted to national statistics using GIS-data from the National Agricultural Census. Climatic datasets (precipitation, temperature, solar irradiation and wind speed) were used to estimate the water demand for irrigation of sugarcane (detailed in **Section 9.4.4**). Other GIS-datasets such as population and livestock were used to estimate water demands for residential use and livestock consumption; groundwater depth and elevation data was used to estimate water pumping demands for groundwater irrigation (detailed in **Section 2.2.4**). **Table A.2** shows the aggregated area data at regional level for the modelled land cover types,

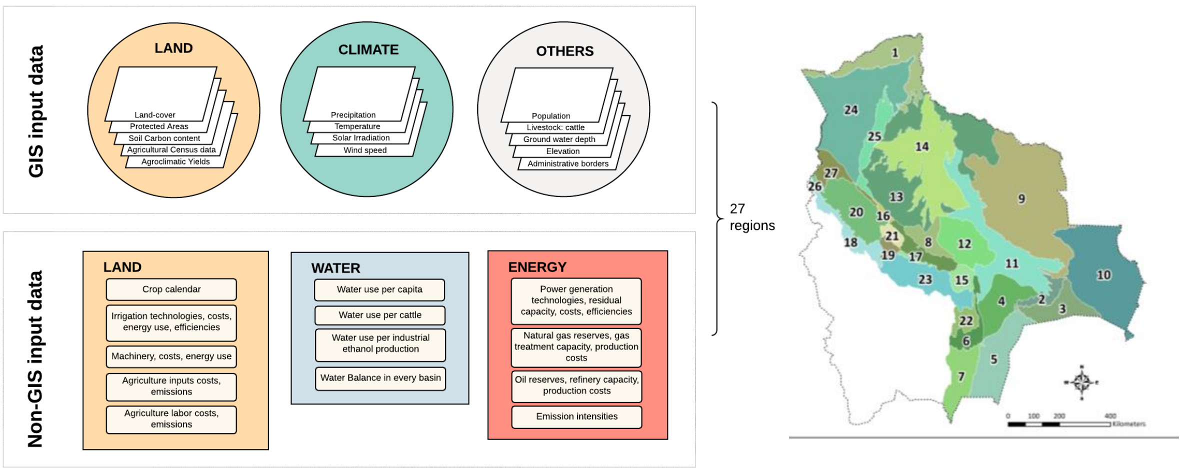

Figure A.2. Input datasets and map of spatial zonation

Table-A. 1 GIS datasets used in the analysis

Dataset	Resolution	Type	Source
Land-cover (ha)	300 m x 300 m	Raster	(ESA 2017).
Protected areas (ha)	--	Polygon	(GeoBolivia 2018)
Forest type (ha)	--	Polygon	(GeoBolivia 2017)
Sugarcane Area (ha)	--	Polygon	(GeoBolivia 2019c; 2019a)
Cropland area, irrigated and rainfed (ha)	--	Points	(Instituto Nacional de Estadistica 2015)
Agroclimatic yields (tonne/ha)	5 arc-min	Raster	(Fischer et al. 2012)
Organic soil carbon content, first 100 cm (tonne C)	30 arc-sec	Raster	(FAO et al. 2013)
Elevation (m)	1 km x 1 km	Raster	(A. Jarvis, H.I. Reuter, A. Nelson 2008)

Maximum monthly temperature (ºC)	1 km x 1 km	Raster	(Fick et al. 2017)
Minimum monthly temperature (ºC)	1 km x 1 km	Raster	
Average monthly temperature (ºC)	1 km x 1 km	Raster	
Average monthly wind speed (m/s)	1 km x 1 km	Raster	
Average monthly precipitation (mm)	1 km x 1 km	Raster	
Average monthly solar radiation (kJ/m^2)	1 km x 1 km	Raster	
Groundwater depth (m)	10 km x 10 km	Raster	(BGR et al. 2017)
Population	--	Points	(Instituto Nacional de Estadística and Viceministerio de Electricidad y Energías Alternativas 2016)
Cattle livestock population	--	Polygon	(GeoBolivia 2012a)

Table-A. 2. Area for each land-cover types for the base year 2013

		Non protected land					Protected land		Agricultural land		
Region	**Total Area, ha**	**Baren**	**Settle-ments**	**Water bodies**	**Forest**	**Grass-land**	**Forest**	**Grass-land**	**Other Agri-culture**	**Sugar-cane**	**Cattle**
1	3514	0.0	2.3	15.0	3165.0	136.4	83.1	6.4	7.3	0.2	98.4
2	790	0.0	0.7	0.0	177.1	0.0	556.3	32.5	0.0	0.0	23.5
3	1992	0.0	1.5	0.2	347.1	204.9	961.7	433.0	0.0	0.0	43.2
4	2518	4.1	2.4	2.0	1345.1	373.8	606.9	78.0	25.6	0.0	80.4
5	3597	1.4	9.1	2.1	2342.5	228.5	505.3	201.9	61.6	0.1	244.1
6	1078	0.1	2.6	0.1	762.0	9.6	119.7	19.5	35.7	0.4	128.4
7	2156	0.6	5.9	0.2	1478.4	94.6	409.4	24.2	42.4	9.5	91.1
8	1177	0.0	5.1	3.7	462.8	316.6	192.8	85.1	58.1	0.0	52.8
9	12806	0.0	8.0	37.7	7112.4	1085.2	3020.5	552.3	49.5	0.7	939.6
10	7909	0.1	4.9	25.0	2396.8	618.0	2786.8	1443.5	6.5	0.5	626.9
11	5761	4.0	22.7	60.4	2008.5	0.0	482.9	81.4	1420.1	7.5	1673.5
12	2691	4.1	11.4	17.5	787.4	60.5	115.1	99.8	847.6	129.3	618.6
13	8255	0.0	6.7	196.3	2083.9	430.1	1849.0	1213.7	13.4	0.3	2461.4
14	7144	0.0	9.4	238.5	1131.6	2526.9	102.9	388.1	12.0	0.4	2733.9
15	930	0.1	3.6	0.9	155.6	30.4	422.2	156.3	32.8	0.0	128.1
16	189	0.0	0.0	0.0	40.9	0.0	115.7	20.3	0.1	0.0	12.3
17	1226	0.0	1.8	0.0	213.3	0.0	907.9	9.2	8.8	0.0	85.2
18	1416	163.1	25.1	0.9	9.0	1024.2	0.9	106.4	34.5	0.0	51.4
19	412	2.6	2.7	0.5	7.1	130.2	2.0	226.2	11.7	0.0	28.5
20	3251	0.3	16.7	1.7	1979.8	632.4	352.2	131.8	79.0	0.2	56.7
21	436	0.0	1.1	0.0	380.4	35.6	16.4	0.8	0.6	0.0	1.2
22	790	0.1	1.3	0.5	271.5	46.5	358.0	35.9	34.2	0.0	42.2
23	2987	315.2	38.9	3.3	74.7	1337.3	330.2	457.4	103.5	0.6	326.4
24	8584	0.0	5.3	80.8	5606.9	1290.6	1245.3	155.7	16.4	0.5	182.4
25	1588	0.0	2.2	22.0	598.9	465.0	171.0	30.3	3.2	0.0	295.8
26	132	0.3	0.2	0.8	0.0	0.0	1.8	128.4	0.3	0.0	0.0
27	1152	0.0	1.3	0.0	33.1	0.0	1002.1	101.9	2.3	0.1	11.4
Rest of the country	24649	16298.1	124.4	616.3	94.0	6109.1	9.1	357.4	458.1	0.1	582.3
Total	109130	16794.1	317.3	1326.5	35065.7	17186.4	16727.0	6577.3	3365.4	150.4	11619.8

9.2.1 Relevant data from the Agricultural Census referenced in the article

Table-A. 3 Agriculture machinery ownership at national level (all crops) retrieved from (Instituto Nacional de Estadistica 2015)

Process	Machinery with mechanical traction		Machinery for manual use		Machinery with animal traction	
	quantity	type	quantity	type	quantity	type
Land preparation	29 018	Tractor-drawn harrows	--	--	50 055	Animal-drawn iron plows
	36 562	Tractors	--	--	398 663	Animal-drawn wooden plows
Planting	154 849	Mechanical planters	--	--	--	--
Harvesters	6 175	Mechanical harvesters	869 375	Manual harvesting	--	--
	4 725	Rototillers	259 062	Mowers or cutters	--	--

9.3 Characterization/classification of sugarcane production systems

9.3.1 Methodology

Microdata from the National Agricultural Census of 2013 was made available for our research and used to classify and group sugarcane farms into the six differentiated agriculture production systems described previously in **Section** Error! Reference source not found.. A mix of qualitative and quantitative data from the Census was used for the classification. Qualitative binary data referring to the orientation of production (market or self-consumption), use of irrigation, use of fertilization, use of pesticides, herbicides and weed control was used together with quantitative data of farm-size and machinery ownership as described in **Table-A. 4**. Each variable was divided into three classes with fixed thresholds applied to score and quantitative data.

A methodology used by Solano et al. to classify farming systems based on surveyed data was adopted to classify sugarcane production systems in our study (Solano et al. 2000). Multiple correspondence analysis (MCA) was used to analyze the mix of quantitative and qualitative data features. MCA is a multivariate statistical method used to transform data from a high number of features (also referred to dimensions or factors) into a lower number of features that retain as much of the information (variance) in the original dataset. Multi-collinearity analysis was performed to the Census variables to check the level of association between variables. Only non-collinear variables were used for the multivariate classification.

Using the main features obtained from the MCA analysis, hierarchical clustering is performed to classify the farms. Hierarchical clustering is an unsupervised machine learning method to form groups – of a mutually exclusive subset data – that are maximally similar in specified attributes (Ward 1963). Clustering methods vary depending the measures and criteria to determine whether two objects are similar or dissimilar.The Euclidean centroid distance was chosen as method of cluster aggregation and the number of clusters were selected based on the R^2. The closer the values of R^2 to 1, the better the clustering preserves the original distances. The cluster analysis carried on the main features obtained from the MCA identified three clusters. Each cluster was further divided into irrigated and rainfed conditions based on the irrigation data from each observation (binary). Note that irrigated production of sugarcane is very low, 3.6% in 2013 (Instituto Nacional de Estadistica 2015), therefore existing information for irrigated conditions is very limited. The outputs of the classification are used to calculate the areas of each agriculture production system in each area for the base year (residual capacity, see **Section** Error! Reference source not found.).

Table-A. 4 Variables selected from the Census and classification

Variable	Definition	Type	Classification	Code	Observations	Area, ha
Agricultural land area	Area of land used for sugarcane agricultural purposes	Quantitative	≤ 10 ha	SizeS	2 880	16 464
			10 - 100 ha	SizeM	2 080	59 164
			> 100 ha	SizeL	230	70 508
Subtotal					*5 190*	*146 136*
Market	Orientation to commercial or subsistence production	Binary	Market-oriented	ProdMarket	4 527	128 026
			Dual market-self use	ProdDual	236	5 133
			Self-use	ProdSelff	90	1 501
Subtotal					*4 853*	*134 660*
Machinery	Score of machines used (tractors, harvesters, rototiller and planters) with a value of one each	Multiple binary variables	0 machines	MachineN	1 441	31 580
			1- 2 machines	MachineI	3 308	76 652
			3 - 4 machines	MachineH	441	37903

Subtotal					*5 190*	*146 136*
Fertilization	Fertilizers used in production	Binary	No fertilization	FertiN	1 951	34 916
			Fertilization Organic	FertiO	2380	77533
			Fertilziation Organic + agrochemicals	TertiCh	859	33687
Subtotal					*5 190*	*146 136*
Agrochemicals	Score of agrochemicals used (herbicides, pesticides, weed control) with a value of one each	Multiple binary variables	0	AgrocheN	889	14 839
			1	AgrocheI	3 304	74 626
			2 - 3	AgrocheH	997	56 671
Subtotal					*5 190*	*146 136*

9.3.2 Results of the classification

Based on the main factors obtained in the MCA, results from the cluster analysis identify three clusters which are sufficient to characterize the sugarcane agricultural production systems. This is demonstrated by a strong increase in R^2 occurrying at cluster number 3 as presented **Table A.5**, smaller increases in the R^2 occur with increasing number of clusters.

Table-A. 5. Criteria for the selection of clusters based on the coefficient of determination

	Number of clusters									
Parameter	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
R^2	0.000	0.281	0.743	0.767	0.772	0.814	0.858	0.864	0.910	0.921

Table A.6 shows the characteristics of the quantitative variables in each cluster. Cluster 1 is composed by 871 farms defined as High-inputs (Hi) sugarcane production systems. This group has the largest agricultural area and the highest scores on machinery and agrochemicals use. Large values of the coefficient of variation on the agricultural area indicate a high dispersion on the sugarcane farm-size. This can be explained because a large number of the farms produce multiple crops and often the main crop is not sugarcane, therefore not all small areas use low mechanization/agricultural inputs. Cluster 2 is made of 3498 farms and defined as Intermediate-inputs (Ii) sugarcane production systems. This group has smaller mean agricultural area than the Hi cluster and smaller scores on machinery and agrochemicals use. Cluster 3 is made of 821 farms defined as Low-input (Li), this group is composed by the smallest farms with zero or little use of machinery and agrochemicals.

Table-A.6. Variables and classification. Mean and coefficient of variation

Variable	**Cluster 1[a]**		**Cluster 2[b]**		**Cluster 3[c]**	
	Mean	**CV**	**Mean**	**CV**	**Mean**	**CV**
Agricultural area, ha	47.58	2.69	24.29	3.26	0.441	3.67
Machinery, score	1.91	0.39	1.03	0.86	0.025	6.172
Agrochemicals, score	1.46	0.49	0.96	0.70	0.11	2.95

[a] N= 871, [b]N= 3498, [c]N=821

Qualitative variables (market production and fertilization) are not presented

Table A.7 shows the total cultivated area (aggregated at national level) of the farms classified in each input level with further dissagreggation into irrigated and rainfed classes. For each of the 27 regions, this information is used as residual capacity in the base year 2013.

Table-A.7. Distribution of sugarcane agriculure management systems in 2013 based on data of the National Census on Agriculture

Water supply	**Unit**	**High-inputs and mechanized**	**Intermediate-inputs and semi-mechanized**	**Low-inputs and no mechanized**	**Sub total**
Rainfed	Hectares	40 257 (26.78%)	104 411 (69.45%)	390 (0.26%)	145 058 (96.48%)
Irrigated	Hectares	1 468 (0.98%)	3 800 (2.53%)	18 (0.01%)	5 286 (3.52%)
Sub-total	Hectares	41 725 (27.75%)	108 211 (71.98%)	408 (0.27%)	150 344 (100%)

In brackets each area as the percentage of the total area

Table A.8 details the model assumptions for manual/mechanized operations and use of materials deriving from surveyed data on sugarcane agricultural farms in Bolivia for three production systems: mechanized, semi-mechanized and traditional (Observatorio Agroambiental y Productivo et al. 2014).

Table-A. 8. Sugarcane production assumptions for three agriculture management levels

Process		High-inputs and mechanized	Intermediate-inputs and semi-mechanized	Low-inputs and no mechanized
1. Operational activities				
1.1	Soil preparation	mechanized	mechanized	manual
1.2	Seedling planting	mechanized	manual	manual
1.3	Harvesting	mechanized	manual	manual
1.4	Transport	mechanized	mechanized	animal-powered
1.5	Irrigation	mechanized	mechanized	mechanized
2. Materials				
2.1	Seeds	yes	yes	yes
2.2	Fertilizers, NPK	yes	yes	only manure
2.3	Insecticide, pesticide, fungicide	yes	no	no
2.4	Herbicide	yes	no	no

9.4 Production costs, energy inputs and emissions in sugarcane production systems

9.4.1 Production costs and energy use of mechanical and manual operations

For each region modelled, the total production cost is calculated per unit of area. Annualized production costs for land preparation, planting and agricultural operations are commonly expressed per unit of area (hectare) while the production costs of harvesting and transport are expressed per unit of product (ton). The total annualized production cost is calculated as shown in **Equation A.1**. For each process, operational and labor costs are accounted. The production costs are calculated based on assumptions on mechanization for each input level (detailed in **Table A.8**). Note that costs assumptions detailed in the following tables are applied equally to all regions, but the total cost differ between regions due to differences in potential yields.

$$Total\ cost_k\left(\frac{US\$}{ha}\right)=\sum_{i}^{n}Cost_i\left(\frac{US\$}{ha}\right)+\sum_{j}^{m}Cost_j\left(\frac{US\$}{ton}\right)\cdot Yield\ \left(\frac{ton}{ha}\right)\ for\ k=\ 1,..,6 \quad \text{Eq. A.1}$$

where:

$$Cost_i\left(\frac{US\$}{ha}\right)=Operational\ cost_i\left(\frac{US\$}{ha}\right)+labour\ cost_i\left(\frac{US\$}{ha}\right)\ for\ i=1,\ldots,n$$

$$Cost_j\left(\frac{US\$}{ton}\right)=Operational\ cost_i\left(\frac{US\$}{ton}\right)+labour\ cost_i\left(\frac{US\$}{ton}\right)\ for\ j=1,\ldots,m$$

Labor requirements for manual and mechanized operations are detailed in **Table A.9.** The cost of labor was calculated multiplying the labor requirements for the average labor cost of 15.22 US$/man-day according to labour cost information from (Observatorio Agroambiental y Productivo et al. 2014), which is equivalent to 1.905 USD/man-hour considering 8 working hours per day.

Table-A. 9. Labour data for manual and mechanized operations

Process	Unit	Manual	Mechanized	Source
Land preparation	Man-hour/ha	332	7	(Yadav et al. 2003)
Manuring	Man-hour/ha	238	-	(Yadav et al. 2003)
Planting	Man-hour/ha	338	20	(Yadav et al. 2003)

Harvesting, loading and transportation	Man-hour/tonne	9.9	0.032	(Yadav et al. 2003)

Annualized production costs for mechanized operations are detailed in **Table A.10.** Production costs are specified for tradictional production (no trash recovery) and with trash recovery.

Table-A. 10. Annualized capital and operational costs of mechanized processes

Technology	Unit	Production with no trash recovery	Production with trash recovery	Source
Soil preparation[a]	US$/ha	61.6	61.6	(Cardoso et al. 2018)
Seedling Planting[a]	US$/ha	256.4	256.4	(Cardoso et al. 2018)
Harvesting	US$/ton	8.4	10.9	(Cardoso et al. 2018)
Transport - tractor	US$/ton	1.5	3.4	(Cardoso et al. 2018)
Transport – bull cart	US$/ton	2.0	4.5	(Observatorio Agroambiental y Productivo et al. 2014; Cardoso et al. 2018)

[a] Annualized considering a ratoon period of 5 years

Energy use and lifecycle emissions for mechanized operations are detailed in **Table A.11**.

Table-A. 11. Energy use by process and inputs

Process/input	Energy use		Emissions	
	value	units	value	units
Sugarcane farming (mechanized land preparation and planting)	14.8	MJ/tc	1.3	kgCO2,eq/tc
Agriculture inputs (fertilizers and agrochemicals)	57.7	MJ/tc	11.6	kgCO2,eq/tc
Sugarcane harvesting (mechanized)	46.9	MJ/tc	4.1	kgCO2,eq/tc
Sugarcane and inputs transportation	58.3	MJ/tc	5.2	kgCO2,eq/tc
Trash burning and decomposition	0	MJ/tc	14.8	kgCO2,eq/tc
Field emissions	0	MJ/tc	5.9	kgCO2,eq/tc
Total	**177.7**	**MJ/tc**	**42.9643**	kgCO2,eq/tc

Source: (Macedo et al. 2008; Seabra et al. 2011)

Table A.12 aggregates the cost assumptions for the operational processes and materials used for the three input-levels for production with and without trash recovery.

Table-A. 12. Cost data for mechanized and manual agricultural production of sugarcane

Process		Unit	High-inputs and Mechanized		Intermediate-inputs and semi-mechanized		Low inputs and no mechanized		Reference
			no trash recovery	trash recovery[2]	no trash recovery	trash recovery[2]	no trash recovery	trash recovery[2]	
1. Operational costs[3]									
1.1	Soil preparation[4]	USD/ha	64.3	64.3	64.3	64.3	126.5	126.5	(Yadav et al. 2003; Observatorio Agroambiental y Productivo et al. 2014; Cardoso et al. 2018; Kahil et al. 2018)
1.2	Seedling planting[4]	USD/ha	264.0	264.0	128.8	128.8	128.8	128.8	
1.3	Harvesting	USD/ton	8.5	11.0	18.9	24.4	18.9	24.4	
1.4	Transport[5]	USD/ton	1.5	3.4	1.5	3.4	2.0	4.5	
1.5	Irrigation (supply side)	USD/ha	133.0	133.0	133.0	133.0	133.0	133.0	
2. Materials									
2.1	Seeds	USD/ha	87.6	87.6	52.6	52.6	52.6	52.6	(Cardoso et al. 2018; Salassi et al. 2004; Pokharel et al. 2019; Observatorio Agroambiental y Productivo et al. 2014)
2.2	Fertilizers	USD/ha	239.9	356.5	172.2	353.6	172.2	353.6	
2.3	Insecticide, pesticide, fungicide	USD/ha	472.4	472.4	0.0	0.0	0.0	0.0	
2.4	Herbicide	USD/ha	41.7	41.7	0.0	0.0	0.0	0.0	

[1] According to (Cardoso et al. 2018) mechanized planting requires a more seedlings per hectare than manual planting. 12 tons per hectare of seedling are used for manual seedling planting and 20 tonnes per hectare for mechanized planting. According to (Observatorio Agroambiental y Productivo et al. 2014), the costs of one ton of sugarcane seedlings is 30.5 Bolivianos (4.38 US$/ton).

[2] Additional costs for harvesting and transport are included when sugarcane trash is recovered from the fields. Compared to traditional production where sugarcane trash is burned, additional fertilization is required in the production with trash recovery. Cost assumptions for conventional and trash recovery production are detailed in (Cardoso et al. 2018). It is assumed that 50% of the total trash available on the field is transported to the sugarmill (Hassuani et al. 2005).

[3] Note that labor costs and fuel costs are included in the operational costs. Manual operations include annualized costs of hand-tools and rental of other man or animal-driven equipment (such as bull cart). Mechanized operations include the annualized cost of debt considering 12% per year interest rate over a 15-year period.

[4] Costs for land preparation and seedling planting are annualized, considering a ratoon period of 5 years.

[5] For the transportation process, an average distance from the field to the sugarcane mill of 25 km was assumed (T. Cardoso et al. 2018).

Similarly, **Table A.13** shows the energy use and emissions for each process for the three input levels.

Table-A. 13. Energy use and emissions for one example

	unit	Fossil Energy use			Renewable Energy use			Total Energy Use			unit	Emissions		
Sugarcane production		High	Interme-diate	Low	High	Interme-diate	Low	High	Interme-diate	Low		High	Interme-diate	Low
Sugarcane farming	MJ/tc	14.8	29.5	73.5	--	0.8	3.1	14.80	30.25	76.58	kg $CO_{2,eq}$/tc	1.3	2.7	6.7
Agriculture inputs	MJ/tc	57.7	46.6	6.6	--	--	--	57.70	46.60	6.60	kg $CO_{2,eq}$/tc	11.6	9.4	1.3
Harvesting	MJ/tc	46.9	85.6	201.8	--	2.1	8.4	46.90	87.72	210.19	kg $CO_{2,eq}$/tc	4.1	7.7	18.3
Transportation	MJ/tc	58.3	58.3	37.8	--	--	1.6	58.30	58.30	39.33	kg $CO_{2,eq}$/tc	5.2	5.2	3.4
Trash burning and decomposition	MJ/tc	--	--	--	--	--	--	--	--	--	kg $CO_{2,eq}$/tc	14.8	14.8	14.8
Field emissions	MJ/tc	--	--	--	--	--	--	--	--	--	kg $CO_{2,eq}$/tc	5.9	5.9	5.9
Irrigation	MJ/tc	36.7	36.7	36.7	--	--	--	36.72	36.72	36.72	kg $CO_{2,eq}$/tc	2.7	2.7	2.7
TOT	**MJ/tc**	**214.4**	**256.7**	**356.4**		**2.9**	**13.0**	**214.4**	**259.6**	**369.4**	kg $CO_{2,eq}$/tc	45.6	48.3	53.2

9.4.2 Energy value and emisions from human labor

The human labor energy input E_{labor} is calculated following **Equation 1** and the emissions from human labor are calculated following **Equation 2**. In 2019, for example, the minimum monthly wage in Bolivia was US$303 (or US$15.22 per day) (Trading Economics 2019), primary energy supply per capita was 26.37 GJ (Ministerio de Hidrocarburos 2019), GNI per capita was US$3533 (The World Bank 2019) and the average emission intensity of primary energy consumption was 87.3 kg $CO_{2,eq}$ /MJ (Ministerio de Hidrocarburos 2019). Therefore the energy intensity of labor is 113.6 MJ/man-day and emissions from human labor us 9.9 kgCO2/man-day.

$$E_{labor}\left(\frac{MJ}{man\ \cdot day}\right) = wage\ \left(\frac{US\$}{man \cdot day}\right) \cdot \frac{per\ capita\ primary\ energy\ consumption\ \ (MJ)}{per\ capita\ GNI\ (US\$)} \quad \textbf{Equation 1}$$

$$Emissions_{labor}\left(\frac{kg\ CO_{2,eq}}{man\ \cdot day}\right) = \ E_{labor}\left(\frac{MJ}{man \cdot day}\right) \cdot Avg.emissions\ intensity\ \left(\frac{kg\ CO_{2,eq}}{MJ}\right) \quad \textbf{Equation 2}$$

9.4.3 Lifecycle emission intensity and costs of all fuels considered in the study

Table-A. 14. Assumptions on lifecycle emission intensity, low heating value and costs of fuels

Fuel	**Emissions content**		**Low heating value[1]**		**Cost[1]**		**References**
	value	**unit**	**value**	**unit**	**value**	**unit**	
Diesel	3.16	kg$CO_{2,eq}$/L	35.8	MJ/L	0.54	USD/L	(Macedo et al. 2008)
	88.37	g$CO_{2,eq}$/MJ			0.02	USD/MJ	
Gasoline	2.93	kg$CO_{2,eq}$/L	32.1	MJ/L	0.54	USD/L	(Macedo et al. 2008)
	81.77	g$CO_{2,eq}$/MJ			0.02	USD/MJ	
Natural gas	90.93	g$CO_{2,eq}$/MJ					(Macedo et al. 2008)

Ethanol	0.03 1.18	$kgCO_{2,eq}$/L $gCO_{2,eq}$/MJ	21.197	MJ/L	0.47 0.02	USD/L USD/MJ	(Khatiwada et al. 2011; Deshmukh et al. 2013)
Electricty**	261.92 72.76	$gCO_{2,eq}$/kWh $gCO_{2,eq}$/MJ			16.71 0.005	USD/MWh USD/MJ	Carbon intensity based on data from (Comité Nacional de Despacho de Carga 2018),
Bagasse dry****	26.5 1.5	$CO_{2,eq}$/kg $gCO_{2,eq}$/MJ	17.5	MJ/kg			(Deshmukh et al. 2013)
Bagasse (50% wt moisture)	13.3	$gCO_{2,eq}$/ton	7.565	MJ/kg			(Dias et al. 2011)
Sugarcane trash burning (15 wt% moisture)	88	$gCO_{2,eq}$/kg	12.96	MJ/kg			(Khatiwada, Venkata, et al. 2016)
Sugarcane trash decomposition (15 wt% moisture)	18	$gCO_{2,eq}$/kg					(Khatiwada, Venkata, et al. 2016)
Labour	9.918	$kgCO_{2,eq}$/man-day	113.618	MJ/man-day	15.22	USD/lman-day	Estimated in this study, see Section 9.4.2

[1]Low heating values obtained from EIA otherwise specified as second reference, cost data obtained from national sources (ANH 2019)

9.4.4 Irrigation

In the national Water Balance of Bolivia, the reference crop evapotranspiration (Et0) is estimated using the Soil Moisture (SM) hydrological model of WEAP (Yates et al. 2005). The equation to estimate the Et0 is the modified version of the Penman-Monteith method for a crop of height 0.12 m with a surface resistance of 69 s / m, and defined as follows (Maidment 1993):

$$ET_0 = \frac{\Delta}{\Delta - \gamma^*}(R_n - G) + \frac{\gamma}{\Delta - \gamma^*}\frac{900}{T + 275}U_2(P_s - P_a) \quad \text{Equation A.5}$$

Where: ET_0 is the reference evapotranspiration, $mm\ day^{-1}$, R_n is the net radiation at the crop surface, $MJ\ m^2\ day^{-1}$, G is the soil heat flux density, $MJ\ m^2\ day^{-1}$, T is the mean daily air temperatura at 2 m height, $°C$, U_2 is the wind speed at 2m height, $m\ s^{-1}$, P_s is the saturation vapour pressure, kPa, P_a is the actual vapour pressure, kPa, $(P_s - P_a)$ is the saturation vapour pressure deficit, kPa, Δ is the slope vapur pressure curve, $kPa\ °C^{-1}$, γ is the psychrometric constant, $kPa\ °C^{-1}$, $\gamma^* = \gamma(1 + 0.33\ U_2)$

Climate data-sources and functions used to estimate missing meteorological data are detailed in the Water Balance of Bolivia document (Ministerio de Medio Ambiente y Agua (MMAyA) 2017). The averaged effect of both crop transpiration and soil evaporation are integrated into the Kc coefficient. As presented in **Table-A. 15**, we assumed the indicative nominal values for the single crop coefficient Kc for sugarcane in ratoon provided by (Allen et al. 1998). To obtain more accurate values at monthly basis throughout the different agricultural seasons, a function (**Equation A.6**) was developed to represent and fit the kc curve presented in **Figure A.4** (Pegios 2018).

$$k_{ci} = k_{c,prev} + \left[\frac{i - \sum(L_{prev})}{L_{stage}}\right] \cdot (k_{c,next} - k_{c,prev}) \quad \text{Equation A.6}$$

Where i is the number of the month during the growth stage, k_{ci} is the required crop coefficient in one month *I*, L_{stage} is the length of the season under consideration (days), $\sum(L_{prev})$ is the sum of the lengths of all previous stages (days). The method used to estimate the montly crop water needs rakes into account effective rainfall (mm) and the montly Etc values as described in **Equation A.7.**

Equation A.7

$if\ (PCP < 15\ mm);$

yes → $water\ deficit = ET_0 \cdot k_c$

no → $if\ (ET_0 \cdot k_c - eff\ \cdot (PCP - 15)) > 0;$

yes → $water\ deficit = ET_0 \cdot k_c - eff \cdot (PCP - 15)$

no → $water\ deficit = 0$

Where: PCP is the precipitation, $mm\ \ month^{-1}$, ET_0 is the reference evapotranspiration, $mm\ month^{-1}$, k_c is the crop coefficient, eff is the monthly effective rainfall ratio, used as 75%.

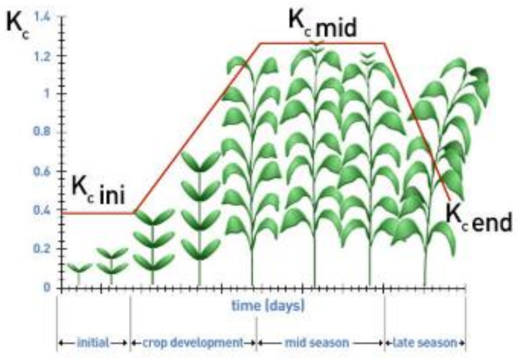

Figure A.3. Crop coefficient (kc) curve (Allen et al. 1998)

Table-A. 15 Crop calendar and single crop coefficient adopted from (Allen et al. 1998)

Parameter	**Planting**	**Growing**		**Harvesting**	**Total**
	Initial- season	Crop development	Mid-season	Late-season	
Start date	01-sep	01-oct	20-nov	19-may	
End date	30-sep	19-nov	18-may	17-jul	
Duration, days	35	85	180	60	320
Kc	0.4	1.25	1.25	0.75	

Data specific for sugarcane in ratoon for reference tropical climatic region

Average electricity requirements for pumping water, water efficiency and costs were adopted from (Kahil et al. 2018) and are described in **Table-A. 16.** The electricity demand for irrigation can be calculated following **Equation A.7**.

$$E_{irrigation} = water\ deficit \left[\frac{m^3}{year}\right] \cdot \left(\frac{I_{supply\ side}}{e_{supply\ side} \cdot e_{demand\ side}} + \frac{I_{demand\ side}}{e_{demand\ side}}\right) \left[\frac{kWh}{m3}\right] \qquad \textbf{Equation A.7}$$

Table-A. 16 Cost efficiency and energy requirements of water management options

Technology	**Water efficiency, %**	**Electricity intensity, kWh/m3**	**Investment cost**		**O&M cost**		**Lifetime, year**
			Value	**Unit**	**Value**	**Unit**	
Supply-side							
Surface water diversion	90	0.03	57	US$/m3	0.01	US$/m3	10
Groundwater pumping	80	0.1	8.5	US$/m3	0.01	US$/m3	10
Demand-side							
Flood irrigation	60	0	460	US$/ha	23	US$/ha	30
Sprinkler irrigation	75	0.24	650	US$/ha	33	US$/ha	20

Data adopted from (Kahil et al. 2018)

9.5 Production of bioethanol in biorefinery (industrial operations)

9.5.1 Parameters adopted in the simulation of first generation (1G) ethanol production plant

Table A.17 shows the data used to model the mass transfer in each process.

Table-A. 17. Parameters adopted in the simulation of sugar and ethanol production plants

Parameter	**Value**	**Unit**	**Reference**
Sugarcane sucrose content			(MDRyT 2012)
Santa Cruz	12.22	wt%	
Tarija	14.20	wt%	
La Paz	12.70	wt%	

Rest of Bolivia	12.00	wt%	
Sugars recovery on the mills	96	%	(Dias et al. 2011)
Sugars recovery on juice treatment	99.5	%	(Dias et al. 2011)
Fermentation yield	90	%	(Dias et al. 2011)
Bagasse recovery	140	kg_{dry} /tonne sugarcane	
Sugarcane fibre content	12.5	wt%	(MDRyT 2012)
Sugarcane trash produced in the field	140	kg_{dry} /tonne sugarcane	(Dias et al. 2011)
Fraction of trash recovered from the field	50	%	(Dias et al. 2011)
Ethanol recovery on destilation and dehydration	99.7	%	(Dias et al. 2011)

9.5.2 *Conversion chain for the modelled biorefinery configurations*

Figure A.4 illustrates the conversion chain to process one tonne of sugarcane in blue boxes and in yellow boxes the conversion chain to obtain one liter of ethanol for each of the biorefinery configurations.

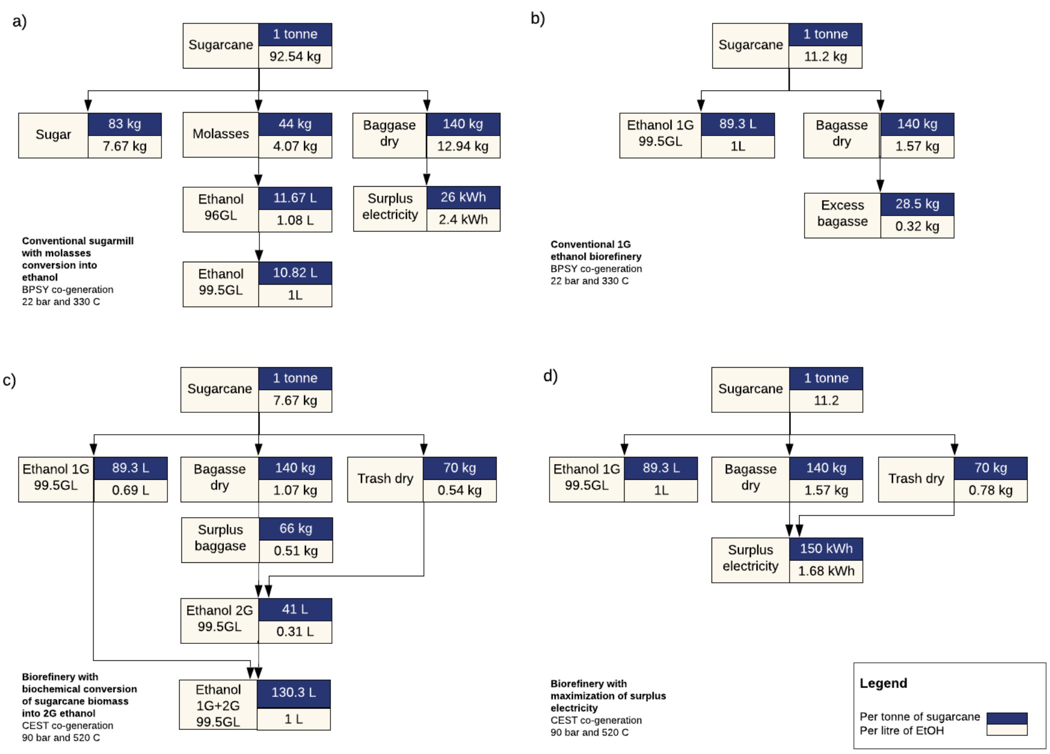

Figure A.4. Sugarcane to ethanol conversion chain for multiple biorefinery configurations

9.5.3 *Characteristics of sugarcane biorefineries*

Conversion factors and operational and investment costs for the biorefinery configuration a) are presented together in **Table A.18** while **Table A.19** shows the same data for the biorefinery configurations b),c) and d). **Table A.20** presents the investment cost breakdown for biorefinery configurations b),c) and d).

Table-A. 18 Overall conversion factors for the sugar-ethanol biorefinery configuration (a) Option in Figure A.2

Parameter	Units	Value
Sugarcane milling capacity	tonne sugarcane/day	6000
Sugar refinery capacity	tonne refined sugar/day	500

Hydrous Ethanol production capacity	liter hydrated ethanol/day	70000
Net electricity generation[a]	kWh/tonne sugarcane	46
Electricity surplus to the grid[a]	kWh/tonne sugarcane	26
Milling days per year	Days/year	165
Total investment costs	Million USD	105
Total O&M costs	Million USD/year	12.58

Note: The investment cost of San Buenaventura was 105 million US$ for the factory and 104 million US$ for building a road to connect the sugar factory.

[a] Source: (Deshmukh et al. 2013) for a traditional sugar factory with condensing-extraction steam turbines at 30 bar, 340 C, 530 kg-steam/tonne sugarcane and mechanical drives.

Table-A. 19 Conversion factors and costs for biorefinery configurations b),c) and d)

Conversion efficiencies	Unit	Biorefinery configurations		
		Biorefinery EtOH 1G[a]	**Biorefinery EtOH 1G (+electricity)[b]**	**Biorefinery EtOH 1G2G[b]**
Anhydrous ethanol	l/tonne sugarcane	88.9	89.3	130.3
Surplus electricity	kWh/tonne sugarcane	0	92.6	150
Surplus bagasse	kg/tonne sugarcane	28.5	0	0
Lignocellulosic material	kg/tonne sugarcane-dry	0	0	100
Total Investment cost[c]	Million US$	160.2[a]	199[a]	318 [a]
Total Annualized O&M fixed costs[c]	Million US$[b]	19.22	23.88	46.36

[a] Conversion efficiencies and costs adopted from simulation results from (Dias et al. 2011) for a sugarcane processing capacity of 2 million tonne of sugarcane per year. Conventional BPST co-generation with 22 bar and 220 Celsius.

[b] Conversion efficiencies and costs adopted from simulation results from (Dias et al. 2013) for a sugarcane processing capacity of 2 million tonne of sugarcane per year. Efficient CEST co-generation with 90 bar and 520 Celsius.

Table-A. 20 Investment costs breakdown for biorefinery configurations b),c) and d)

Process	**Unit**	**Biorefinery 1G[a]**	**Biorefinery 1G (+electricity)[a]**	**Biorefinery 1G2G (+ethanol)[b]**
Sugarcane reception and juice extraction	million USD	22.5	22.5	22.5
Juice treatment, fermentation and distillation	million USD	25.5	28.05	28.05
Automation and buildings	million USD	57	**75.25**	75.25
Total co-generation system with boilers at 22 bar	million USD	45	--	--
Total cogeneration system with boilers at 82 bar	million USD			52
Total cogeneration system with boilers at 90 bar	million USD		63	
Molecular sieves for ethanol dehydration	million USD	10.2	10.2	10.2
Second generation-current technology	million USD		--	130
Second generation - future technology	million USD		--	
Total investment costs	**million USD**	**160.2**	**199**	**318**

Note: The biorefinery has a procesing capacity of 500 tons of sugarcane per hour (wet basis), equivalent to 2 million tonne of sugarcane per year. This size represents the average capacity of existing mills in Bolivia. Operational and Maintenance fixed costs split in working capital, start-up costs and spare parts and are considered to be 5%, 3% and 1% of the annualized investment cost respectively. For second generation technologies enzyme price is assumed to be 0.1 US$/l of lignocellulosic ethanol produced.

[a] Costs are adopted from (Dias et al. 2011) for a sugarcane processing capacity of 2 million tonne of sugarcane per year.

[b] Costs are adopted from (Dias et al. 2013) for a sugarcane processing capacity of 2 million tonne of sugarcane per year.

[c] Costs are adopted from (Khatiwada, Leduc, et al. 2016)

9.5.4 Residual Capacity

Residual capacity for sugarcane mills and destilation units are presented in **Tables A.21** and **A.22** respectively. The capacity existing in 2013 is introduced as residual capacity and the additional investments between 2013-2019 are introduced as commited projects (forced investments to represent existing capacity expansions).

Table-A. 21 Sugarcane milling and sugar refinery capacity in Bolivia in 2019

Sugarmill	**Location**	**Region**	**Mill Capacity, 10^3 tonne/day**	**Milling days/year**	**First year in Operation**	**Refurbishment/ expansion**	**Estimated miling production per year, 10^6 tonne**	**Estimated sugar production capacity, 10^6 tonne**
Roberto Barbery	Santa Cruz	12	24	165	1977	2017	3.96	0.46
Guabirá	Santa Cruz	12	18	165	1956	2015	2.97	0.35
Aguaí	Santa Cruz	11	12	165	2013	--	1.98	0.23
San Aurelio	Santa Cruz	11	12	165	1951	2000	1.98	0.23

La Belgica	Santa Cruz	12	6,5	165	1592	2003	1.0725	0.13
Bermejo	Tarija	7	4.5	165	1968	2007	0.7425	0.09
San Buenaventura	La Paz	24	7	165	2015	--	1.155	0.13
Total			84				13.86	1.62

Table-A. 22 Destilation capacity in Bolivia in 2019

Destilery	Location	Region	Destilation Capacity, 10^6 liters/day	Ethanol	Main feedstock
Roberto Barbery	Santa Cruz	15	0.18	Hydrous	Molasses
Guabirá	Santa Cruz	15	0.5	Hydrous	Molasses
Guabira	Santa Cruz	15	1.1	Anhydrous	Cane juice
Aguaí	Santa Cruz	14	0.75	Anhydrous	Cane juice
San Aurelio	Santa Cruz	14	0.09	Hydrous	Molasses
Bermejo	Tarija	10	0.15	Hydrous	Molasses
San Buenaventura	La Paz	32	0.1	Hydrous	Molasses
Santa Cecilia	Santa Cruz	15	0.02	Hydrous	Molasses
Total			2.89		

9.6 Demand projections

This section details the methods used to project exogenously-defined demands. **Table A.23** summarises the projections drivers and which demand components are endogenously calculated in the model.

Table-A. 23. Assumptions for demand projections

Sector	Demand	Projections drivers:	Endogenously/Exogenously calculated
Water	Water for residential consumption	Water consumption per capita, population growth	Exogenous
	Water for livestock consumption	Water consumption per cattle head, cattle population growth	Exogenous
	Water for agricultural irrigation	--	Endogenous
Agriculture	Agricultural land Sugarcane	--	Endogenous
	Rest of agricultural land	Linear projection of historical data of total agricultural land	Exogenous
	Pasture land for livestock	Livestock population growth	Exogenous
Energy	Gasoline	Gasoline consumption per distance travelled, transport demands, stock of vehicles.	Exogenous
	Diesel	Gasoline consumption per distance travelled, transport demands, stock of vehicles.	Exogenous
	CNG	Gasoline consumption per distance travelled, transport demands, stock of vehicles.	Exogenous
	Ethanol Anhydrous	Production targets	Exogenous
	Ethanol Hydrous	--	Endogenous
	Electricity demand	Multiple drivers	Exogenous
	Electricity for irrigation	Cultivated area	Endogenous
Others	Sugar	Population growth	Exogenous

9.6.1 Energy demand for the transport sector

Using a bottom-up approach detailed in (Peña Balderrama et al. 2017), energy demands are allocated to the main components of the road transport sector for a given base year (2013). Projections to 2030 are generated using top-down drivers (population and GDP projections). **Figure A.5** illustrates the demand components of the transport model by type of vehicle and fuel. Two demand scenarios are modelled based on different assumptions of GDP growth as detailed in **Section** Error! Reference source not found..

The vehicle fleet of private cars was projected using the projections of vehicle ownership (vehicles per capita) multiplied by population projections. The mathematical formulation of (Joyce Dargay 2007) was used to project vehicle ownership using a Gompertz saturation function using GDP growth as the predictor. For public transport of passengers and freight transport, the historical demand of passenger-km (pkm) and tonne-km (tkm) are calculated, adding the pkm and tkm of all transport modalities. For each transport modality the pkm/or tkm is calculated by multiplying the stock, the average number of passengers/or tons in each travel and average annual distance travelled. Projections for pkm and tkm were generated using a simple autoregressive model using GDP growth as a predictor. Fuel switch targets were introduced following government targets of gasoline and diesel engine retrofits to CNG.

Results from the energy demand projections indicate Bolivia's transport sector energy demand grows at an average annual rate of 2.7% in the baseline scenario and 3.1% in the alternative scenario for the period 2013-2030. If no biofuel blending targets are introduced, the demand of gasoline demand grows at an average rate of 3.1% in the base scenario (reaching 74 PJ in 2030) and at an average rate of 3.33% in the alternative scenarios (reaching 77 PJ in 2030). By 2025, the introduction of the contracted ethanol volumes and ethanol blending (25% v/v) replace 64% and 51% of pure gasoline in the Baseline and Alternative scenario, respectively (See **Figure.a**.).

To completely substitute the demand of pure gasoline with E25 by 2030, the demand of ethanol anhydrous increases from 8.5 PJ in 2025 to 14 PJ in 2030 for the Baseline scenario and 24 PJ in 2030 for the Alternative scenario. The share of ethanol anhydrous in the total energy demand of the transport sector is 7% in the baseline and 11% in the alternative scenario in 2030. Accumulated savings of avoided gasoline imports in the period 2018-2030 account for 2.1 billion US$ in the baseline scenario and 2.78 billion US$ in the alternative scenario (considering baseline scenario projections of gasoline market prices, see **Figure.b**).

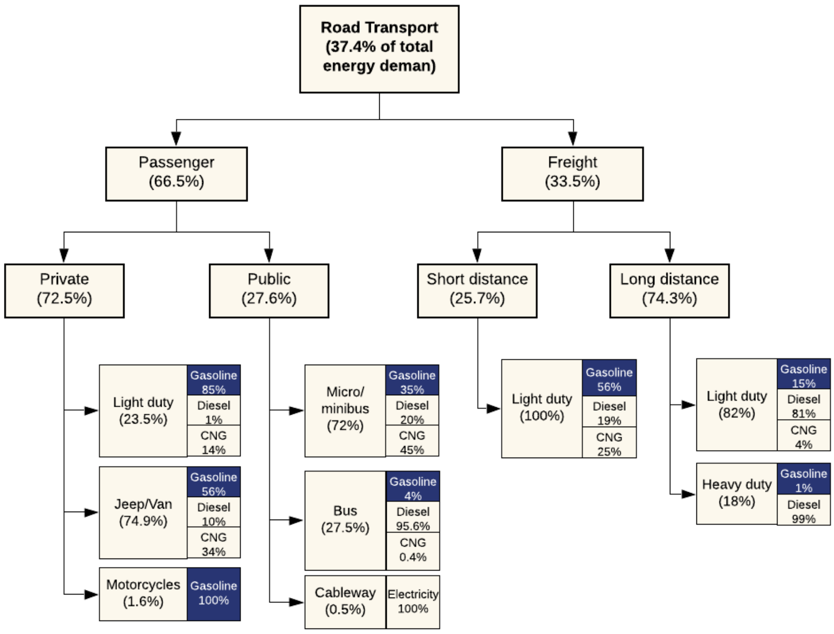

Figure A.5. Representation of the transport model for energy demand. In brackets, the share of energy demand in every branch. HIghlighted in blue where ethanol blending is applied

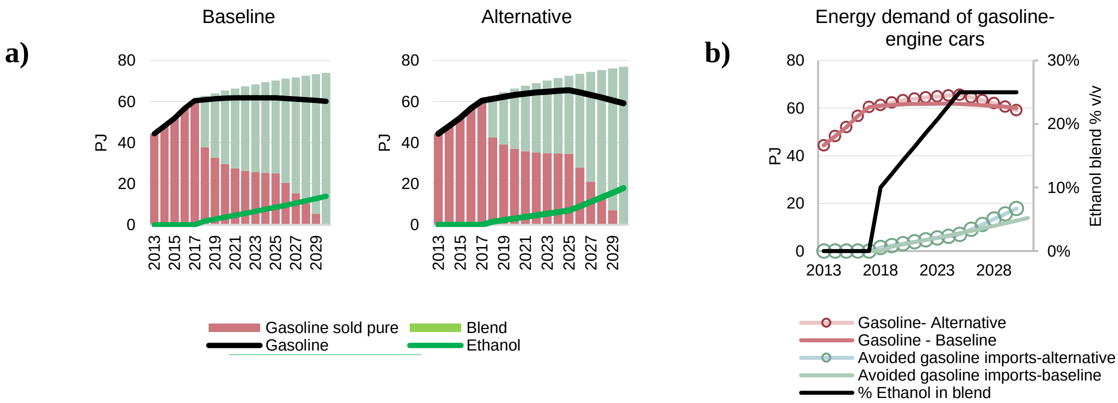

Figure A.6. a) Energy demand projectionsin the transport sector by fuel type for the Baseline and Alternative Scenario. b) Comparison of gasoline demand and avoided gasoline import.

9.6.2 Water and land demand for cattle ranching

Table A.24 shows the data assumptions used to project land and water demands for cattle ranching. The departments of Beni, Santa Cruz and Tarija produce the 85% of the cattle in Bolivia (INE 2020) and each has different historical growth rates on cattle population and land requirements. Historical data of cattle population from 2005-2017 was used to project linearly the cattle headcount to 2030. According to (MDRyT 2012), 90% of all cattle feeding in Bolivia is extensive, with land-use requirements comparably larger than production systems under intensified pastures (0.3-0.14 ha/head) (Vale et al. 2019; zu Ermgassen et al. 2018). Specific cattle population growth rates and land requirements were used for regions in the departments of Beni, Santa Cruz and Tarija. For the rest of the country, average values of cattle ranching in the other 6 departments of Bolivia were used.

Table-A. 24. Assumptions on Land-use and Water consumption

Departmento	Regions	Land-use, ha/head[a]	Water use, L/day[b]	Cattle population in millions				
				2013	2015	2020	2025	2030
Beni	13, 14, 24, 25	1.57		3.740	3.872	4.244	4.605	4.966
Santa cruz	2,4,9,10,11,12	1.33		2.735	2.831	3.100	3.360	3.620
Tarija	5,7	0.61	66.2	0.888	0.919	0.962	0.971	0.981
Rest of Bolivia	1,3,6,8,15,16,17,18,19, 20,21,22,23,25,26,27	1.03		1.279	1.325	1.423	1.498	1.573

[a] Based on historical cattle head-count data and cattle grassland feeding area at departmental level from (INE 2020)

[b] Average water consumption between cattle less than 2 years (92 liters per day) and cattle older than 2 years (46 liter/day)

9.6.3 Other demand projections

Agricultural area for other crops apart from sugarcane were aggregated into a single cathegory in every region and projected to expand following the average agricultural growth rate at national-level. Water demand for residential consumption was projected in every region using water consumption per capita ratios specific to each municipality multiplied by population. Official population growth projections to 2030 were obtained from (Instituto Nacional de Estadística 2018).

9.7 Potential yields and yield gap

Actual or observed yields in a given region are inevitably smaller than their theoretically potential yields. Achieving the potential yields requires near-perfect management conditions of soil and crop factors influencing the plant growth and development throughout the growing cycle (Lobell et al. 2009). Yield gaps are the difference between the theoretical potential yield and actual yields that can be expressed as a percentage difference of the potential yield (M van Ittersum et al. 1997). The yield gap concept, however, depends on the definition and measurement of the yield potential (Lobell et al. 2009).

Van Ittersum et al. show in a methodological review 11 published studies at global-level estimating geospatially-explicit potential yields and yield gaps using empirical, statistical and crop-growth simulation approaches (Martin van Ittersum et al. 2013). They conclude that simulation models allow the most reliable estimation of potential yields providing the means to capture spatial and temporal variations of weather, soils, water regime management and other yield-limiting or yield-reducing factors. Among these models, we use results from the GAEZ model.

In the GAEZ model, climatic data and soil moisture conditions are used together with agroclimatic yield-reducing factors to estimate agro-climatically attainable yields. The yield-reducing factors, vary with crop type, climate (soil and terrain conditions) and depend on assumptions regarding level of inputs/management (Fischer et al. 2012). **Table-A. 25** presents the five agro-climatic constraint factors used in the GAEZ model and **Equation A.8** shows the way these are combined.

Table-A. 25 Agro-climatic constraints from the GAEZ model. (Fischer et al. 2012)

Agroclimatic yield-reducing factors	Description
a	Long-term limitation to crop performance due to year-to-year rainfall variability
b	Pests, diseases and weeds damage on the plant growth
c	Pests, diseases and weeds damage on the quality of produce
d	Climatic factors affecting the efficiency of farming operations
e	Frost hazards

$$f_{combined} = \min\left\{ \begin{matrix} (1-f_a)\cdot\ (1-f_b)\cdot(1-f_c)\cdot(1-f_d) \\ 1-f_e \end{matrix} \right\}$$ **Equation. A.8**

Due to the GAEZ input-level classification may not represent the actual yields in all the sugarcane farms classified in each cathegory, differences between actual yields and agro-climatically attainable yields were accounted using the yield gap concept. A simple approach was used to estimate the yield gap factor as its shown in **Equation A.9**. To adjust the yields in every region, the averaged agro-climatically attainable yields for all input levels were multiplied by the yield gap factor *f*. Note that with this simplified approach we assume a yield gap that applies equally to all regions. This assumption may be imprecise as some regions may have larger yield gaps than others. Restrictions in data availability and inaccuracies found at microdata-level of area and production reported in the Census lead us to use this assumption.

$$f = \frac{Total\ production}{\sum_i^{i=27} \begin{pmatrix} A_{i,HIr}\cdot y_{i,HIr} + A_{i,IIr}\cdot y_{i,IIr} + A_{i,LIr}\cdot y_{i,LIr} \\ +A_{i,HR}\cdot y_{i,HR} + A_{i,IR}\cdot y_{i,IR} + A_{i,LR}\cdot y_{LR} \end{pmatrix}} = 0.871$$ **Equation A.9**

Where *i* represents the region, *A* is the area in hectares, *y* is the yield in ton per hectare, *H* is high-inputs, *I* is intermediate inputs, *L* is low-inputs, *Ir* is irrigates and *R* is rainfed. **Figure** illustrates the differences in yields for each agriculture management level.

9.7.1 The GAEZ model

The Global Agro-Ecological Zones, GAEZ, project was developed by IIASA and released its first global assessment in 2000. The latest version (GAEZ 3.0) has been released with a data portal in partnership with FAO in 2012. The version 3.0 provides a major update of data and extension of the methodology compared to the earlier version. The model employs simple and robust crop models and provides standardized crop-modeling and environmental matching procedure to identify crop-specific limitations of prevailing climate, soil, and terrain resources under assumed levels of input and managements conditions (Fischer et al. 2012). The main components of the GAEZ methodology are presented in **Figure A.6**. **Figure A.7** shows the differences of the averaged potential yields (adjusted by the yield factor) between the 27 regions modelled.

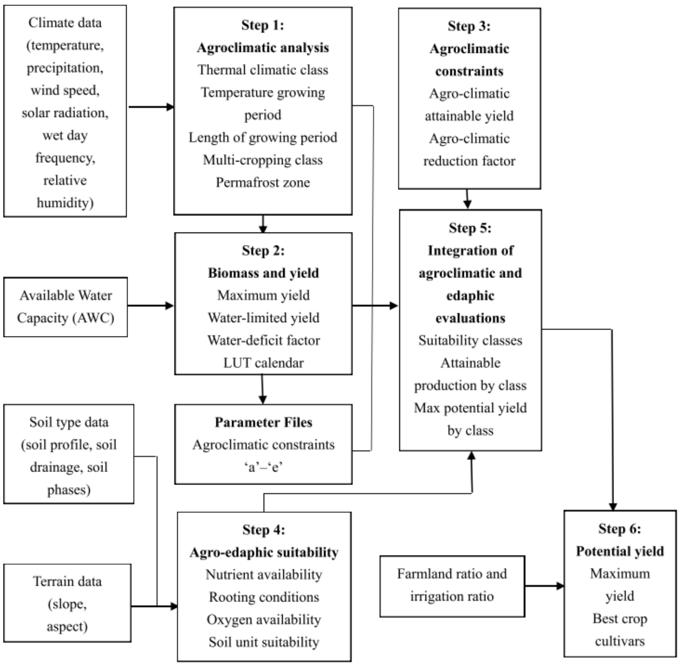

Figure A.6. Representation of the transport model for energy demand. In brackets, the share of energy demand in every branch. HIghlighted in blue where ethanol

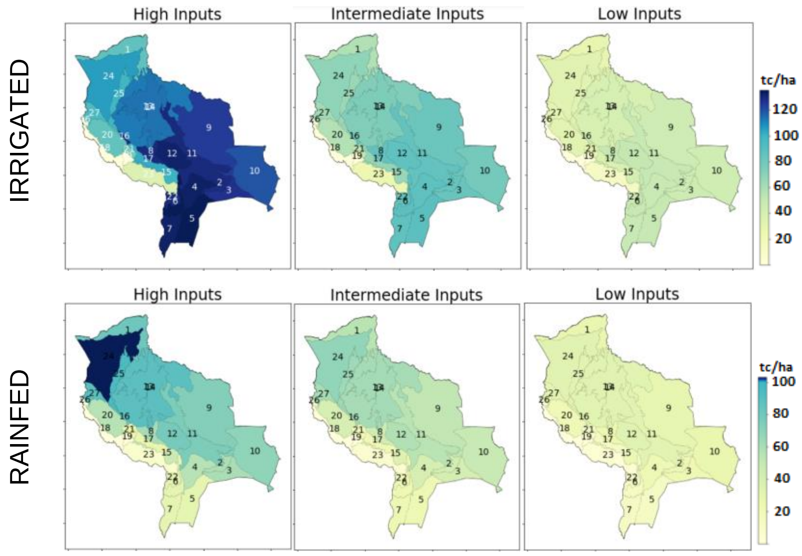

Figure A.7. Averaged agroclimatic sugarcane yields for rainfed and irrigated conditions under high, intermediate and low inputs in tonne/ha. Based on data results from the GAEZ project (Fischer et al. 2012)**. The charts below show superimosed agroclimatic yields in descendend order.**

Table-A. 26. Average potential yields and area in 2013 for each region modelled

	Area, ha							Yield, ton/ha					
Region	**HI**	**II**	**LI**	**HR**	**IR**	**LR**	**tot**	**HI**	**II**	**LI**	**HR**	**IR**	**LR**
1	0	17	0	0	160	34	**211**	76.1	50.1	28.5	71.2	47.5	27.0
2	0	0	0	0	0	0	**0**	112.4	74.0	45.4	51.1	36.5	22.4
3	0	0	0	0	0	0	**0**	111.0	73.1	46.1	51.8	36.5	23.0
4	0	5	1	0	7	0	**14**	116.1	76.4	48.7	48.9	34.4	22.1
5	1	2	0	3	68	2	**76**	117.8	77.5	49.4	26.6	19.4	12.7
6	0	4	0	80	284	2	**371**	117.8	77.5	49.5	26.5	20.2	14.8
7	136	410	0	1701	7234	2	**9482**	115.5	76.0	48.5	25.9	20.1	12.5

8	0	3	0	0	10	1	**13**	112.8	74.2	50.1	52.4	37.9	25.3
9	0	26	1	0	553	119	**699**	108.7	71.5	46.1	63.8	44.9	28.9
10	0	18	1	0	486	21	**526**	103.9	68.4	44.1	60.1	42.4	27.3
11	78	183	0	2020	5217	12	**7511**	112.8	74.2	49.7	65.6	47.3	31.6
12	1244	2880	0	36380	88776	3	**129283**	115.4	75.9	50.7	67.7	50.1	33.4
13	0	13	2	0	218	32	**265**	97.9	64.4	38.7	77.5	53.5	32.1
14	0	36	1	0	376	29	**442**	99.4	65.4	40.4	77.0	53.9	33.4
15	0	3	0	1	19	0	**23**	87.3	57.4	41.7	41.0	30.6	22.2
16	0	0	0	0	0	0	**0**	113.7	74.8	47.6	74.7	53.5	34.1
17	0	4	0	0	6	1	**10**	89.3	58.7	37.5	24.3	18.0	13.3
18	0	0	0	0	0	0	**0**	0.0	0.0	0.0	0.0	0.0	0.0
19	0	0	0	0	0	0	**0**	0.0	0.0	0.0	0.0	0.0	0.0
20	1	7	3	0	156	37	**202**	75.2	49.5	31.3	48.7	34.4	21.8
21	0	0	0	0	0	0	**0**	68.5	45.1	29.2	24.2	17.2	11.1
22	0	2	0	0	20	0	**23**	113.4	74.6	47.6	26.1	17.8	12.7
23	8	173	1	70	364	2	**618**	31.4	20.6	13.2	6.3	4.9	3.8
24	0	12	7	0	384	57	**460**	92.0	60.5	34.0	89.6	59.5	33.4
25	0	0	0	0	26	8	**34**	86.7	57.1	32.4	82.4	55.4	31.5
26	0	0	0	0	0	0	**0**	0.0	0.0	0.0	0.0	0.0	0.0
27	0	2	1	0	48	28	**79**	82.4	54.2	30.8	78.2	52.7	29.9

9.8 OSeMOSYS model formulation

The Open Source Energy Modelling Systems (OSeMOSYS) is an open-source modelling tool that uses linear and mixed-integer linear programming (LP and MILP) methods. The objective function is to minimize the present value of expanding and operating the energy system to meet exogenously defined demands (Howells et al. 2011). A set of constraints are defined to represent real-world restrictions such as energy resources availability, load demand profiles, environmental targets, investment limitations, activity or capacity of processes, availability and price of fuels, market penetration of new technologies, among other posibilities. A detailed description of the model can be found in (Howells et al. 2011).

The model is driven by exogenously defined demands for commodities/services (e.g. electricity, water for domestic use, agricultural products). These can be met through a range of conversion technologies which draw on a set of resources defined by their potential and costs. Each technology is characterized by economic, technical and environmental parameters, for example, capital investment and operational costs, conversion efficiencies and emissions intensities.

The objective function of the model is presented in **Equation A.10**. The NPV of the system is composed of the discounted costs incurred by each technology, in each year and each region modelled. The costs associated to technologies include operating costs (fixed and variable), investment costs, emission and salvage value costs. Each cost is discounted to its present value, given a discount rate. Emission penalties are subject to an exogenously defined emission price. The salvage value is the cost of a technology invested during the model period, which still has operational life at the end of the modelling period. See the complete model in Howells *et al.* (Howells et al. 2011).

$$Minimize \sum_{r}^{R}\sum_{t}^{T}\sum_{y=2013}^{y=2050}\begin{bmatrix}Discounted\\Investment\\Cost\end{bmatrix}_{y,t,r}+\begin{bmatrix}Discounted\\Operating\\Variable\ Cost\end{bmatrix}_{y,t,r}+\begin{bmatrix}Discounted\\Operating\\Fixed\ Cost\end{bmatrix}_{y,t,r}+\begin{bmatrix}Discounted\\Emisssions\\Penalty\ by\\Technology\end{bmatrix}_{y,t,r}$$

$$+\begin{bmatrix}Discounted\\Emisssions\\Penalty\ by\\Technology\end{bmatrix}_{y,t,r}-\begin{bmatrix}Discounted\\Salvage\\Value\end{bmatrix}_{y,t,r}$$

Equation A.10

Subject to linear energy balances, linear activity and capacity constraints with the form:

$$Production_{r,t,y,l,m} = Demand_{r,y,l,m}$$

Equation A.11

$$f(x_{r,t,y,l,m}) \geq 0$$

Where *r* represents each region of the total *R* regions of the model; *t* represent each technology in the energy system with a total of *T* technologies, *y*, each year of the model and *DR* the discount rate or the model.

9.9 CLEWs model in detail

Table A.27 details the nexus interactions modelled.

Table-A. 27. Nexus interactions modelled

	Land-use	Energy	Water
Land-use		Diesel is consumed in agriculture machinery and production processess..	Water increases crop yields, therefore increases the productivity of land-use for sugarcane production
Energy	Land-use is required for sugarcane production, which is then converted into energy products (ethanol and electricity).		Water is used in biorefineries to produce ethanol.
Water	--	Electricity use for water pumping for agricultural irrigation, livestock and domestic water demands.	
Climate	*	Carbon emissions released by fossil fuels.	Green, blue and gray water footprint

* Indirected land-use emission from land-use change were not estimated in our analysis.

9.9.1 Modelling land-use change

The land-use model consists of 27 regions which zonation are described in **Section 9.1**. Each region aggregates nine classified land-cover types. The land-cover map for 2015 from the European Space Agency at 300m resolution was geo-processed together with the maps of forest and protected areas at 30m resolution from the Ministry of Water and Environment of Bolivia to create a map with nine aggregated land-cover types (ESA 2017; GeoBolivia 2017). Forest, protected forest, grasslands, protected grasslands, cropland, cultivated pastures, barren, settlements, and water bodies were classified. In each region, the cropland area was adjusted using data from the National Agricultural Census (Instituto Nacional de Estadistica 2015; GeoBolivia 2019b). Pastoral activities of cattle farming are also considered due to their extensive farming characteristics (large land requirements). The pasture area is estimated in every region using geospatial data of cattle stocks and an average size of grazing areas.

In the land-use model, sugarcane agriculture is separated from the rest of the agricultural products. The model determines the least-cost combination of agriculture intensification and extensification possibilities to supply increasing demands of sugarcane. In turn, the area for the rest of agriculture and for cultivated pastures are projected linearly in every region using average growth rates deriving from historical data of national cattle stocks and cropland, respectively. Land-use conversion possibilities are illustrated in Figure. In the model, grasslands can be converted into cropland or pasture land with priority over forest land, if no grassland area is available, then forest land is converted into grassland. Protected areas of forest and grasslands are introduced into the model as constraints representing the minimum area of forest and grassland to be preserved.

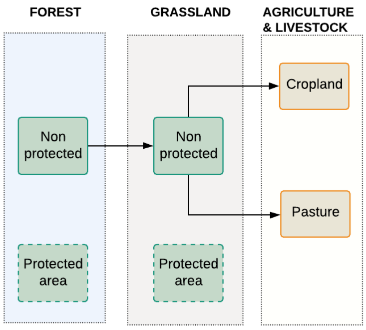

Figure A.8. Forest, grassland and cropland land-use change posibilities

9.9.2 Water balance model

The representation of the water system use results from the recently published Water Balance of Bolivia (WBB) (Ministerio de Medio Ambiente y Agua (MMAyA) 2017). The WBB is an hydrogeological and water systems model developed using the Water Evaluation and Planning System software, WEAP. Released in 2017, the WBB is the first national effort unifying hydrometric, meteorological, land-use and satellite-based data with climate models to estimate water balances and and perform validations in each hydrological unit. The model has monthly time resolution and uses data from 1980 to 2016.

The water balance use the “two bucket” soil moisture accounting method from WEAP. This method models the impact of vegetation and soil type in the hydrological process. Due intrinsic characteristics of each macro-basin, additional methods were used to represent hydrological processes not included in the soil moisture method. In the Altiplano basin, the water inflows and outflows from two main lakes (Titicaca and Poopó) were modelled to represent their volumetric annual variability. In the Amazon macro-basin, dynamics of temporary flood lagoons were represented (Ministerio de Medio Ambiente y Agua (MMAyA) 2017). The components from the soil moisture method are illustrated in **Figure A.9**.

The water balance is specific for each land cover type. The water balance for each region was calculated by overlaying the water inflows and outflows of the basins contained. The components represented in our model are precipitation, evapotranspiration, ground water recharge and run-off water. For simplicity, the surface runoff , interflow, base flow and river flood inflow were aggregated into the run-off water flow.

The water balance was introduced as Input and Output Activity Ratios (IAR and OAR) to each mode of operation representing each land-use type. The activity unit of each land-use technology (representing each of the 27 regions) was expressed in area units (thousand km2). Therefore the IAR and OAR were expressed in units of water (annual flows) per area (billion m3/thousand km2).

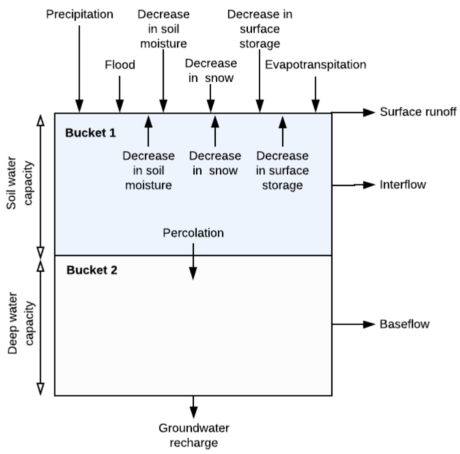

Figure A.9. Soil moisture method components

9.10 Sensitivity Scenarios

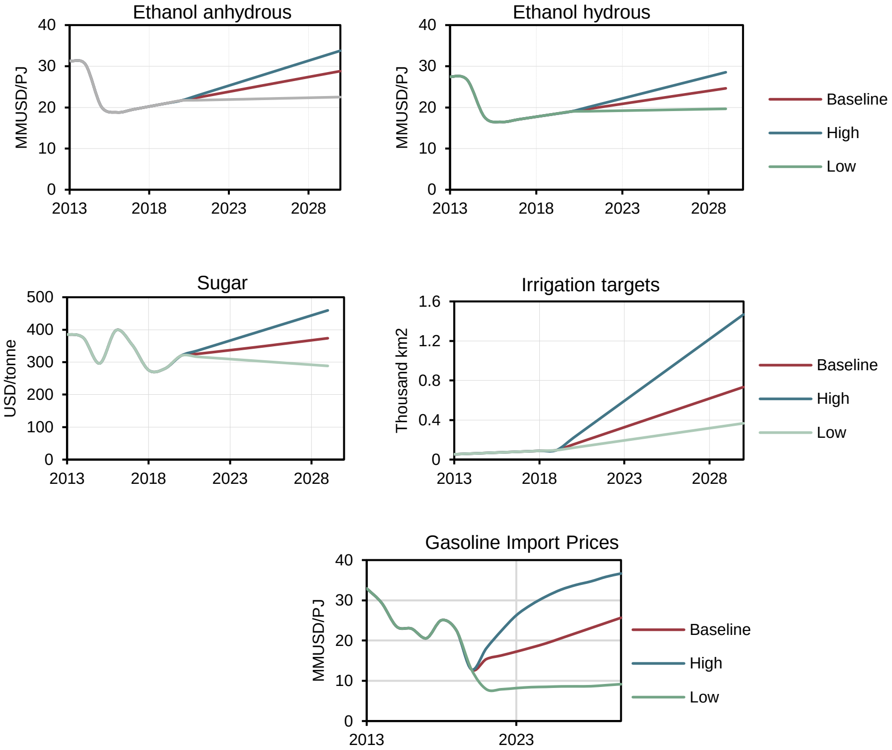

Figure A.10. Scenarios for selected parameters. Projections of crude Oil prices to 2030 are taken from the World Bank, while international prices of hydrous ethanol, anhydrous ethanol and sugar are taken from FAO. (OECD-FAO 2017; World Bank 2020)

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