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SUGARCANE BIOENERGY IN SOUTHERN AFRICA
Economic potential for sustainable scale-up

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ABBREVIATIONS

1G	First generation
2G	Second generation
AdX	Açucar de Xinavane (sugar company)
BRL	Brazilian real
cm	Centimetre
CO_2	Carbon dioxide
CTBE	Brazilian Bioethanol Science and Technology Laboratory
FAO	Food and Agriculture Organization of the United Nations
GAEZ	Global Agro-Ecological Zones
GHG	Greenhouse gases
GIS	Geographic Information System
GJ	Gigajoule
GWh	Gigawatt-hour
ha	Hectare
IIASA	International Institute for Applied Systems Analysis
K	Potassium
kg	Kilogram
kha	Kilohectare
kL	Kilolitre
km	Kilometre
kt	Kilotonne
kWh	Kilowatt-hour
L	Litre
L/t	Litre per tonne
m	Metre
Mha	Million hectares
ML	Million litres
mm	Millimetre
MS	Moderately suitable soil quality
Mt	Million tonnes
MWh	Megawatt-hour
N	Nitrogen
O&M	Operating and maintenance
P	Phosphorous
ppm	Parts per million
km^2	Square kilometre
m^3	Cubic metre
S	Suitable soil quality
SADC	Southern Africa Development Community
SHF	Separated hydrolysis from fermentation
t/ha	Tonnes per hectare
TWh	Terawatt-hour
USD	US dollar
VS	Very suitable (soil quality)

EXECUTIVE SUMMARY

Substantial potential exists to scale up sustainable production of bioenergy from sugarcane cultivation in southern Africa. This study evaluates the potential for seven sugar-producing countries in the Southern Africa Development Community (SADC): Eswatini (formerly Swaziland), Malawi, Mozambique, South Africa, the United Republic of Tanzania, Zambia and Zimbabwe. The potential for both liquid biofuel and electricity production is evaluated, as surplus to current and projected sugar demand for domestic consumption and export.

Sugarcane is currently grown on some 554 000 hectares of land in the seven countries studied. If yields were improved and all the sugarcane surplus to sugar requirements were converted to bioenergy, some 1.4 billion litres of ethanol could be produced at an average cost of USD 0.71 (71 USD cents) per litre of gasoline equivalent. But only a very small portion of this, about 5 % – coming from molasses by-products of sugar production – would compete with gasoline at a world crude oil price of USD 50 per barrel, close to prices in recent years.

This study evaluates the potential for seven Southern African countries to convert surplus sugarcane into sustainable biofuel and electricity

Prospectively, sugarcane cultivation could expand as much as nine-fold, to some 5.1 million hectares (Mha) of rainfed land without irrigation, or 99-fold, to some 54.9 Mha of land if irrigation were introduced. If irrigation were introduced to only the 3.7 Mha of very suitable land, implying overall expansion to 8.8 Mha of rainfed and irrigated land, bioenergy output could expand to some 72 billion litres of ethanol and 156 terawatt-hours (TWh) of electricity per annum.

Most of the ethanol could compete with gasoline at a crude oil price below USD 90 per barrel, close to midcase projections by the US Energy Information Administration for 2030 (EIA, 2018); the electricity would cost around USD 0.062 per kilowatt-hour (kWh).

New technologies for sugarcane growth and conversion could further expand the bioenergy potential. Energy cane, with yields up to twice those of conventional sugarcane, offers one key technology vector. Second-generation conversion plants, which can produce ethanol not only from the sugar portion of the cane but also the straw, offer a second key technology vector.

These twin technology vectors, applied to all land suited to sugarcane cultivation, could further expand energy production to some 129 billion litres of ethanol manufacture and 159 TWh of electricity generation per annum. With crude oil prices towards the middle of a prospective range of USD 50 to USD 100 per barrel, most of the ethanol thus produced would be cost-competitive on an energy-equivalent basis. The electricity could be generated for as little as USD 0.054 per kWh.

1 INTRODUCTION

Sugarcane has been produced in Africa for centuries, but little has been used for biofuel. In seven countries of particular interest in southern Africa (Eswatini, Malawi, Mozambique, South Africa, United Republic of Tanzania, Zambia and Zimbabwe), over half a million hectares (Mha) of land were devoted to sugarcane production in 2010, yielding 35 million tonnes (Mt) of sugarcane, an average of 70.6 tonnes per hectare (t/ha). Yet only 4.1 million litres (ML) of ethanol were produced from this sugarcane (FAO, 2018; ISO, 2018). Potential sugarcane and energy production is much greater.

Sugarcane is a highly productive feedstock for bioenergy due its semi-perennial production cycle, which allows annual harvests and replanting at intervals of five years or more, and its high energy content. With conventional technology widely deployed, it can produce over 8 000 litres (L) of ethanol and 6.5 megawatt-hours (MWh) of electricity per hectare (ha) per year. With advanced technology, it can produce much more. Sugarcane ethanol can be cost-competitive and reduce greenhouse gas (GHG) emissions by up to 80 % compared to gasoline.

Sugarcane is one of the highest-yielding crops for producing biofuels, as shown in Table 1.1. It typically yields 38 t/ha, of which roughly onethird consists of sugars that can readily be converted to biofuels through conventional processes and twothirds consists of cellulose or residues that can be converted through more advanced processes. In southern Africa, as just noted, the yields are much higher, so the potential is even greater.

New varieties of “energy cane” offer the potential for still higher yields, allowing much more to be grown on existing sugar plantations without converting forests or grasslands to farming.

Table 1.1 Feedstock used for modern liquid biofuels production

FEEDSTOCK	TOTAL DRY BIOMASS (t/ha)	GRAIN OR SUGAR (t/ha)	EASY ACCESS BIOFUEL (GJ*/ha)	CELLULOSIC CONTENT (GJ/ha)	RESIDUE CONTENT (GJ/ha)	TOTAL ENERGY CONTENT (GJ/ha)
SUGARCANE (Brazil)	38.0	12.0	156.8	167.0	113.9	437.7
MAIZE (USA)	18.4	9.2	72.8	40.4	27.6	140.8
OIL PALM (Indonesia)	34.0	17.0	128.8	149.4	50.9	329.2

* GJ = gigajoule

Source: Souza (2015)

In view of the apparently large potential for bioenergy from sugarcane in southern Africa, the actual amount of land existing that could be suited to sugarcane production is interesting to explore. Also of interest are how much sugarcane could be produced on such land, which technologies can convert sugarcane to fuel and electricity most efficiently, how much bioenergy might be extracted from the sugarcane by using these technologies, and how much that bioenergy would cost.

The chapters that follow aim to tackle these questions, aiming to better inform investors and policy makers about options that may be available.

Chapter 2 assesses sugarcane production potential in the seven countries studied, based on the amount of suitable land available and the expected yield on this land per hectare. Three land-use categories are considered: land currently planted with sugarcane, land that could grow sugarcane well with natural rainfall (through "rainfed" agriculture), and land that can only grow sugarcane well if irrigated. In each case, account is taken of restrictions such as protected areas, land already occupied, topography, and soil quality. Yields are projected using an agro-climatic model considering fertiliser use, temperature and water availability.

Chapter 3 reviews technology pathways for converting sugarcane to bioenergy. First presented are the processes for the conventional production of ethanol (from sugarcane molasses and direct juice) and electricity generation (from sugarcane bagasse and straw). Two promising innovations, currently under development and already implemented in some countries, are then highlighted. One of these is for energy conversion: ethanol production from lignocellulosic hydrolysis (2G, or second-generation, processes). The other is for feedstock production: energy cane varieties with much higher yields than conventional sugarcane.

Chapter 4 estimates costs for producing sugarcane bioenergy in southern Africa. Costs for feedstock production and processing are separately assessed, based on production conditions and processing technologies described in the previous chapters.

Chapter 5 then develops supply curves for ethanol and electricity from sugarcane, based on the production potential and cost estimates derived. Six scenarios are considered for each country, hypothesising the progressive expansion of cultivated area from existing sugarcane fields to other suitable rainfed areas to drier areas that must be irrigated. The first two scenarios look at energy production from molasses produced in existing sugar mills from existing sugarcane cultivation, with and without improved sugarcane yields per hectare.

The next two scenarios look at energy production using conventional technology, with expansion of sugarcane culture to other suitable rainfed areas, with and without further expansion of sugarcane culture to areas requiring irrigation. The final two scenarios look at energy production with sugarcane culture on all suitable rainfed and irrigated land, with half of the sugarcane straw feeding integrated first-generation (1G) and 2G ethanol plants (as the other half is left in the field to protect and increase organic matter in soil), with and without the introduction of high-yield energy cane.

2 SUGARCANE PRODUCTION POTENTIAL IN SOUTHERN AFRICA

Evaluating a country's potential to produce bioenergy from sugarcane requires knowing how much land is available to grow the crop, as well as the yield per hectare that can be expected. This section assesses land availability and yields for sugarcane in countries of southern Africa.

2.1 LAND SUITABLE AND AVAILABLE FOR EXPANSION OF SUGARCANE PRODUCTION

The amount of land available for sugarcane cultivation, beyond the area already cultivated, can be assessed from a previous study of rainfed areas and analysis of potentially irrigated areas. The assessment should incorporate criteria to ensure sustainability, considering aspects such as protected areas, topography, and areas used to produce food and other products.

Land for rainfed sugarcane culture

A detailed assessment supported by Geographic Information Systems (GIS) images with 1 square kilometre (km2) resolution, developed by the project Cane Resources Network for Southern Africa CARENSA (SEI, 2018), evaluated the area for expanding sugarcane cultivation in southern African countries (Watson, 2011). South Africa and Eswatini were excluded because a previous assessment (Garland and Watson, 2003) indicated limited potential there.

The land potentially suitable for rainfed sugarcane was identified by the spectral signature of sugarcane and similar crops shown in GIS images. This potential land was then subjected to a set of successive sustainability constraints. To avoid impacts on biodiversity, all categories of protected areas, closed canopy forests and wetlands were excluded. To avoid harming food security, all areas under food and/or cash crop production were excluded. Areas unsuitable due to climate (annual rainfall lower than 800 millimetres [mm] and other climatic data), terrain slope (greater than 16 %) and soil quality constraints were also excluded. Irrigation was not considered, since the main objective was to estimate the area potentially available.

Based on this screening, 4.8 Mha of suitable land for sugarcane was found to be available in Eswatini, Malawi, Mozambique, South Africa, Tanzania, Zambia and Zimbabwe. That is similar to the area currently cultivated with sugarcane for ethanol production in Brazil. It equates to 2.0 % of agricultural land or 2.5 % of pasture land in these countries (FAO, 2018).

A detailed GIS assessment shows areas for expanded sugarcane cultivation

Table 2.1 Land cultivated (2015) and potential for rainfed sugarcane culture

COUNTRY	AREA CURRENTLY WITH SUGARCANE (A) (1 000 hectares)	AREA SUITABLE AND AVAILABLE FOR SUGARCANE (B) (1 000 hectares)	A/B (%)
ESWATINI	57	not evaluated	–
MALAWI	27	206	13 %
MOZAMBIQUE	45	2 338	2 %
SOUTH AFRICA	258	not evaluated	–
TANZANIA*	84	467	18 %
ZAMBIA	40	1 178	3 %
ZIMBABWE	43	620	7 %
TOTAL	**554**	**4 809**	**11 %**

* United Republic of Tanzania

Source: FAO (2018), Watson (2011)

Land for irrigated sugarcane culture

Despite a detailed assessment including field visits and interviews, Watson's study evaluated only rainfed sugarcane cultivation potential. However, the semi-arid climate of large areas in southern Africa also invites consideration about the amount of land available for sugarcane cultivation with irrigation. The Global Agro-Ecological Zoning (GAEZ) tool, developed by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA), can be used to do so. GAEZ provides a methodology and database for assessing agricultural resources and land suitability for agricultural production of 154 crops around the world, including sugarcane (FAO and IIASA, 2012a).

GAEZ was implemented with a GIS at 5 arcminute grid resolution (squares of roughly 9.3 kilometres [km] by 9.3 km), considering three levels of crop management (high, intermediate and low) as well as the water availability for both rainfed and irrigation systems. The land suitability was classified in five categories from "very suitable" to "not suitable" based on the comparison of agro-climatic yield with the maximum attainable yield. The suitability index was addressed by combining several factors, directly or indirectly related to climate, terrain and soil conditions (FAO and IIASA, 2012b).

GAEZ assessment of suitable land requiring irrigation was conducted assuming that sugarcane should be produced with good yields, so only areas with soils classified as VS (very suitable), S (suitable) and MS (moderately suitable) were selected. Areas shown by GAEZ as proper for rainfed sugarcane culture were not included. Suitable land for irrigated sugarcane was then evaluated in relation to its effective availability considering three screening factors: current land use, protected and forest areas, and topography.

The first screening excluded current cultivated crop area. This ensures estimated additional sugarcane production would not diminish the current level of agricultural production. Spatial data on harvested area was retrieved from the HarvestChoice (2015) platform based on the Spatial Production Allocation Model (SPAM), which had initially been developed by the International Food Policy Research Institute and the IIASA.

The second screening considered environmental sustainability in sugarcane production, excluding protected areas, forests and other use areas. Protected areas were found using the dataset compiled by GAEZ (FAO and IIASA, 2012a), based on WDPA 2009 (the World Database of Protected Areas annual release for 2009) (IUCN, 2018).

All protected areas, including areas with limited agricultural use, were excluded. Forests and land reserved for infrastructure and housing were excluded using land cover data compiled by GAEZ from FAO datasets such as GLC (Global Land Cover) 2000 and FRA (Forest Resource Assessment) 2000 and 2005. Use of GAEZ data ensured consistent grid resolution.

The third screening, for topography, focused on the need to protect the soil and reduce the risk of soil erosion. In the GAEZ analysis, terrain slopes over 16 % are evaluated as suitable for sugarcane cultivation, although at lower levels: 50 % suitability for a 16–30 % slope and 25 % for a 30–45 % slope. However, complying with Watson's study, all slopes over 16 % were filtered out in the present analysis.

Table 2.2 Existing and potential area for rainfed and irrigated sugarcane culture

COUNTRY	AREA NOW CULTIVATED WITH SUGARCANE (2005)	IRENA ANALYSIS BASED ON GAEZ			
		POTENTIAL RAINFED AREA	POTENTIAL AREA WITH IRRIGATION		
	(kha)	VS + S + MS (kha)	VS (kha)	VS + S (kha)	VS + S + MS (kha)
ESWATINI	51	–	–	–	–
MALAWI	21	4	–	63	456
MOZAMBIQUE	35	2 888	1 289	4 483	14 361
SOUTH AFRICA	324	57	603	2 591	9 374
TANZANIA*	19	1 694	138	1 688	8 067
ZAMBIA	23	–	1 286	3 009	12 491
ZIMBABWE	44	–	375	1 973	5 065
TOTAL	**518**	**4 643**	**3 691**	**13 807**	**49 814**

Obs. Soil quality: VS: very suitable, S: suitable, MS: moderately suitable, kha = Kilohectare

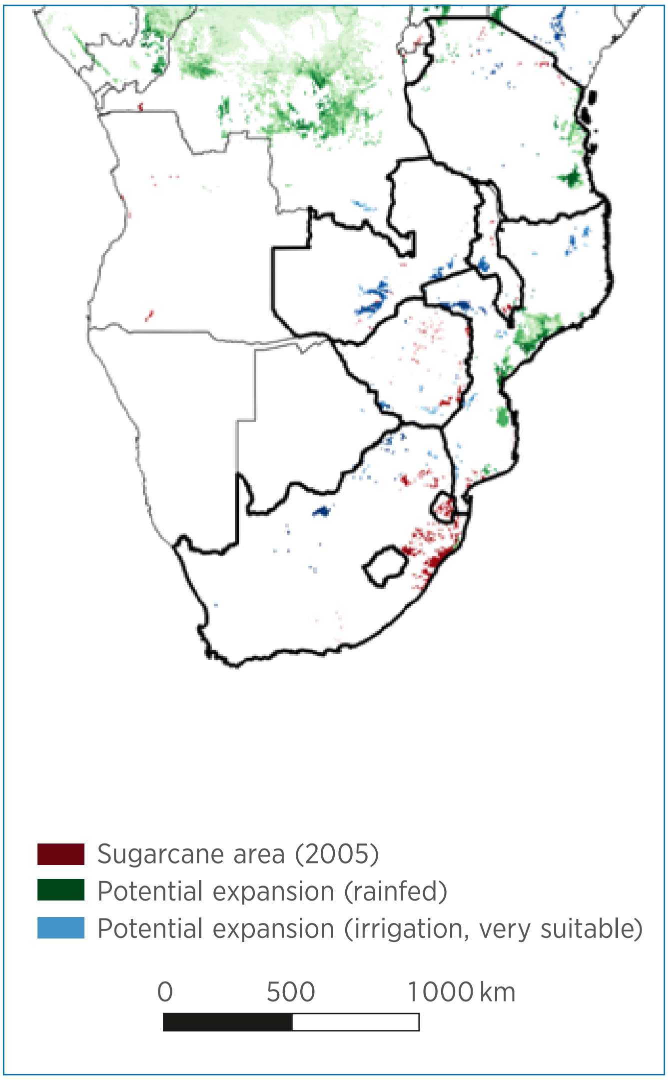
* United Republic of Tanzania

Source: GAEZ (FAO and IIASA, 2012a) and IRENA analysis

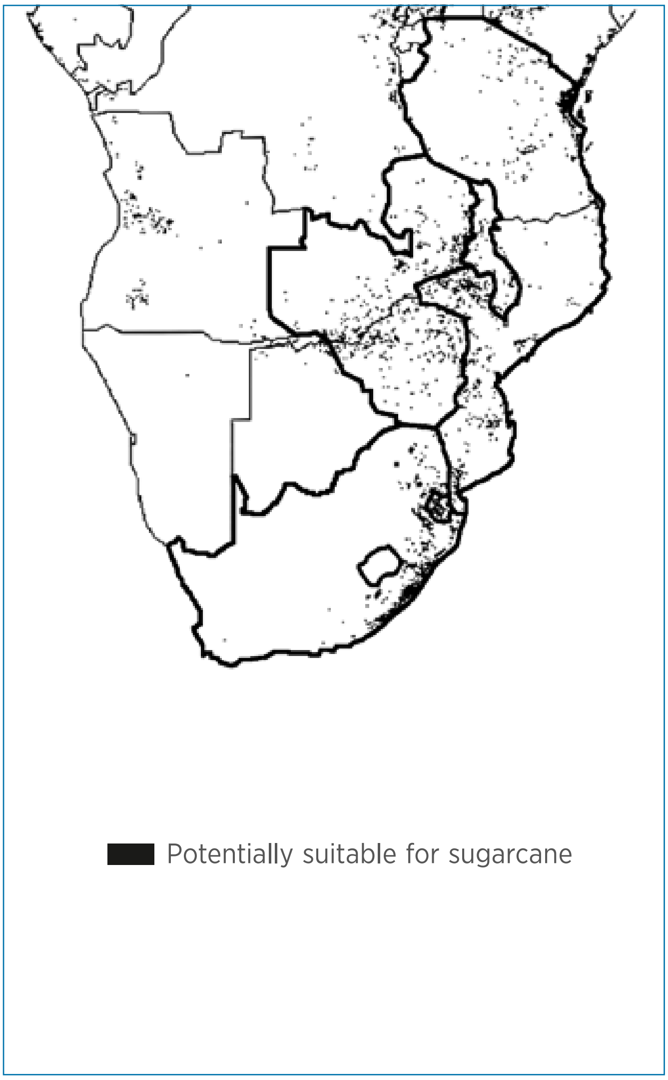
As Table 2.2 shows, some 54.9 Mha of land with good soil in the seven selected countries of southern Africa were found to be suitable and available for expansion of sugarcane cultivation. The table also shows the estimate of area for rainfed cultivation of sugarcane, roughly 5.1 Mha, which is comparable to Watson's (2011) assessment of 4.8 Mha, although significant differences can be observed at the country level, possibly due to differences in spatial resolution.

Compared with these potential areas for expansion, the 0.55 Mha currently occupied by sugarcane corresponds to just 11 % of rainfed area suitable and available as indicated by Watson (2011) and 1 % of area suitable and available for irrigated culture, considering all three levels of soil quality.

Figure 2.1 Potential sugarcane land



Based on IRENA analysis



Based on Watson (2011)

Disclaimer: Boundaries and names shown on these maps do not imply any official endorsement or acceptance by IRENA.

Summary of land suitable and available for sugarcane culture

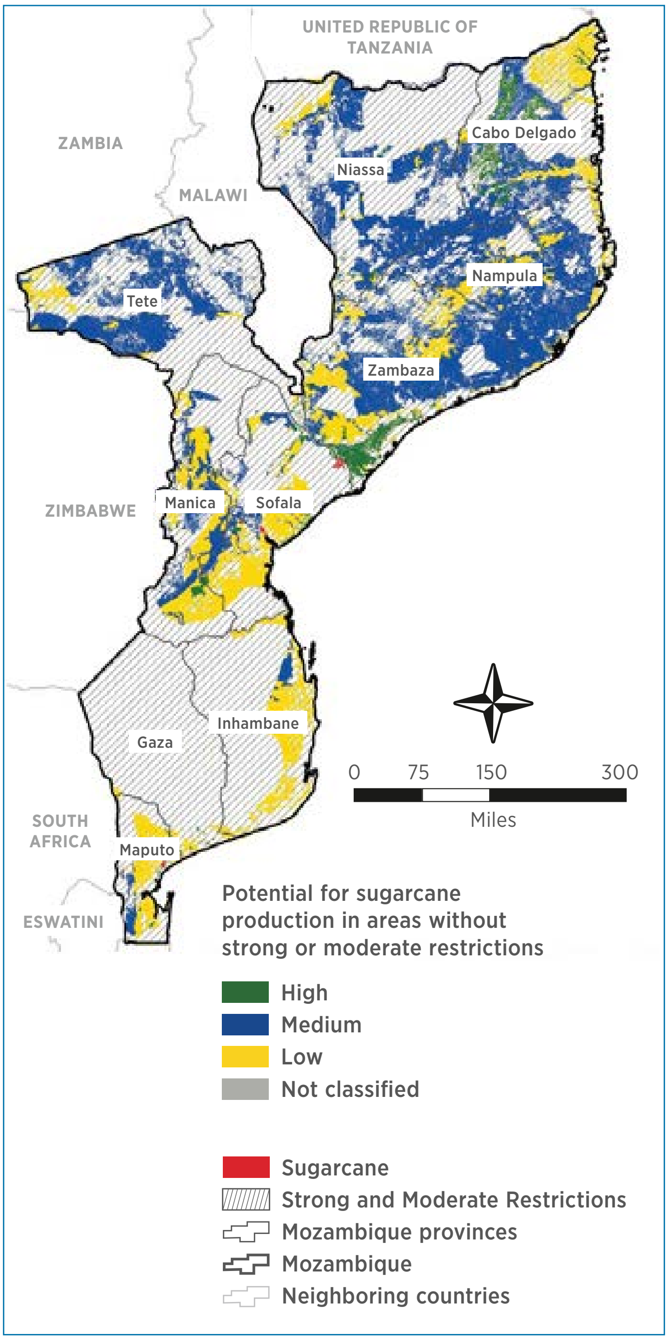
To fulfil the main objective of this study – to evaluate the potential for bioenergy production from sugarcane in selected countries of southern Africa – data obtained from Watson (2011) and GAEZ (FAO and IIASA, 2012a) provide a suitable foundation for rainfed and irrigated land, respectively. The data can be used to explore different technology and production profile scenarios. But possible constraints on irrigation due to limited water availability need also to be considered.

Yields for sugarcane depend directly on water availability. GAEZ assessment of irrigated land implicitly considers the constraints of minimum rainfall and water resources (FAO and IIASA, 2012b). But GAEZ works at an aggregated level, without considering local aspects and information. GIS-based assessment should be complemented by other methodologies, such as field evaluation, to assess biodiversity, rural livelihoods, and water resources availability and quality in detail.

The 50 Mha of area identified as suitable and available for irrigated sugarcane in southern Africa is 2.5 times the global area currently used to grow sugarcane. Thus, investment in irrigation can largely be assumed to focus on the best land available. The present study, therefore, considers only 3.7 Mha of "very suitable" land, 7.4 % of the area identified, for expansion beyond rainfed area through irrigation.

In line with the growing interest in developing modern bioenergy production and use in southern Africa, a recent study assessed the sugarcane potential of land in Mozambique. The potential was based on images from Landsat-7 and Landsat-8 satellites, complemented with soil data and local visits, evaluating land cover and land use in great detail, mapping potentially suitable areas in higher resolution (30 x 30 metres [m]), and producing maps as shown in Figure 2.2 (Moreira, Gomes and Costa, 2018).

Figure 2.2 Potential for sugarcane production in Mozambique



Source: Moreira, Gomes and Costa (2018)

Disclaimer: Boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

According to this study, 72 kha were planted with sugarcane in 2013. For expanding sugarcane land, considering climate and soil data, land was classified in three levels of productivity (high, medium and low). Land was also submitted to a screening, under strong and moderate restrictions. Strong restrictions included legal restrictions, used for other crops, slope greater than 12 %, and forested areas. Moderate restrictions included lack of rainfall, which can be remedied with irrigation, and medium productivity, which can be improved with fertilisation.

For rainfed sugarcane, this study identified 30.8 Mha without strong or moderate restrictions. Of this land, 1.6 Mha was found to have high productivity and 19.5 Mha medium productivity. For irrigated land, considering just strong restrictions, 57.4 Mha of land was identified, of which 2.8 Mha was found to have high productivity and 31.01 Mha medium productivity.

These impressive values, for Mozambique only, supported by a specific and very detailed assessment, are much higher than the estimates presented above. Therefore, bioenergy potential in other countries of southern Africa could also be much higher than estimated above. Table 2.3 summarises these conservative estimates of the area currently cultivated and the land suitable and available for expanding sugarcane culture in rainfed and irrigated areas to be adopted in the scenarios for evaluating sugarcane bioenergy supply curves in southern Africa.

Table 2.3 Existing and potential land use for rainfed and irrigated sugarcane culture (kha)

COUNTRY	LAND CURRENTLY WITH SUGARCANE (2015)	LAND EXPANSION POTENTIAL FOR RAINFED SUGARCANE	LAND EXPANSION POTENTIAL FOR IRRIGATED SUGARCANE
ESWATINI	57	–	–
MALAWI	27	176	–
MOZAMBIQUE	45	2 293	1 289
SOUTH AFRICA	258	–	603
TANZANIA*	84	383	138
ZAMBIA	40	1 138	1 286
ZIMBABWE	43	577	375
TOTAL	**554**	**4 570**	**3 691**

* United Republic of Tanzania

Sources: FAO (2018), Watson (2011), FAO, IIASA (2012a) and IRENA analysis

This assessment shows that land availability is not a major limiting factor for expansion of bioenergy production from sugarcane in Southern Africa. The amount of land suitable to and available for sugarcane production has been evaluated under conservative conditions. However, more detailed studies could help to define better energy planning targets.

Also, investment decisions should be backed by complementary studies, refining the GIS analysis and identifying even greater potential, as indicated above for Mozambique. The potential for expanding sugarcane in this region is significant. The rainfed expansion area alone would be able to produce an amount of ethanol equivalent to about 180 million barrels of oil annually.

The potential for expanding sugarcane cultivation in the region is significant

2.2 SUGARCANE YIELD ESTIMATING MODEL

To assess the potential for producing ethanol from sugarcane in a given context, data are needed on feedstock productivity and corresponding cost. These depend on several interrelated factors, as depicted in Figure 2.3:

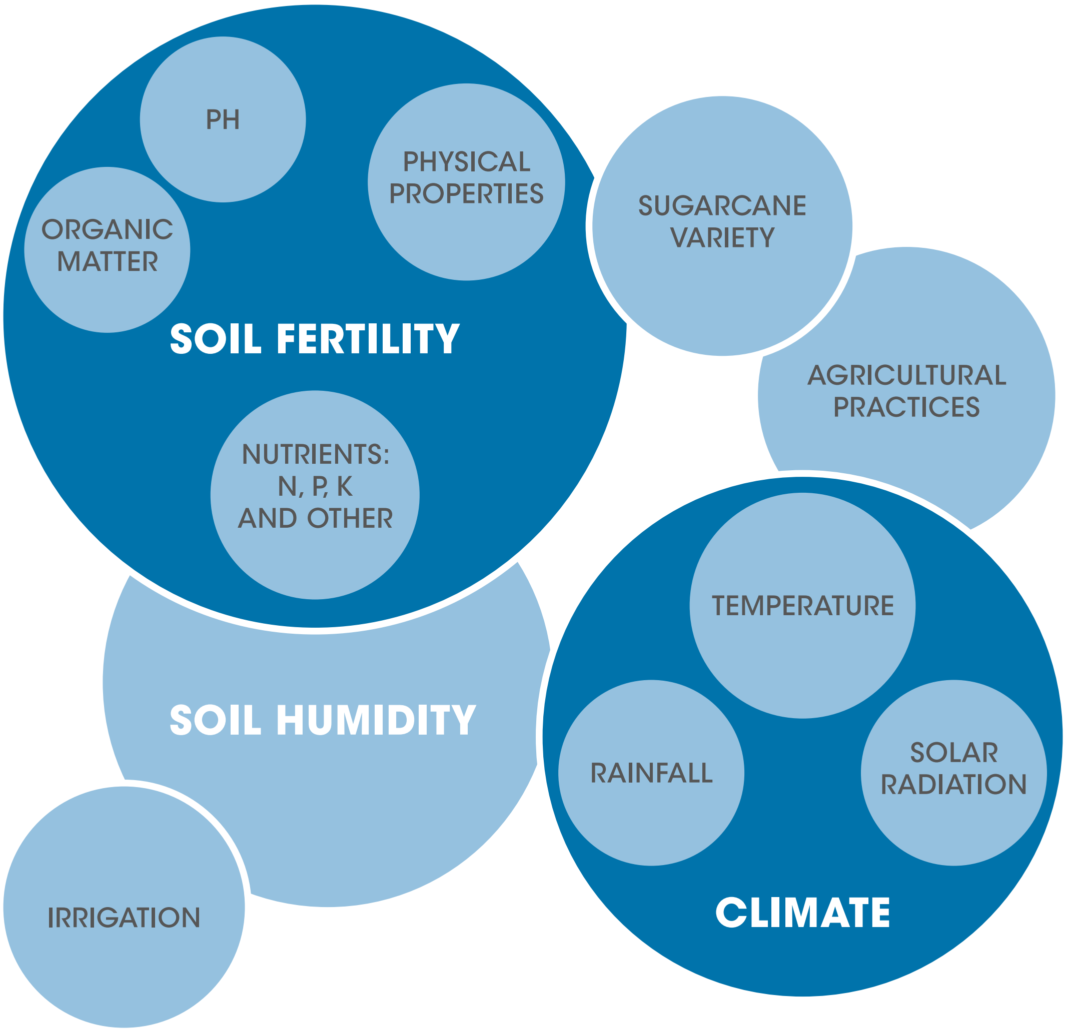
Natural conditions:

- Soil fertility as a function of chemical composition (nutrients such as nitrogen, phosphorus and potassium; acidity (pH), free aluminium, and organic matter) and physical properties (depth, texture, structure, density, and porosity and humidity)
- Climate as specified by average, minimum, and maximum values of temperature, humidity, solar radiation, rainfall, and water availability in soil
- Other conditions such as topography and drainage patterns.

Agricultural technology:

- Sugarcane variety as characterised by yield potential, sucrose content, sugar-to-fibre ratio, seasonal ripening type (early, mid-late, and late), resistance to specific diseases, and resistance to drought (hydric stress)
- Weed, disease and pest control of specified type, intensity and frequency
- Operational practices such as land preparation, planting, cultivation and harvesting; level of mechanisation; and whether or not precision agriculture is applied (using global positioning systems and other advanced monitoring systems to observe, measure and respond to plant conditions at each specific plot in the field in a continuous fashion)
- Irrigation technology, system, intensity and frequency.

Figure 2.3 Sugarcane: Main productivity factors



Sugarcane is among the most efficient plants at converting solar energy to chemical energy, typically achieving a photosynthetic efficiency of 1% to 2%. Under good soil and climate conditions, commercial sugarcane culture yields 80–110 t/ha, far below the theoretical maximum of some 470 t/ha under optimal conditions (Moore, 2009), yet well above the 25–35 t/ha observed under adverse conditions of water stress, poor soils and limited technology.

Sugarcane is one of the most efficient plants for solar-to-chemical energy conversion

Sugarcane yield model

Sugarcane production potential mainly depends on soil and climate conditions. Hence, this study models sugarcane yield as a function of rainfall, temperature and fertiliser application. It does so at a national level; more refined estimates would be needed for specific projects.

Climate effect modelling

Models have been proposed to estimate potential sugarcane yield with proper agricultural practices under different climatic conditions (O'Leary, 2000). Besides plant and soil characteristics, the most sensitive parameters in these models are:

- Frequency and intensity of warm days, evaluated by annual growing thermal time – the accumulated product of daily average temperature and number of days above a threshold temperature required for efficient photosynthesis (assumed 20 °C) (Valade et al., 2013).
- Water available to sugarcane root systems in the soil, measured in litres or millimetres of water per m^2 at a depth of 100 centimetres (cm) and estimated by the soil water balance, taking into account the inputs and outputs of water in a column of soil (namely rainfall, evapotranspiration[1] by the sugarcane plant during its growth cycle, runoff and subsoil groundwater) (Valade et al., 2013).

Where rainfall is deficient, irrigation can compensate. The amount of irrigation needed is the difference between the sugarcane water requirement (evapotranspiration) and the effective precipitation, plus additional water to compensate for losses and non-uniformity of water application, keeping the soil moist and adequately aerated (Doorenbos and Kassam, 1979).

Based on a yield model developed and calibrated with data from sugarcane fields in Piracicaba, Brazil (Scarpari and Beauclair, 2004), which is at roughly the same latitude as southern Africa, has similar thermal conditions and van Köppen climate classification (mostly "Aw" [tropical savanna] and "Cw" [subtropical with dry winter]), Beauclair (2014) proposed the following model for predicting sugarcane productivity in Mozambique considering climate effects:

$$Y_{climate} = 80.0 + 0.01\ DD - 0.1\ HD \qquad (1)$$

where

$Y_{climate}$ = average yield of sugarcane stalks [t/ha]

DD = degree days, for 20 °C base temperature [°C-day]

HD = annual hydric deficiency, for 100 cm soil depth [mm]

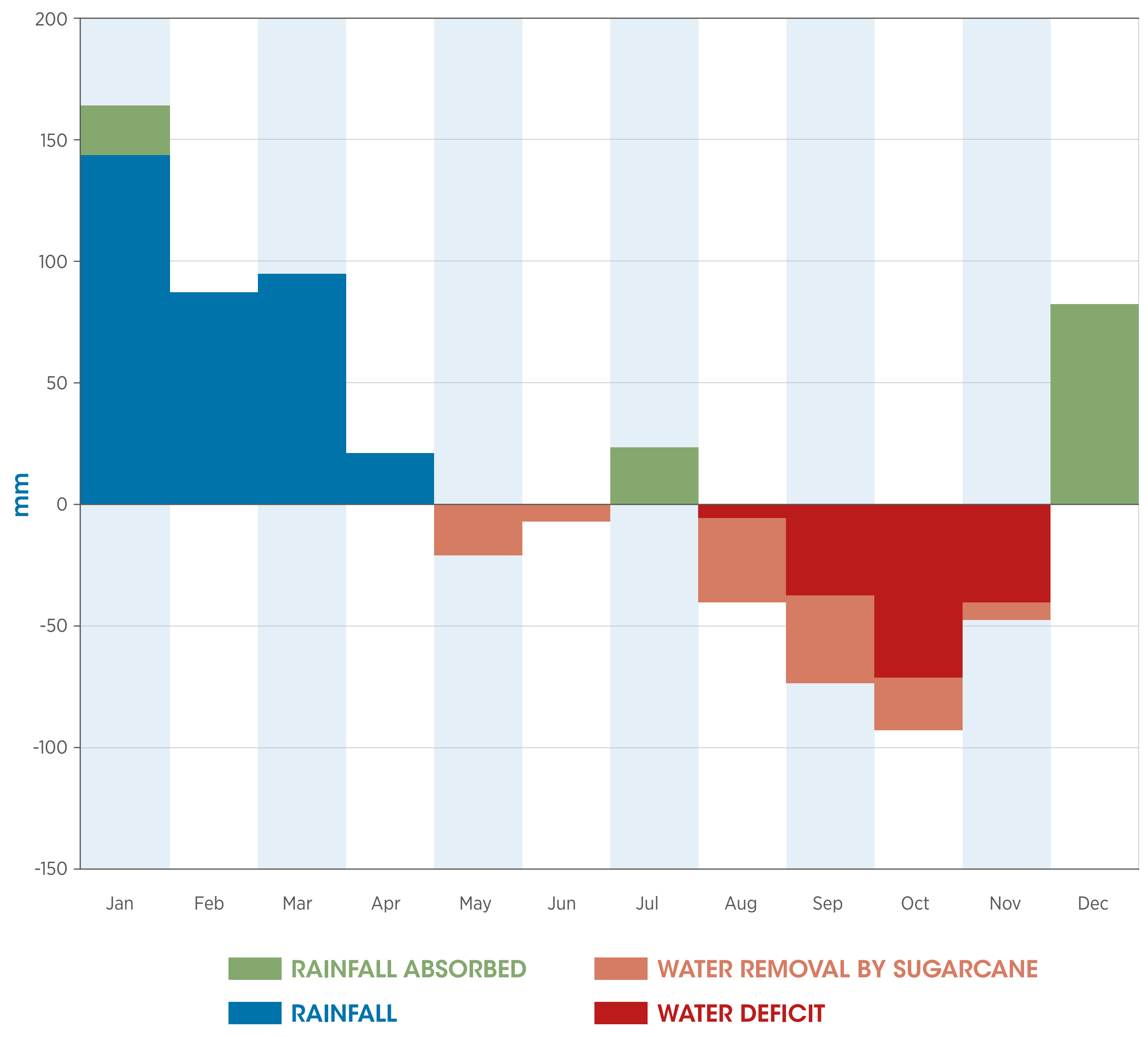
To evaluate the hydric deficiency in Mozambique, Beauclair (2014) studied ten sites. Based on monthly values of rainfall and evapotranspiration, he graphed soil water balance at each site. Figure 2.4 tracks the soil water balance over a typical year for Quelimane, in Zambezia Province.

A hydric deficiency can be observed (red columns), requiring supply of 159.7 mm of water by irrigation from September to November, despite a large water surplus during the rainy season from December to March, when soil is very wet and little rainfall is absorbed (runoff indicated in blue columns).

Each country's production potential depends on soil and climate conditions

1 Evapotranspiration is the water transfer to the atmosphere by evaporation from the soil and mostly by transpiration from plants. Photosynthesis is a highly exothermic reaction and imposes a large amount of transpiration to keep leaves in ambient temperature. Therefore, high yields mean necessarily elevated water consumption; about 120 cubic metres (m^3) of water is required to produce 1 tonne of sugarcane (based on Pacheco, Alonso and Gutierrez, 1983).

Figure 2.4 Soil water balance estimated for a sugarcane field in Quelimane, Mozambique



Note: In this figure, "mm" corresponds to 1 L of water per 1 m^3 of soil with 1 m depth.

Source: Beauclair (2014)

Since the amount of water applied by irrigation should not be greater than the hydric deficiency, the irrigation ratio should vary from 0 (no irrigation) to 1 (irrigation at maximum level and no yield reduction), with the yield equation then being modified to take account of irrigation:

$$IR = WI/HD \qquad (2)$$

$$Y_{clim+irrig} = 80.0 + 0.01\ DD - 0.1\ (1 - IR)\ HD \qquad (3)$$

where:

IR = irrigation ratio

WI = water annually supplied by irrigation [mm]

Yclim+irrig = average yield of sugarcane stalks considering climate and irrigation [t/ha]

DD = degree days, for 20 °C base temperature [°C-day]

HD = annual hydric deficiency, for 100 cm soil depth [mm]

Table 2.4 summarises the data and modelled yield estimates for Mozambique. The estimated yields are in the range observed in Mozambique and other southern African countries. As water is typically deficient, irrigation can substantially boost sugarcane productivity.

Table 2.4 Sugarcane yield modelling data and results for Mozambique

SITE	DEGREE DAYS (°C-day)	HYDRIC DEFICIENCY (mm)	ESTIMATED YIELD (t/ha)	
			WITHOUT IRRIGATION	WITH IRRIGATION
BEIRA	1 680	129.6	90.4	107.3
CHIMOIO	527	199.8	60.2	86.2
CIDADE DE MAPUTO	1 099	322.8	54.6	96.7
INHAMBANE	1 393	228.0	72.3	102.1
LICHINGA	-268	202.3	45.3	71.6
NAMPULA	1 587	392.6	54.4	105.6
PEMBA	1 899	490.3	47.4	111.3
QUELIMANE	1 814	159.7	89.0	109.8
TETE	2 542	807.7	17.9	123.1
XAI-XAI	1 182	110.9	83.7	98.2

Source: Beauclair (2014)

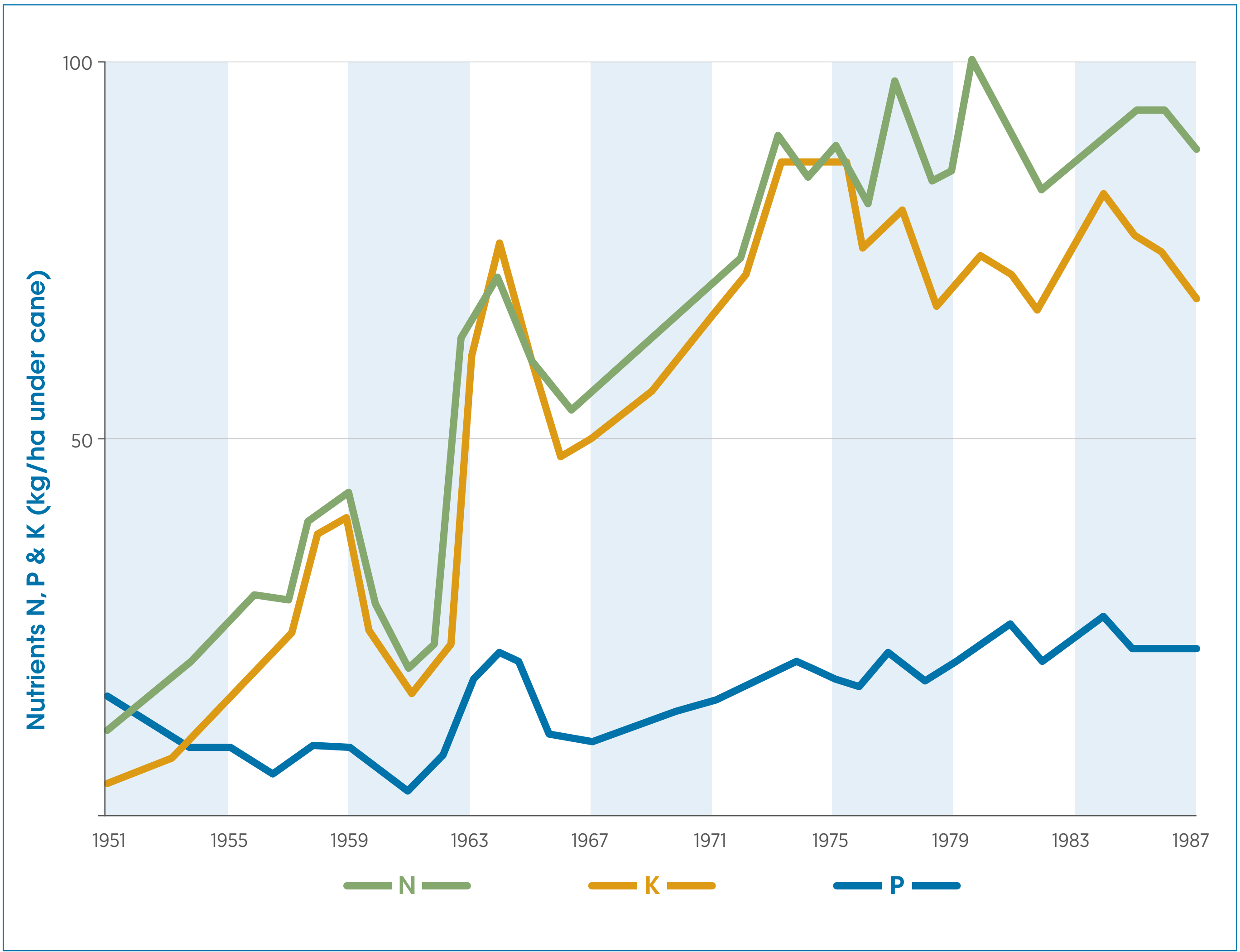
Fertiliser application modelling

Sugarcane production requires fertile soil. It should contain adequate macronutrients, such as nitrogen (N), phosphorous (P) and potassium (K). It should also have sufficient amounts of other nutrients, such as calcium, sulphur, magnesium, zinc, boron and manganese. To make these elements available to the plant, soil should not be too acid; pH correction with alkaline lime or gypsum may be needed.

Fertilisers and lime are frequently applied to sugarcane plants to maintain the availability of nutrients taken up by their roots (Bakker, 1999; Cantarella and Rossetto, 2010).

Figure 2.5 shows the growing application of fertiliser to sugarcane fields in South Africa. This, along with other good practices such as rational irrigation and breeding of better varieties, led to growth in average yield from about 25 t/ha in 1951 to over 55 t/ha in 1985 (Wood, 1989). This is among the highest sugarcane yields in the region for countries with similar conditions.

Figure 2.5 Fertiliser application to sugarcane in South Africa, 1951–1987



Source: Wood (1989)

The response of sugarcane yield to fertiliser application depends on several site-specific factors, the most important of which are current level of production, stage of culture, soil type and organic content, rainfall and weather, and time and method of application. Field studies in several contexts have indicated that, holding other conditions constant and adopting good agricultural practices, response to fertiliser is greater at low application rates than at high rates, when saturation is observed.[2]

This has been separately shown for nitrogen (Schultz, Reis and Urquiaga, 2015), phosphorus (Bokhtiar and Sakurai, 2003) and potassium (McKray and Powell, 2016).

Nitrogen can reasonably be adopted as a proxy variable for modelling the impact of fertiliser on sugarcane yield, assuming the other nutrients are also applied in correct proportions. Based on the results of 20 field trials in São Paulo State, Brazil, shown in Figure 2.6, Cantarella and colleagues (2007) obtained the following equation to express with excellent correlation (R^2= 0.973) the effect of nitrogen application on sugarcane ratoon yield,[3] without irrigation:

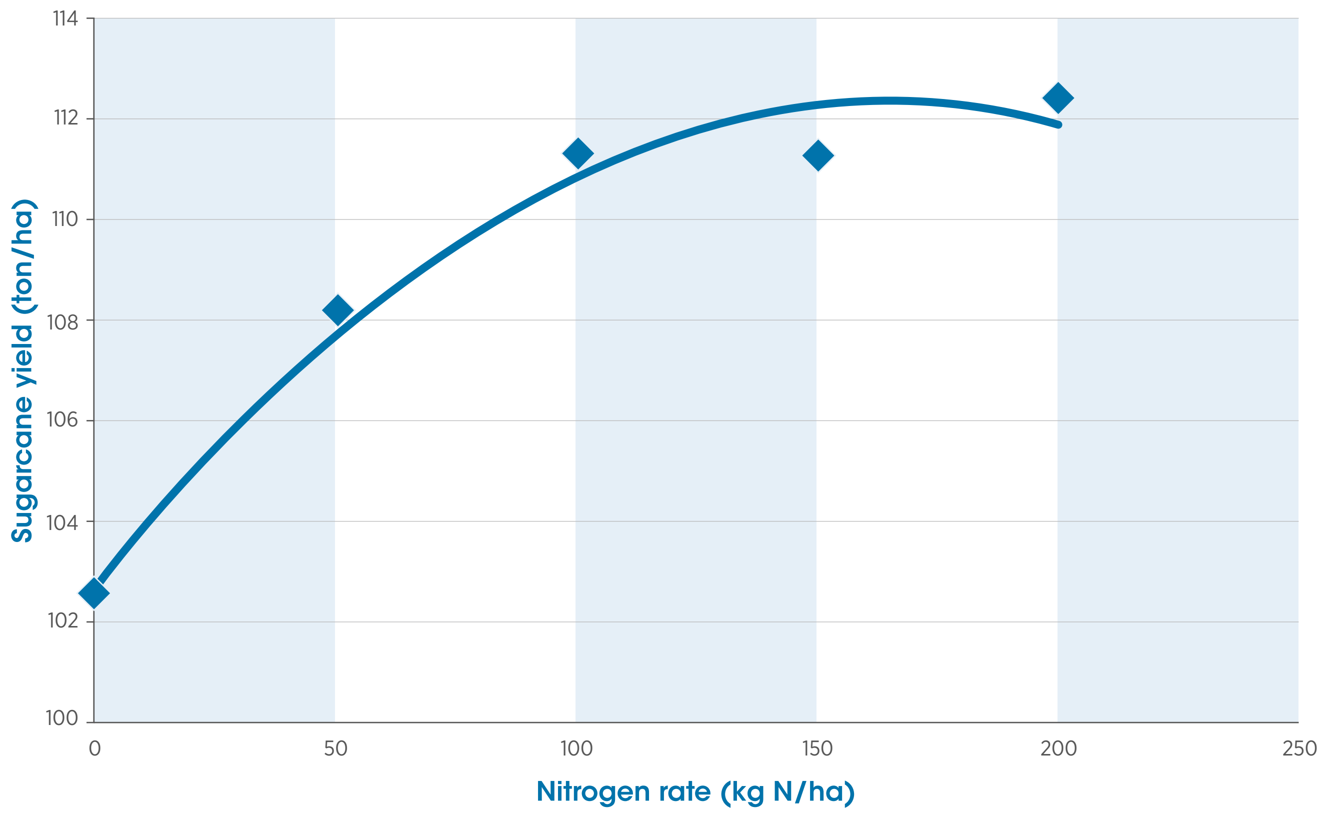
$$Y_N = 102.3 + 0.1203\ N - 0.0004\ N^2 \qquad (4)$$

where:

Y_N = average yield of sugarcane stalks [t/ha]

N = nitrogen application rate [kilogramme (kg) N/ha]

Figure 2.6 Nitrogen effect on sugarcane yield, per 20 field trials in São Paulo State



Source: Cantarella, Trivelin and Vitti (2007)

2 For example, as soils of volcanic origin usually show elevated potassium content, they neither need nor should receive additions of such nutrients.

3 Ratoon is cane that grows from buds in the stubble left in the ground after cane has been harvested. One plant usually grows three to four ratoon crops. Cantarella, Trivelin and Vitti (2007) find nitrogen has less impact on cane yield at stages of initial root formation and first harvest than it does over the whole productive cycle including ratoons.

According to this equation, in the conditions evaluated, the maximum gain occurs for an application rate of around 150 kg N/ha. But for economic and efficiency reasons, rates between 80 and 100 kg N/ha are typically recommended. This allows an 8 % productivity boost compared with no fertiliser use, if all other factors are held constant.

For urea, a common form of fertiliser with 46 % nitrogen content, these values imply the application of 174 to 217 kg/ha. For an NPK fertiliser blend with two parts phosphorus (P) and one part potassium (K) for each part nitrogen (N), such as that adopted in programmes to foster smallholder farmers production in Mozambique (IFDC, 2009), these values correspond to the application of 667 to 834 kg/ha.

Combined (climate and fertiliser) sugarcane yield model

As the impacts of climate and fertiliser were modelled assuming other conditions held constant, the combined agro-climatic model adopts the following equation, obtained by multiplying Equations 3 and 4, which allows sugarcane yields to be estimated for a given climatic context (DD and HD) and intermediate levels of fertiliser use and irrigation:

Yields are estimated for each given climate and levels of fertiliser use

$$Y_{clim+irrig+N} = [80.0 + 0.01\ DD - 0.1\ (1\text{-}IR)\ HD][1 + 1.17 \times 10^{-3}\ N - 3.91 \times 10^{-6}\ N^2] \qquad (5)$$

where:

Yclim+irrig+N = average yield of sugarcane stalks [t/ha]

DD = degree days, for 20 °C base temperature [°C day]

IR = irrigation ratio, given by Equation (2)

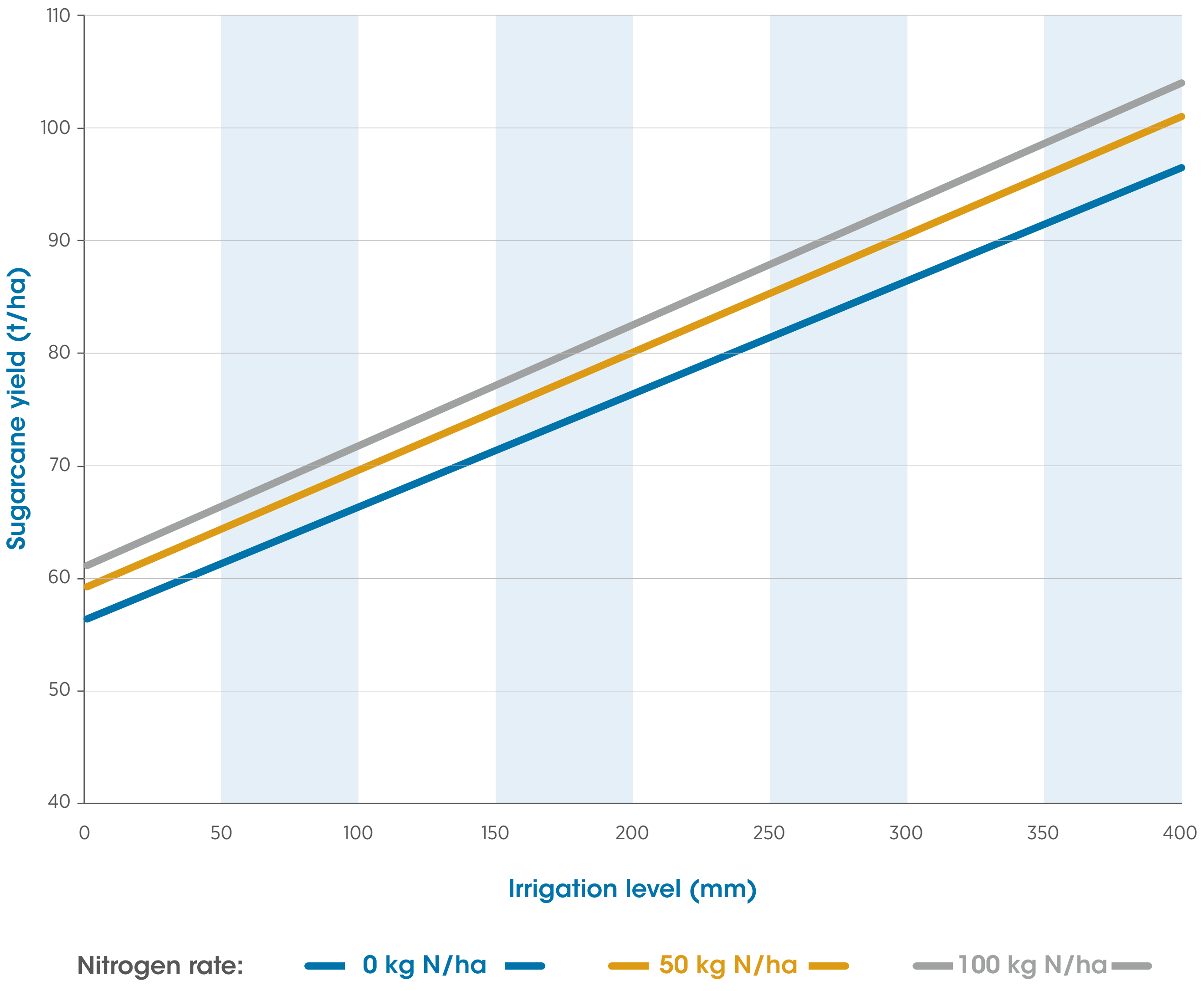
HD = hydric deficiency, at 100 cm soil depth [mm/year]

N = nitrogen application rate [kg N/ha]

For a generic site in southern Africa, with relatively good conditions for sugarcane production (DD = 1600 °C-day; HD = 400 mm), Figure 2.7 depicts yield values based on Equation 5, for different levels of fertiliser application with irrigation to compensate for hydric deficiency. This equation is appropriate for assessing sugarcane production in contexts of fertile soil, favourable topography and good agricultural practices.

Such practices could include cultivation of selected sugarcane varieties, balanced fertiliser application and active weed and disease control. The modelled yield estimate is conservative because synergies between irrigation and fertiliser use should allow an additional increase in yield, as indicated by Uribe et al. (2013), which is not considered.

Figure 2.7 Sugarcane yields for a generic site as a function of irrigation and fertiliser



Note: Modelled yields assume 1600 degree-days and 400 mm hydric deficiency per annum.

Sugarcane yield model application in southern Africa

The sugarcane yield model developed above can be readily applied using available climate and fertiliser application data. Data on ambient thermal conditions, measured in degree-days, are provided on the internet by meteorological stations in every country of the region, (see, for instance, BizEE [2018]). Hydric deficiency can be estimated from information on crop water needs and rainfall data.

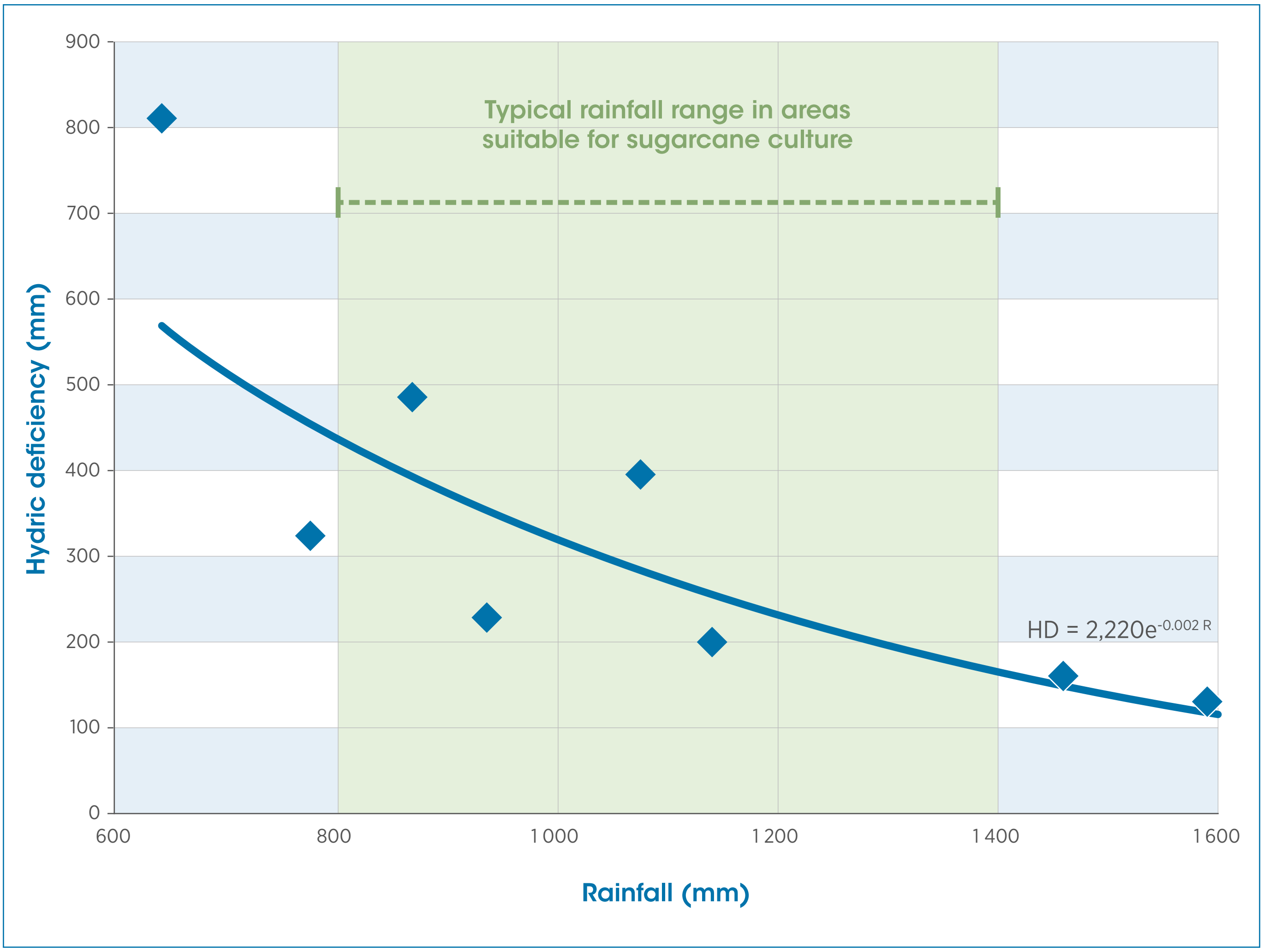
Table 2.5 shows hydric deficiency as a function of rainfall for different sites in Mozambique (Beauclair, 2014). From this information, a regression curve can be derived, showing the correlation between rainfall and hydric deficiency (R2=0.749), as illustrated in Figure 2.8. Applying this curve to rainfall data (Watson, 2011), the hydric deficiency can be estimated for each site, and combining this with degree day data on thermal conditions, potential yield with fertiliser, both with and without irrigation, can be estimated as shown in Table 2.6.

Table 2.5 Rainfall data and hydric deficiency estimates for sites in Mozambique

SITE	RAINFALL (mm)	HYDRIC BALANCE (mm)
BEIRA	1 590	129.5
CHIMOIO	1 143	199.8
CID DE MAPUTO	780	322.8
INHAMBANE	939	228.0
NAMPULA	1 079	392.6
PEMBA	872	490.3
QUELIMANE	1 461	159.7
TETE	648	807.7

Source: Beauclair (2014)

Figure 2.8 Hydric deficiency as a function of rainfall data in Mozambique



Based on: Beauclair (2014)

Table 2.6 Sugarcane yields in southern African countries with proper fertilisation

COUNTRY	SELECTED SITE	GEOGRAPHIC CO-ORDINATES	DD (°C day)	RAINFALL (mm)	HD (mm)	YIELD (t/ha)	
						NOT IRRIGATED	IRRIGATED
ESWATINI	Manzini	31.31E, 26.53S	960	898	368	57.0	96.8
MALAWI	Chileka	34.97E, 15.68S	1 876	1 068	262	78.3	106.7
MOZAMBIQUE	Xinavane	32.78E, 25.04S	1 600	780	467	53.3	103.7
SOUTH AFRICA	Durban	31.13E, 29.60S	604	935	342	56.0	92.9
TANZANIA*	Dodoma	35.77E, 6.17S	1 196	658	595	35.0	99.3
ZAMBIA	Lusaka	28.45E, 15.33S	1 034	885	378	56.7	97.6
ZIMBABWE	Harare	31.11E, 17.77S	907	861	397	53.3	96.2

* United Republic of Tanzania

The yield model developed above, like other similar simplified models applied in large areas, has certain limitations and corresponding potential for improvement. In view of limited water resources in southern Africa, the proper modelling of irrigation is of particular interest.

Sugarcane yield model limits and improvement

Sugarcane yield models have been developed and progressively improved in recent decades. The basic aim has been to support trading decisions and planning of agriculture operations, for which estimates of productivity, composition and ripening of sugarcane are relevant variables. In specific contexts, with good availability of data about previous harvests and parameters about climate, soil and sugarcane varieties utilised, highly accurate yield estimates can be obtained, with a deviation between estimated and actual value lower than ±1.0 % for a given harvest (Pagani et al., 2017. However, in most non-specific approaches, like the one adopted in this study, such deviation can be higher, about ±16 % mainly due to differences in actual and average climate conditions (Vianna and Sentelhas, 2014). Yet considering the average yield of several harvests, the climate variation effect decreases, so this deviation is effectively reduced.

Agro-climatic yield models, for application to large geographic areas, can be improved in several ways. First, they can be calibrated to actual yield values, considering the sugarcane varieties cultivated and agricultural practices adopted. Second, they can incorporate variables such as average plant age and soil type. Third, they can be designed to estimate not just the annual stalk production, but also the total sugar content and the sugar/fibre ratio. Of course, such improvements depend on better databases and more detailed information from the field, but they might reduce errors in estimated yields about four-fold, to around ±4 % (Marcari, Rolim and Aparecido, 2015).

Modelling of sugarcane yields can usefully take account of the potential to reduce fertiliser needs by recycling vinasse, which is a residue from the fermentation of sugarcane to ethanol. About 10 to 12 L of vinasse are generated per L of ethanol produced. Vinasse is rich in nutrients, particularly potassium, so recycling it into the sugarcane fields reduces the consumption of fertiliser from external sources and returns economic and environmental benefits. The typical rate of fertiliser application in ratoon sugarcane fields of the State of São Paulo, Brazil, with and without vinasse application, is presented in Table 2.7 (Macedo, 2005).

Table 2.7 Fertiliser application rate in sugarcane ratoon fields in São Paulo, Brazil

NUTRIENT	WITHOUT VINASSE (kg/ha)	WITH VINASSE (kg/ha)
NITROGEN	90	75
PHOSPHORUS (P2O5)	115	~ 0
POTASSIUM (K2O)	25	~ 0

Source: Macedo (2005)

Yield models may also usefully take account of climate change impacts, since the carbon dioxide (CO_2) concentration in the atmosphere, air temperature and water availability directly affect plant growth. For example, Marin et al. (2013) projected for southern Brazil in 2050 rainfed sugarcane yields 15 % to 59 % higher than the current values. Knox et al. (2010) estimated for 2050 an increase up to 16 % in irrigated sugarcane yield in Eswatini.

Singels et al. (2014), evaluating irrigated sites in Australia and rainfed sites in southern Brazil and South Africa, projected yield increases from 4 % to 20 % for future global climate models (assuming 734 parts per million [ppm] CO_2). In contrast, a study by Cheeroo-Nayamuth and Nayamuth (2001) predicted large reductions in cane yield in Mauritius, by 32 % to 57 %, for a scenario with doubled CO_2.

The dispersion of results in these studies is mainly due to uncertainties about the availability of water under future climate scenarios (Zhao and Li, 2015). Only to a lesser extent is it due to differences in methodology or assumptions about the impact of CO_2 concentrations on temperature and plant yields.[4] So a good understanding of irrigation and water resources in southern Africa is key to understanding potential sugarcane and ethanol yields going forward.

Sugarcane irrigation needs and opportunities in southern Africa

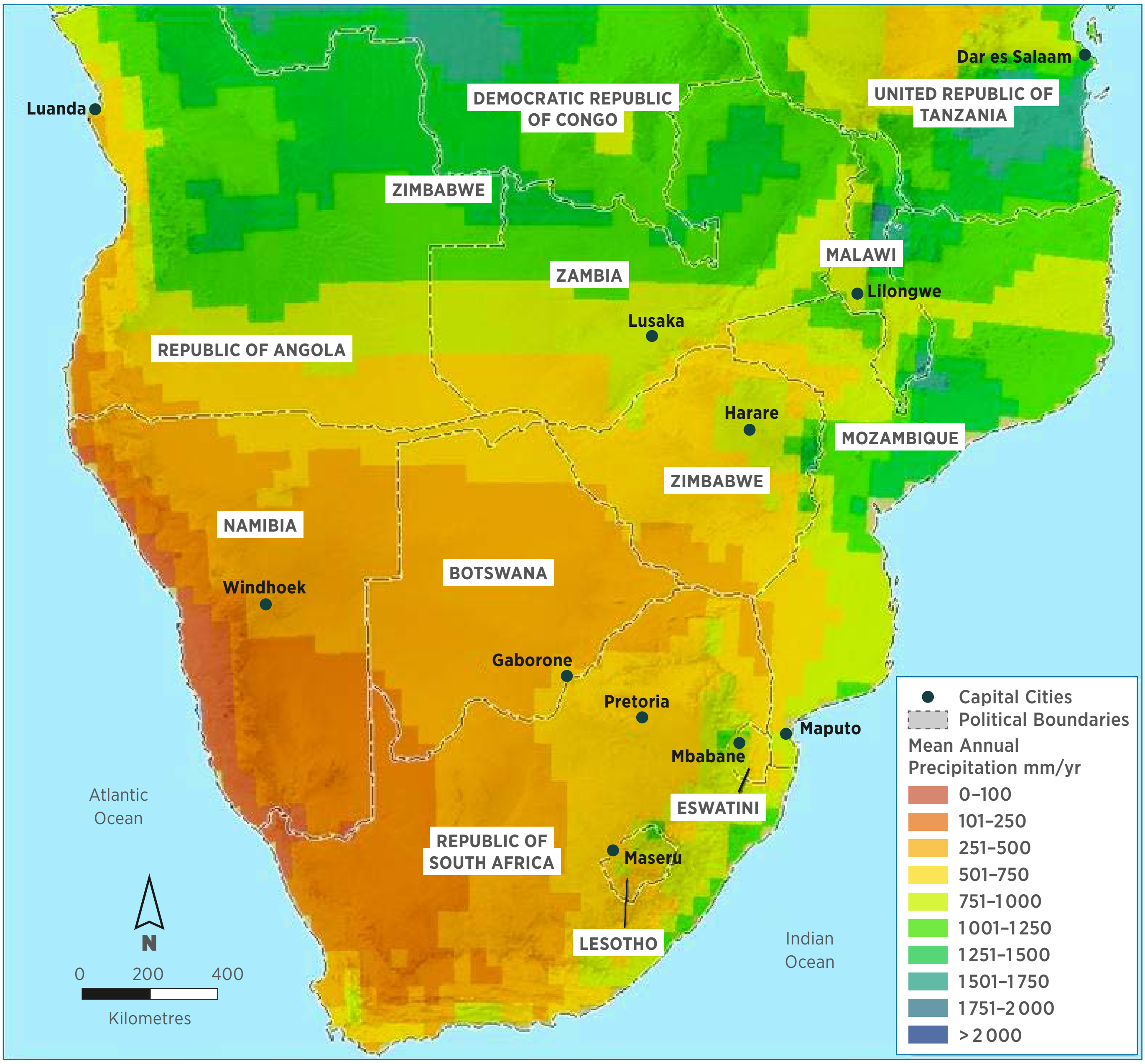
Even though sugarcane converts solar energy to biomass by the C4 photosynthesis path, which makes it more efficient and less thirsty for water than most other plants, sufficient water is important for optimising sugarcane yields. Thus, as explained above, irrigation is needed to compensate for soil hydric deficiency when rainfall is inadequate.

Figure 2.9 shows the average rainfall distribution of southern Africa. It indicates that a large portion of the region is arid or semi-arid. Table 2.8 presents meteorological data for selected countries in the region. It shows where the total runoff values in some cases reinforce the need for active management and rational use of water (FAO, 1993; Pallet, 1997).

CO_2 concentration, air temperature and water availability all affect plant growth

4 Rising atmospheric CO_2 increases photosynthesis in C4 plants, such as sugarcane, up to a saturation level, about 500 ppm (Taiz and Zeiger, 1991). For CO_2 atmospheric values above this limit, there is no gain in photosynthesis.

Figure 2.9 Regional distribution of precipitation in southern Africa



Disclaimer: Boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

Source: FAO (1993)

Table 2.8 Rainfall and potential evapotranspiration in southern African countries

COUNTRY	RAINFALL RANGE	AVERAGE RAINFALL		POTENTIAL EVAPOTRANSPIRATION	TOTAL SURFACE RUNOFF	
	mm	mm	km³	mm	mm	km³
ESWATINI	500–1 500	800	14	2 000–2 200	111	1.9
MALAWI	700–2 800	1 000	119	1 800–2 000	60	7.1
MOZAMBIQUE	350–2 000	1 100	879	1 100–2 000	275	220.0
SOUTH AFRICA	50–3 000	500	612	1 100–3 000	39	47.4
TANZANIA*	300–1 600	750	709	1 100–2 000	78	74.0
ZAMBIA	700–1 200	800	602	2 000–2 500	133	100.0
ZIMBABWE	350–1 000	700	273	2 000–2 600	34	13.1

* United Republic of Tanzania

Source: Pallet (1997)

Proper management of irrigation, to complement rainfall, requires use of the right amount of water at the right time with the right technology, to meet the twin objectives of preserving water resources and consuming energy efficiently. The International Commission on Irrigation and Drainage recommends adopting the water balance framework for irrigation planning and operation, based on sound evaluation of water needs and availability, under the principles of "measure; assess; improve; evaluate".

A practical tool to support this approach is the CROPWAT, free software developed by the Land and Water Development Division of FAO, that helps to calculate the crop water requirements and irrigation requirements based on soil, climate and crop data, indicating the irrigation schedules for different management conditions and the scheme of water supply under both rainfed and irrigated conditions (FAO, 2002).

Among several methods that can be used to distribute nutrients and water to sugarcane plants, drip irrigation[5] has greatly reduced fertiliser and water requirements through fertigation (fertiliser application and irrigation) when correctly designed and deployed (compared to conventional irrigation methods such as furrow, central pivot and dragline sprinkler).

In Eswatini, a 6 715 ha sugarcane field with subsurface drip irrigation registered an increase of average yield over nine years from 107 to 126 t/ha. This technology reduced irrigation power requirements by 4.6 kW/ha and provided yearly savings of USD 140/ha in operation and maintenance costs and 150 mm in water consumption, with an internal rate of return of 29 %. Similar studies have confirmed subsurface drip fertigation as the preferred option for sugarcane irrigation when water resource conservation and fertiliser application efficiency are critical (Kaushal, Patole and Singh, 2012).

5 Application of water directly to the soil surface or below the soil surface in small discharges (< 3 L per hour) through emitters placed at predetermined distances along a distribution pipe, near the roots of plants to wet.

3 SUGARCANE BIOENERGY TECHNOLOGY

Sugarcane is a perennial grass with tall stalks rich in sugars. Native to Southeast Asia, it is today cultivated in almost all tropical and subtropical countries for feed and sugar and increasingly for bioenergy production. The harvested stalks are roughly 70 % moisture and the dry matter is mainly sucrose and lignocellulose, as indicated in Figure 3.1.

Once sugarcane is planted, an initial harvest can be made after 12 to 18 months of growth. Five to six subsequent annual harvests (ratoons) can be made until the reduction in yield justifies starting another cycle with planting operations. The energy content in the aboveground biomass of sugarcane cultivars can be divided into three roughly equal parts. One-third is in sugars (mostly sucrose) in the internodes of the stalk. Another third is present in bagasse, the lignocellulosic fibrous part of stalk. The final third is contained in stalk tops and leaves, which make up the straw (or trash) left in the field after mechanical harvesting.

The average energy content of the total aboveground biomass harvested annually is 7.4 GJ/t of cane for an average crop each year of around 70 t/ha, which totals about 510 GJ/ha (Leal, 2010). Thus, on the whole, one tonne of sugarcane typically contains about the same amount of energy as 1.2 barrels of petroleum. Higher yields and better varieties can produce more energy per hectare. In this chapter, the conventional and advanced processes to recovery the energy available in sugarcane to produce liquid biofuel (ethanol) and electricity are presented.

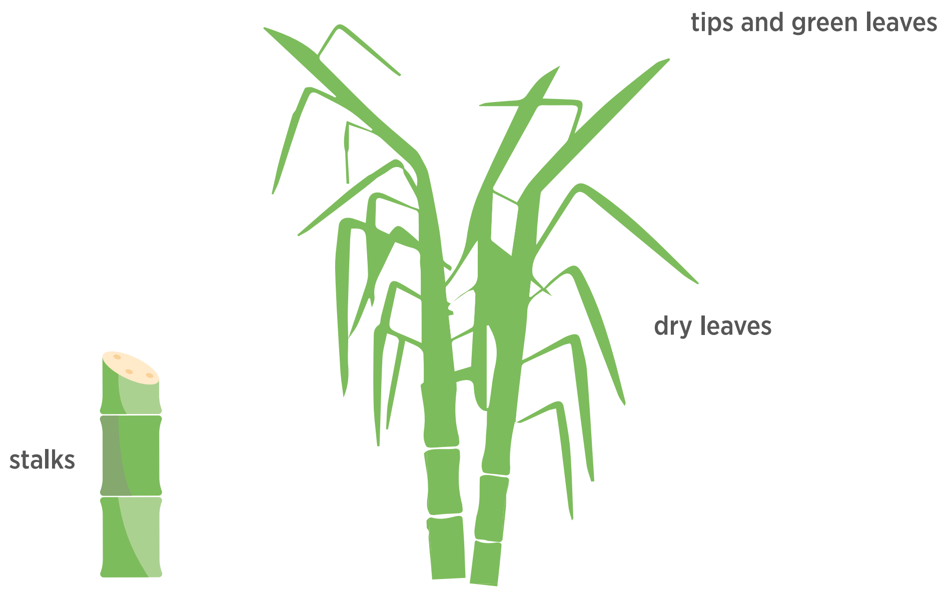
Figure 3.1 Typical sugarcane biomass composition

Straw

- Dry and green leaves plus tips (typical production): **140 kg per tonne of cane**

Stalk composition

- Water: **65–70 %**
- Fibre: **8–14 %**
- Sugars:
  - sucrose: **10–17 %**
  - other: **0.5–1 %**



Source: BNDES and CGEE (2008)

3.1 CONVENTIONAL ETHANOL (1G)

Ethanol is relatively easy to make from sugar. An aqueous solution of sugar can be directly fermented and converted to an alcoholic solution, which can then be distilled to produce fuelgrade ethanol. Such an aqueous solution, called molasses, is a by-product of sugar production. Hence, in all countries where commercial production of ethanol from sugarcane has been introduced, it has started in sugar mills with molasses as feedstock. The mills produce ethanol and sugar jointly, in proportions depending on relative prices. The initial processing stages are the same as for sugar production, as shown in Figure 3.2.

Fresh sugarcane stalks, received from the field, are cleaned, chopped and shredded. Then they are sent to crushing mills or diffusers to separate sugarcane juice and bagasse. The bagasse is used as fuel in mills' boilers in power plants. The juice is screened, chemically treated and clarified for sugar production. Slurry caught in the clarification by a vacuum rotary filter generates filter cake, which is used as fertiliser.

The clarified juice is concentrated in a series of evaporators and crystallised. However, some of the sucrose in the sugarcane is not crystallised, instead yielding molasses. The molasses, which has around 60 % sugar content, can be reprocessed to recover more sugar or can be used to produce ethanol. Depending on feedstock quality, process and level of sucrose extraction, about 6–12 L of ethanol can be produced per tonne of sugarcane processed.

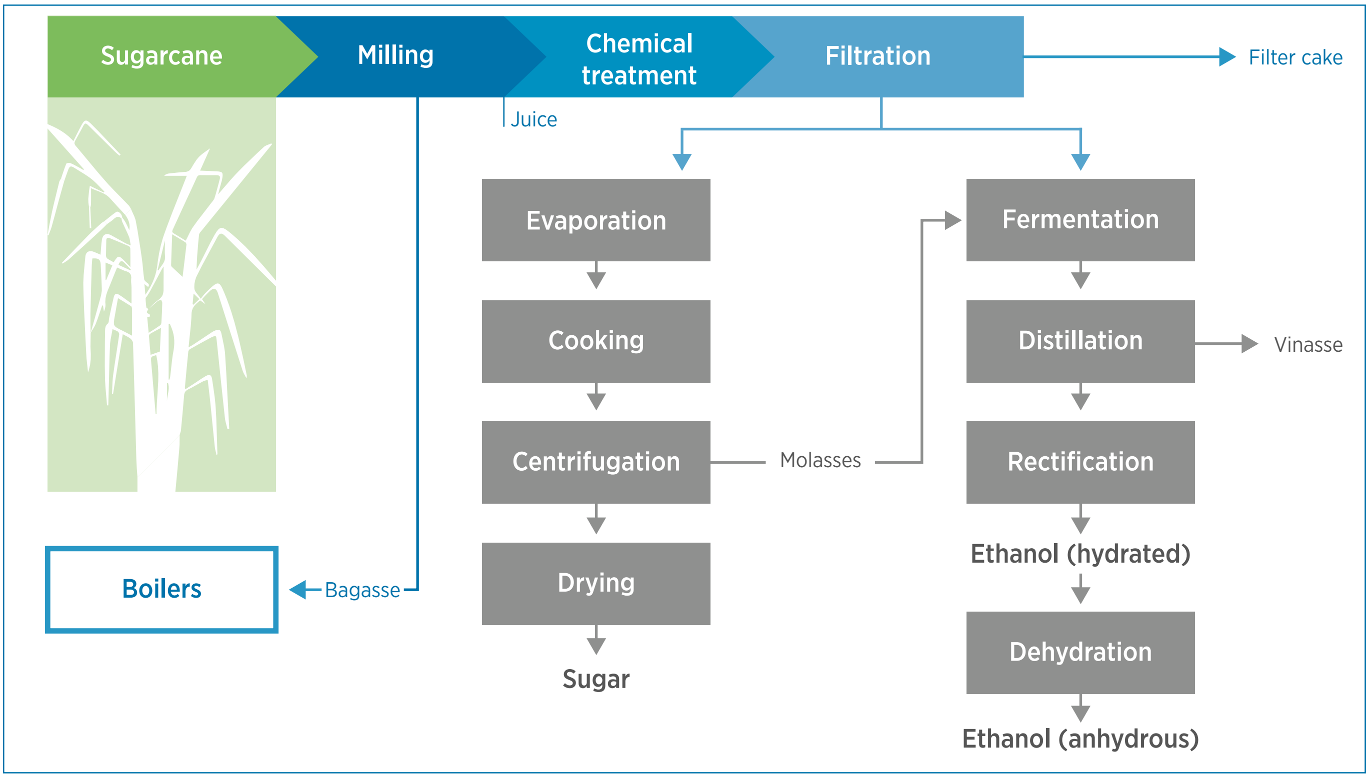
The solution (or "mash") to be fermented for ethanol production may be sugarcane juice alone or a mix of juice and molasses. This mash is sent to fermentation reactors, where yeasts (Saccharomyces cerevisiae species) are added to it and fermented for 8 to 12 hours, resulting in "wine" with an ethanol concentration from 7 % to 10 %.

Modern distilleries generally adopt the Melle-Boinot fermentation process, where yeasts are recovered by centrifuge and treated for new use, while the wine is sent to distillation columns. In distillation, ethanol is initially recovered in hydrated form, with around 6 % water by weight. Vinasse or stillage is produced as residue – about 10–13 L per litre of hydrated ethanol.

Hydrated ethanol can be stored as the final product or sent to be dehydrated. A distillation process or an absorption process is required for the dehydration. The anhydrous ethanol presents less than 0.4 % of water in weight, the usual specification for blending with gasoline.

When market demand for ethanol is established, mills can be fully dedicated to ethanol production. A similar production path is used as that described above, without the equipment and process steps for sugar production. Depending on the feedstock quality and process, 80–90 L of ethanol can be obtained per tonne of sugarcane processed.

Figure 3.2 Integrated sugarcane processing for sugar and ethanol



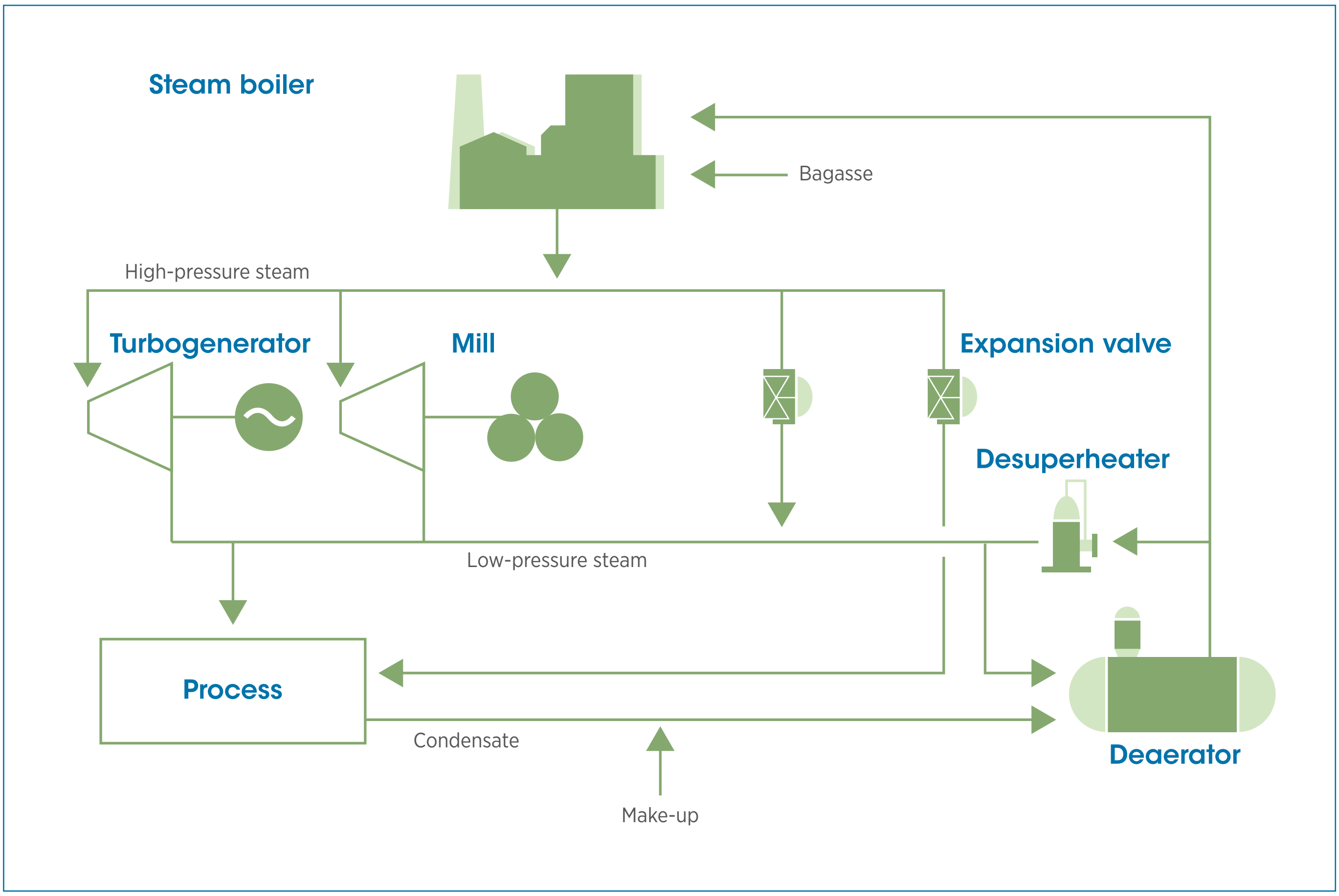
Source: BNDES and CGEE (2008)

3.2 ELECTRICITY FROM BAGASSE AND SUGARCANE STRAW

In sugarcane mills, three kinds of energy are required: thermal energy for heating and concentration processes, mechanical energy for milling and other mechanically driven systems, and electric power for pumping, control systems and lighting. Sugarcane bagasse is used as fuel to supply all these energy needs through cogeneration of electricity and heat. No external energy input is required, and surplus electricity can be sold over the power grid.

Figure 3.3 depicts typical cogeneration systems in the sugarcane agroindustry. High-pressure steam from burning bagasse is sent to steam turbines to generate electricity (and to drive mills directly if they lack electric motors). Low-pressure steam exhausted from the turbines meets the thermal energy requirements. In general, the steam circuit of the plant is balanced, so that the steam supply satisfies the plant's energy needs. Large amounts of additional electricity can be generated for sale to the public grid, specifically by reducing low-pressure steam demand, improving boiler efficiency and steam conditions (through higher pressures and temperatures) and increasing the biofuel available for boilers (by adding sugarcane straw).

Figure 3.3 Common setup of cogeneration system in the sugarcane agroindustry



Source: Seabra and Macedo (2011)

Table 3.1 Electricity and bagasse surplus for cogeneration in sugarcane agroindustry

STEAM BOILERS PARAMETERS	PROCESS STEAM CONSUMPTION	SUGARCANE STRAW USE	ELECTRICITY SURPLUS	BAGASSE SURPLUS
	kg/t cane		kWh/t cane	kg/t cane
21 bar, 300 °C	500	no	10.4	33
42 bar, 400 °C	500	no	25.4	50
65 bar, 480 °C	500	no	57.6	13
65 bar, 480 °C	350	no	71.6	0
65 bar, 480 °C	500	50 %	139.7	33
65 bar, 480 °C	350	50 %	153.0	0

Source: BNDES and CGEE (2008)

Table 3.1 shows how the steam boiler parameters affect the production of energy surplus in sugarcane mills, either as electricity or bagasse. It assumes production of 280 kg of bagasse (with a moisture content of 50 %) per tonne of sugarcane, low-pressure steam for process at 2.5 bar, and the use of back-pressure steam turbines. It also shows the impact of using 50 % of sugarcane straw available in the field as fuel in boilers, which means an effective contribution of 70 kg of this biofuel per tonne of harvested cane.

Allowing sugar mills to connect to the grid has boosted cane-based electricity generation

Implementation of efficient cogeneration schemes, with electricity surpluses sold to public utilities, depends on a proper regulatory framework. The system needs to allow connection of sugar mills' power plants to the grid, stimulate such connection through fair market prices (reflecting the mix of generating costs on the grid), provide for technical co-ordination to keep the grid running smoothly, and protect both power producers and utilities.

The evolution of such a regulatory framework in some countries has produced remarkable results, with sugarcane power supplying a significant share of national needs. For example, in 2016 sugarcane mills generated 35 240 gigawatt-hours (GWh) (6 % of electricity output) in Brazil and 2 600 GWh (29 % of output) in Guatemala, reducing fossil fuels use and associated GHG emissions.

Sugarcane straw harvest and use

To improve the productivity of manual sugarcane harvesting, the common practice in many countries is to burn the sugarcane straw prior to harvest. To avoid environmental impacts and recover this straw for power production, however, pre-harvest burning is being replaced by the use of mechanical harvesters that can handle green (unburned) chopped sugarcane.

On average, there are about 140 kg of dry straw (tops and leaves) per tonne of stalks harvested, and 40 % to 60 % of trash is left as soil cover after harvest.

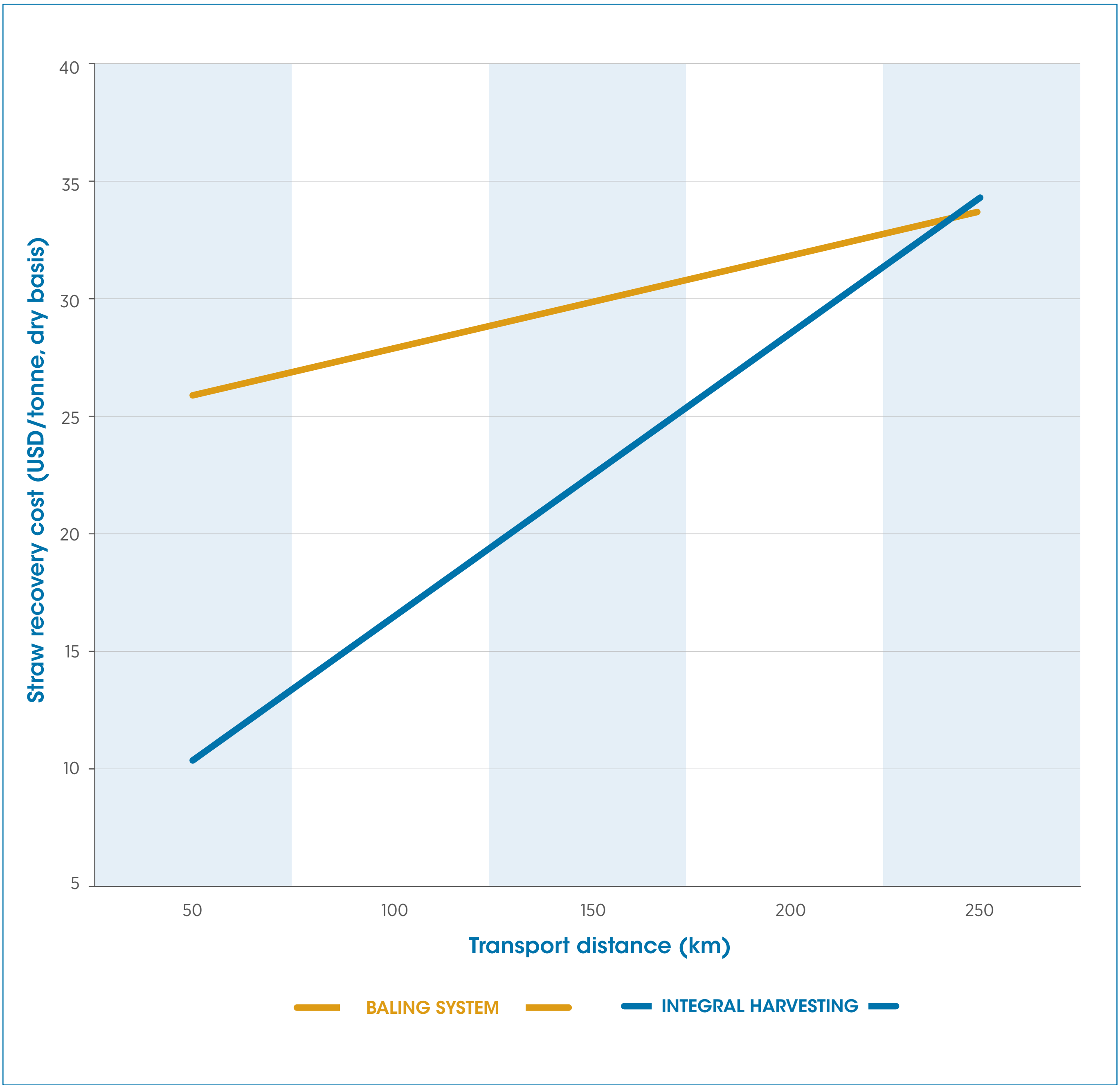
Depending on variables such as logistics systems, transport distances and costs, terrain slope, soil characteristics, and agronomic conditions, two different schemes for trash harvesting have been adopted. With integral harvesting, the straw is harvested, chopped and transported together with the sugarcane stalks. In a baling system, trash is left in the field for about two weeks after sugarcane harvest to reduce its water content, after which straw is windrowed, collected and compacted in bales for transport to the mill, as indicated in Figure 3.4.

Each system presents advantages and problems that impose specific site evaluation to select the best option. Integral straw recovery along with sugarcane stalks leads to lower load density in the transport trucks, and recovery costs are strongly dependent on distances. On the other hand, the baling system involves more agricultural operations, and straw recovery can become very expensive, as indicated in Figure 3.5, which presents costs for each scheme as observed in São Paulo, Brazil (Cardoso et al., 2015)).

Figure 3.4 Rectangular trash bales ready to be transported to the mill

Photograph: Hassuani (2013)

Figure 3.5 Straw recovery cost as a function of transport distance in São Paulo, Brazil



Source: Cardoso et al. (2015)

3.3 NEW FRONTIERS FOR SUGARCANE AGROINDUSTRY

Innovation has been always important to support productivity improvements, product diversification, cost reduction and sustainability in the sugarcane agroindustry. In this section, two promising new technologies are discussed. One pertains to energy conversion – ethanol production from lignocellulosic materials, often referred to as second-generation (2G) ethanol. The other pertains to biomass feedstock – the evolution of energy cane, a group of high-yielding new cane varieties developed for higher energy production.

Second-generation (2G) ethanol production

The sugarcane plant, apart from water and sugars, is constituted of lignocellulosic materials that can be used as feedstock for ethanol production by biochemical or thermochemical conversion processes. In biochemical routes, which are more developed, lignocellulosic feedstock is pre-treated to disaggregate the polymeric matrix of cellulose and hemicelluloses, both polysaccharides, and lignin, an alkyl-aromatic polymer, which makes it more difficult to use such feedstock for ethanol production than sugar or starch. However, lignocellulosic materials are typically very cheap and abundant, justifying the efforts underway to develop conversion plants that can use them as a resource for sustainable biofuels production.

Pre-treatment can be accomplished through diverse techniques using steam, acids and organic solvents. Subsequent enzymatic hydrolysis of cellulose and hemicellulose leads to fermentable sugars that can be converted to ethanol and other products. The lignin fraction, about 25 % of bagasse, can be used as a fuel to supply process heat and electricity, although other bioproducts are being developed. Several processes have been put forward and studied, with different performances in biomass conversion, energy balance and cost. Ethanol concentration (after fermentation) and conversion rates vary depending on catalysts, temperature, time, reactor design and process integration conditions.

The process of deconstructing and converting lignocellulosic materials is inherently complex. While cellulose hydrolysis produces hexose, a molecule with six carbons (C6 sugar), hemicellulose hydrolysis produces pentose (C5 sugar). Hemicellulose hydrolysis is easier than cellulose hydrolysis, but C5 sugar is harder to ferment than C6 sugar.

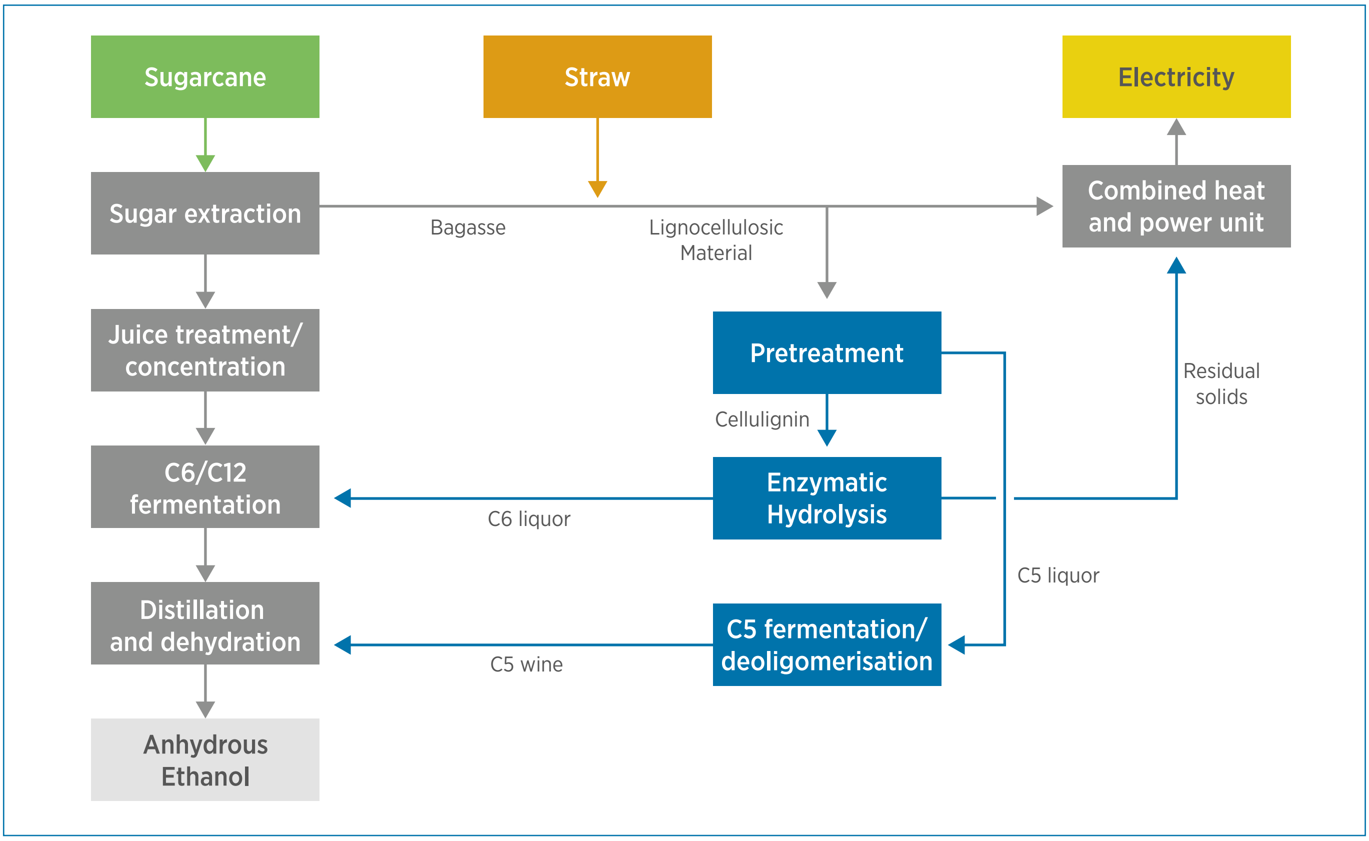
To simplify the equipment required for and deal properly with hydrolysis of real feedstock, the industrial processes for hydrolysis employ various degrees of process integration. Principal process alternatives include separated hydrolysis from fermentation (SHF), simultaneous hydrolysis/C5 fermentation, simultaneous hydrolysis and co-fermentation of C5 and C6 sugars, and consolidated bio processing, which is fully integrated.

Pre-treatment requirements vary from one feedstock to another, generating many technology options and prospects for optimisation. Different routes are being developed and scaled up. Some have made significant progress, with demonstration units operating in the precommercial stage and a few industrial plants already commissioned (CGEE, 2017).

The integration of 2G with conventional (1G) ethanol production is particularly promising in the context of sugarcane agroindustry. There is a good availability of lignocellulosic feedstock (bagasse and straw), and energy utilities can be shared to optimise investment and operations. This allows fully renewable production of energy without using fossil fuels for process heat or electricity. Figure 3.6 depicts the 1G/2G integrated processes for ethanol production from sugarcane, adopting an SHF configuration.

From actual operation of a 2G ethanol plant processing bagasse in Brazil, yields in the range of 211–237 L of ethanol per tonne (L/t) of bagasse (dry) have been obtained. Plant managers expect to reach 289 L/t at full capacity operation. That is still below the theoretical maximum yield, which is estimated to be about 422 L/t (Junqueira et al., 2017).

Figure 3.6 Integrated 1G/2G ethanol production from sugarcane



Note: Diagram assumes separated hydrolysis and fermentation processes

Source: Junqueira et al. (2017)

Energy cane development

For centuries, the breeding of sugarcane varieties has sought to increase the sugar content and reduce the fibre in cane stalks, allowing higher sugar production and easier milling. This selection paradigm led to backcrossing commercial *Saccharum officinarum* hybrid varieties with sugary and low-fibre ancestral species, reducing plant vigour and limiting productivity. The potential field productivity of sugarcane is estimated to be about 400 tonnes of fresh biomass per hectare per year under optimum conditions (Souza *et al.*, 2013), while the world commercial average productivity is less than 25% of that value. Despite recent yield increases, the genetic potential of sugarcane still allows additional important gains, which could greatly boost the amount of lignocellulosic feedstock available for conversion to fuel.

A shift from the breeding focus on sugar alone was recommended by A.G. Alexander during the 1980s in Puerto Rico. He suggested that the fibre content should be reconsidered and the whole plant should be used, including juice, bagasse and straw (Alexander, 1985).

Under this concept, better understood and more feasible after recent advances in genetics, energy cane varieties have been developed with a lower sucrose content and higher fibre content than usual sugarcane varieties, presenting higher yields in tonnes of material per hectare. Interesting results have been achieved, mainly by hybridisation of commercial sugarcane with wild species of *Saccharum officinarum* and *S. spontaneum* (Matsuoka *et al.*, 2014).

Table 3.2 Projected yield for energy cane cultivars improvement

	2010	2020	2030
STALKS (FRESH t/ha)	81	111	130
TRASH (DRY t/ha)	14	19	24
SUGAR (%)	15	13	12
FIBRE (%)	12	18	23
TOTAL ENERGY (GJ/ha)	628	940	1 228
ENERGY OUTPUT/INPUT	8	12	14

Source: Landell *et al.* (2010)

Compared with sugarcane, energy cane grows higher (up to 6 m) and thinner (1.52 cm in diameter), typically presenting narrower leaves, with large amounts of tillers and robust root systems, as shown in Figures 3.7 and 3.8. Such characteristics provide for good sprouting, great longevity and more harvests from the same planting, thereby boosting profit. Energy cane varieties are still being evaluated for resistance to pests and diseases, longevity, and harvest cycles, but commercial cultivars of energy cane are already available in some countries. As indicated in Table 3.2, energy cane cultivars could nearly double yearly energy output from 628 GJ/ha in 2010 to 1228 GJ/ha in 2030 (Landell *et al.*, 2010).

New sugarcane varieties presenting more fibre and higher energy yields are well aligned with the development of processes to convert lignocellulosic feedstock to ethanol. Energy cane, with very high fibre content, creates a new scenario involving new processes, technologies, resources and challenges. In a seminal work, Alexander advised considering ethanol production in the framework of sugarcane agroindustry and emphasised that energy cane is more than just a plant but rather requires a whole new management system (Matsuoka *et al.*, 2014).

Figure 3.7 Energy cane (left) and commercial sugarcane (right) 90 days after planting

Source: Carvalho-Netto *et al.* (2014)

Figure 3.8 Root system of energy cane (left) vs commercial sugarcane (right)

Source: Matsuoka *et al.* (2014)

4 SUGARCANE BIOENERGY COST

The economic cost of producing biofuels and electricity from sugarcane biomass is basically composed of feedstock production costs and biofuel processing costs:

- The feedstock production cost includes all costs of producing sugarcane, from planting to harvest and its transport to processing plants for conversion to energy. The production cost depends on the site where the feedstock is raised and the technology adopted to raise it. It typically accounts for 65 % to 75 % of the total cost of sugarcane ethanol.

- The processing cost, associated with investment and operation of the industrial plants that convert sugarcane into energy vectors, is less dependent on location but is directly affected by technology, production profile and scale.

4.1 FEEDSTOCK PRODUCTION COST

The cost of sugarcane production is affected by local agricultural factors such as soil quality, climate (temperature and solar radiation), water availability (rainfed or irrigated), sugarcane variety, weed and pest control, and application of fertiliser. It is also affected by operational factors, such as cost of land, wages, machinery and transportation of inputs. All of these factors vary over time for any given farm and vary across farms at any given time. Many also depend on the scale of production and how well farms are managed.

The production cost per tonne at any particular location should be evaluated on the basis of a full production cycle, including soil preparation, planting, fertiliser application, weed control and four to five harvests (one cane-plant and three to four successive ratoons). It includes the cost of raising the cane, harvesting it and transporting it to the energy plant.

Sugarcane costs in Brazil

Sugarcane costs in central and southern Brazil may be a useful reference for tropical regions where similar climate and soil conditions are observed, including parts of southern Africa. For São Paulo State, in southern Brazil, a detailed methodology was developed and implemented to track the costs of sugarcane and other agricultural commodities (Martin *et al.*, 1998). This methodology accounts for the direct costs of agricultural operations (fuel, labour, agrochemicals) and equipment, as well as indirect costs, such as land rent, administration, insurance and taxes. (In a strict economic sense, taxes are transfers rather than costs, but they nonetheless appear as costs to producers.)

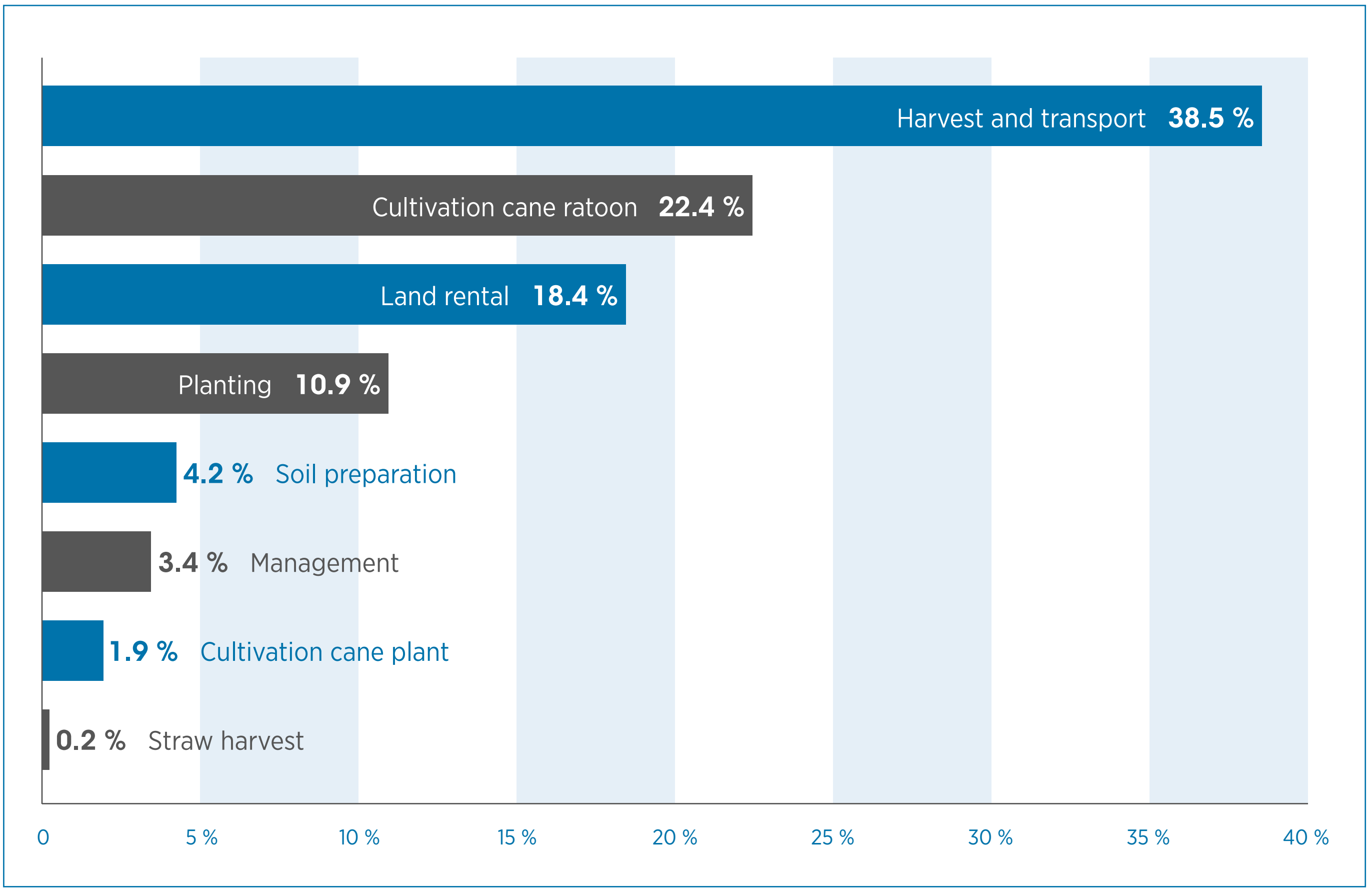
Adopting this methodology, Oliveira and Nachiluk (2011) evaluated sugarcane production costs for the 2009/2010 harvest in São Paulo for six producing subregions. Observed costs ranged from USD 18.9/t to USD 26.5/t, with the most representative value around USD 21.7/t, for harvested sugarcane at the farm gate, ready to be transported. Mechanisation was found to be important for controlling costs, in view of Brazil's rising wage levels. Land cost was found to represent 15 % to 20 % of the final cost, though farmers often neglect to consider it.

Biofuel and electricity production costs reflect sugarcane feedstock and processing costs

To obtain the final cost, studies in Brazil have indicated that harvesting and transport costs from field to the mill correspond to 33 % to 45 % of the final cost of sugarcane stalks at mill gate (Trevisan and Lima, 2015). Figure 4.1 and Table 4.1 depict the average composition of sugarcane cost in São Paulo mills observed in 2015, when mechanised harvest was largely implemented. Table 4.2 presents the evolution of this cost between 2011 and 2015, as tracked by a consulting company focused on monitoring the economic aspects of sugarcane production (Nunes Jr, 2017). The reduction of cost observed in this period can be attributed mainly to productivity gains from the introduction of mechanisation in planting and harvesting operations.

Mechanisation can boost productivity and reduce costs

Figure 4.1 Cost composition of sugar cane production in São Paulo State, Brazil in 2015



Source: Nunes Jr (2017)

Table 4.1 Sugarcane average production costs in São Paulo State, Brazil in October 2015

ITEM	UNITARY COST (BRL)*
Sugarcane field formation	7 405/ha
• Soil preparation	1 836/ha
• Planting	4 730/ha
• Cane plant cultivation	839/ha
Ratoon cane cultivation	1 948/ha
Sugarcane harvest	33/tonne
Straw harvest	68/tonne
Management	212/ha
Support fleet	1 428/ha
TOTAL SUGARCANE COST	**86/tonne**
ADDITIONAL DATA	
Average sugarcane yield	84 tonnes/ha
Average sucrose content in sugarcane (field to mill)	12.9 %
Average transport distance	28 km
Land rental	BRL 1 144/ha

* Including labour and depreciation; BRL = Brazilian real; USD 1 = BRL 3.880
Source: Nunes Jr (2017)

Table 4.2 Evolution of sugarcane cost in São Paulo State, Brazil

YEAR	2011	2012	2013	2014	2015
Cost of sugarcane at mill gate (USD/t)	39.06	35.80	35.30	37.35	25.85
Average sugarcane yield (t/ha)	70.27	77.94	83.29	73.19	83.70

Source: Nunes Jr (2017)

Sugarcane production schemes and costs in southern Africa

Although there are studies about the development of sugarcane to produce sugar and ethanol in southern Africa, data on sugarcane costs in the region are limited. This is likely because such development is at an early stage, with diverse production schemes and business models that have different contractual mechanisms and cost structures.

Before introducing the available data on sugarcane costs, the feedstock supply scheme should be reviewed based on what is currently observed at sugar mills in southern Africa. Then the costs for those that are the most efficient and return the greatest socioeconomic benefits can be examined.

Sugarcane production schemes

As observed in other agroindustries, sugar mills can obtain feedstock for their industrial process from three main sources (based on Marini, 2001):

1) Vertical integration, in which mills source feedstock from their own sugarcane fields, generally adopting capital-intensive technology to reduce labour needs.

2) Outgrower contracting/partnerships, whereby mills outsource sugarcane production to commercial or smallholder farmers, establishing contracts and agreements with respect to price and supply, aiming to assure stable price and market outlet for producers, as well as secure a stable sugarcane supply for energy production.

3) Direct supply from commercial farmers, which involves mills adopting more flexible contracts and accepting market prices for sugarcane traded.

In southern Africa, particularly where sugarcane production is less developed, the second option may be the most appropriate. It could harmonise the need to deploy and operate mills at a cost-effective scale with the prevalence of large numbers of smallholder producers. Outgrower associations or co-operatives could allow the co-ordination of operations and access to technology required to reach better levels of productivity.

Thus, this sourcing scheme, which has been increasingly adopted with small variations in different African countries and promoted by governmental agencies in charge of sugarcane agroindustry (CEPAGRI, 2014), can combine good technoeconomic performance in sugarcane production and processing with the sharing of economic benefits from bioenergy production among farmers, respecting the existing land tenure framework, forming an essential aspect. However, it requires correct design and implementation to provide a balanced sharing of benefits and costs. This depends on the contractual terms adopted, especially with respect to sugarcane pricing (Jelsma, Bolding and Slingerland, 2010).

In the real world, these schemes are combined, depending on local conditions, resources and interests. Table 4.3 presents the actual sugarcane supply schemes linking large and small outgrowers with sugar mills in four African countries, showing how the economic benefit from production is shared between sugarcane outgrowers and the sugar industry.

Sugarcane contracts can allow farmers to share in the benefits of bioenergy production

Table 4.3 Sugarcane production/supply schemes: Main data in selected African countries

COUNTRY	SUGARCANE SUPPLY TO MILLS		AVERAGE YIELD (t/ha)	OUTGROWERS	BENEFIT SHARES	
	OUTGROWERS	OWN ESTATES			OUT-GROWERS	MILL
Kenya	92 %	8 %	63	250 000 smallholders	Sucrose share formula to be implemented	
Mozambique	20 %	80 %	75	4 000 smallholders	Under review	
South Africa	93 %	7 %	42	1 300 large farmers (80 % supply) 20 000 smallholders (20 % supply)	37 %	63 %
Zambia	60 %	40 %	106	Not informed	41 %	59 %

Source: Data from USAID (2015) based on IDRC, SASA, Mozambique Ministry of Agriculture

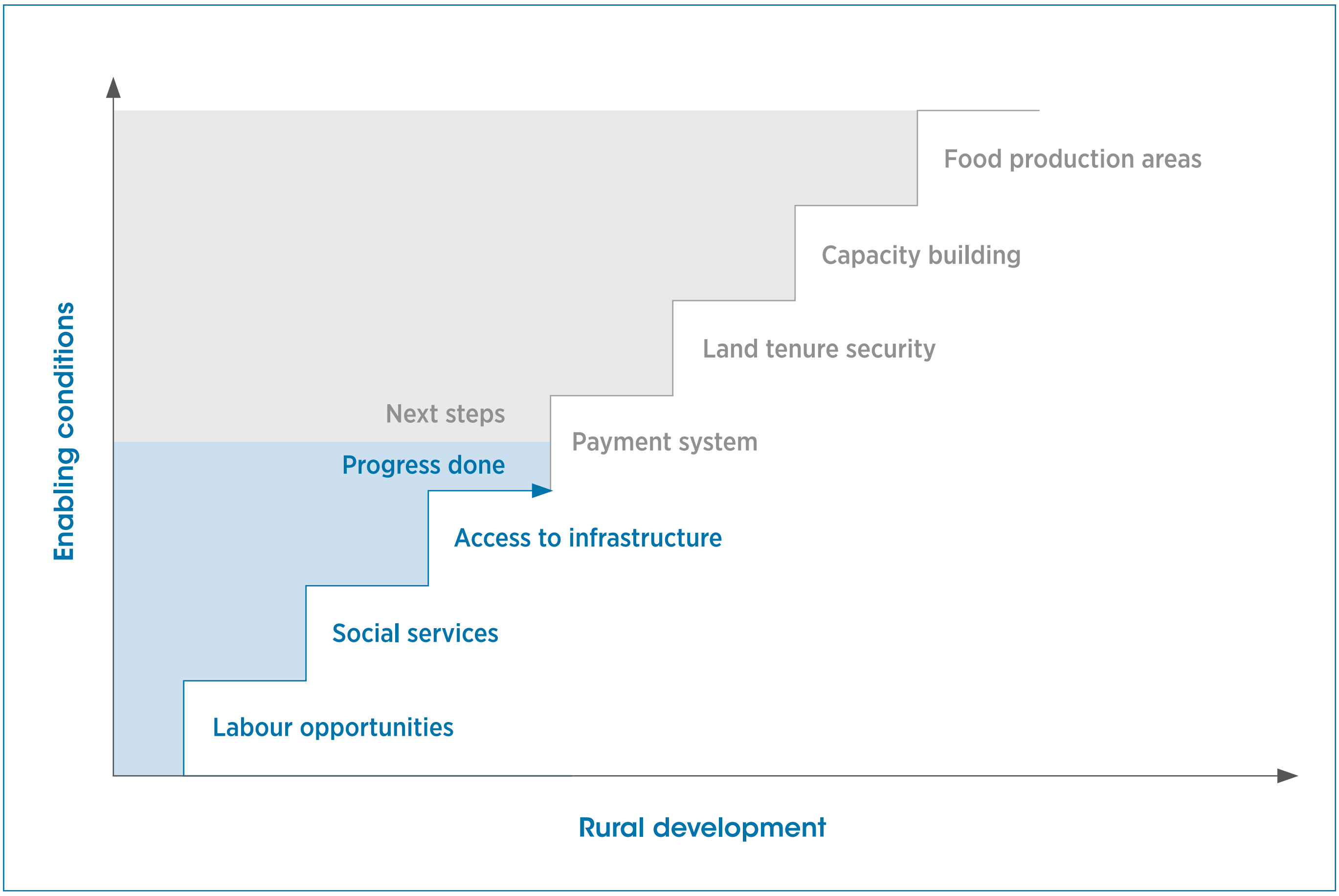
The supply model observed in South Africa, with a mix of large and small outgrowers, resulted from decades of progressive adjustment. Active farmers' organisations negotiate sugarcane prices using a benefit-sharing formula based on the sucrose content of the cane and the value of sugar produced. The formula includes additional payments for co-products such as energy, molasses and ethanol. A similar model, in Kenya, has a great number of unassociated smallholders as outgrowers with very small farms. It thus has much higher administrative costs and lower productivity, in part because the planting and harvesting of cane varieties that mature at different times are hard to co-ordinate (USAID, 2015).

In Mozambique, sugar mills obtain about 80 % of the sugarcane feedstock they use from their own plantations. However, a growing share is coming through contracts with smaller farms. The main sugar company, Açucar de Xinavane (AdX), is a joint venture of South African investors (88 %) and the government of Mozambique (12 %). It cultivated about 18 kha and produced 1.42 Mt of sugarcane in 2018 (Tongaat Hulett, 2018), roughly half of the country's entire sugar output. It began in 2006 as the Xinavane Small Scale Grower Development Project, and it has drawn in more and more smallholders over time.

AdX aims to foster the formation of smallholder sugarcane producer associations and involve them in the production of sugarcane on a contract farming basis. Associations must meet a variety of performance requirements to improve yields, including appropriate use of irrigation and fertiliser. The smallholders in each association must collectively cultivate a minimum of 45 ha, and a minimum plot of 2 ha per smallholder is recommended.

To design and implement this scheme, a variety of social and economic issues had to be addressed. Among these were land entitlements, water use rights, provision for cattle grazing, road construction or upgrade, and expansion of machinery fleet (Sonneveld, 2012). While there was controversy over the economic and social impacts of the scheme when it was introduced (Dubb, Scoones and Woodhouse, 2016), the actual outcome is clear. The Xinavane mill had 1 539 smallholders contracted as of 2010, and this number is still expanding. Outgrowers' contribution to sugarcane supply, just 7 % before the AdX project, rose to 14 % in 2018 and was expected to reach 40 % in "the next few seasons" thereafter (Tongaat Hulett, 2018).

Figure 4.2 Progress for smallholder sugarcane producer associations in Mozambique



Source: Leite, Leal and Langa (2016)

A field study of producer associations in Mozambique, based on interviews, offers their perspective on the AdX scheme, summarised in Figure 4.2 (Leite, Leal and Langa, 2016). They believe that significant progress has been made in employment and social benefits. Nevertheless, a better payment system (allowing producers to provide from higher productivity), more secure tenure, capacity building through training programs, and access to irrigated areas for food production are desired.

Sugarcane production cost for outgrowers

Based on an evaluation of smallholders on 1 ha plots supplying the Xinavane mill, the main components of sugarcane production cost at mill gate are presented in Table 4.4 (Sonneveld, 2012). These figures are based on a realised yield of 105 t/ha, comparable to the better yield values in southern Africa. They do not include other costs charged to outgrower associations such as road maintenance and annual management fees (9 % in the first three years and 4 % thereafter). The cost structure should be broadly representative of that for small outgrowers in southern Africa more widely. Thus, it is a reasonable reference to use in constructing supply curves for bioenergy from sugarcane.

Table 4.4 Sugarcane production cost for efficient smallholder outgrowers in Mozambique

OPERATION	COST AT MILL GATE (2010)		
	(USD/ha)	(USD/t)	SHARE
PLANTING	138	1.31	5 %
RATOON CULTIVATION	812	7.73	32 %
IRRIGATION	632	6.02	25 %
HARVESTING + HAULAGE	983	9.36	38 %
TOTAL	**2 565**	**24.43**	**100 %**

Based on: Leite (2018) and Sonneveld (2012)

In comparison, Xivanane's evaluation of sugarcane production costs on its own estates (Leite, 2018) shows an average cost of USD 2 880/ha for agricultural operations (ratoon cultivation, irrigation and drainage, harvest and delivery). This is 3 % lower than the cost for outgrowers if the figure in Table 4.4 is adjusted for 15.6 % inflation since 2010. Thus, the farming out of contracts to smallholder associations does not significantly increase costs.

To estimate the overall costs of sugarcane production, the additional costs that mills incur must also be included. Among these are administration; safety, health and environment protection; and road maintenance costs. These represent USD 585/ha in the Xinavane mill, implying a total final cost for self-produced sugarcane of USD 3 465/ha.

These costs are comparable to those observed in Brazil. The costs in Brazil are pushed higher by elevated labour costs, but they are also pushed lower by the relatively infrequent use of irrigation, which is responsible for one-quarter of costs in southern Africa. On balance, therefore, the final sugarcane production costs end up in a similar range.

To close this evaluation of feedstock production cost in the context of sugarcane agroindustry, cost estimates need to be introduced for energy cane and molasses. Molasses is a by-product of sugar production and is traded as a very raw sugar, at relatively low prices, generally related to sugar prices. So, when it is used as feedstock for ethanol production, its market value can be assumed as an opportunity cost. According to Leal *et al.* (2016), in Mozambique between 2009 and 2013, the average price of molasses was USD 100/t and the sugar export price was USD 568/t, implying a molasses/sugar price ratio of 0.18. This ratio can be applied to sugar price to estimate molasses cost in each country studied.

Energy cane is a key alternative feedstock for bioenergy because it yields greater energy content than conventional sugarcane per hectare of land cultivated, reducing risks of land-use change and associated carbon release from the soil to the atmosphere. The few cost studies for energy cane cultivation indicate lower feedstock production costs than for conventional sugarcane due to an extended production cycle and reduced land requirements. However, the elevated fibre content requires heavier equipment and greater energy use during harvesting and processing. Hence, this study conservatively assumes for analytic purposes that the production cost is the same for energy cane as for conventional sugarcane.

4.2 INVESTMENT IN SUGARCANE BIOENERGY CONVERSION SYSTEMS

This section examines the investment required for systems to convert sugarcane to energy (ethanol and electricity). Three different system configurations are considered:

- a brownfield sugarcane mill, converting molasses to energy instead of sugar
- a greenfield ethanol mill, converting all sugarcane feedstock to energy
- an advanced ethanol plant combined with a conventional ethanol plant.

Although investment needs can only be evaluated with precision after a plant is built, they are less site-specific and thus simpler to estimate than feedstock cost estimates.

Brownfield sugarcane to ethanol mill

The first configuration is a distillery annex to an existing sugarcane mill to produce energy from the molasses available from sugar production while holding sugar production constant. This represents the most frequent and advisable initial step towards introducing ethanol production in a country where sugarcane is already cultivated and processed to make sugar.

Considering actual data from the Açucar de Xinavane sugar mill in Mozambique, Leal *et al.* (2016) evaluated the capital requirements to install a distillery and the operational costs of jointly producing sugar and ethanol, shown in Table 4.5. The estimated investment of USD 4.4 million would purchase all equipment necessary to prepare the mash (solution of molasses and water), fermentation tanks, distillation columns, tanks for ethanol, and ancillary equipment and control systems, with an installed capacity to convert 64 thousand tonnes of molasses into 16.3 ML of ethanol during the six-month-long yearly milling season.

Greenfield sugarcane to ethanol mill

The second configuration is a greenfield ethanol mill, processing the same amount of feedstock considered in the brownfield case but without sugar production, using all sugarcane to produce 136 ML of ethanol and 296 GWh of electricity during the milling season. Investment needs are much higher than those in the brownfield case and include a complete system drive by electric motors for reception, cleaning and preparation of sugarcane for milling; an electrified milling system to extract sugarcane juice; more juice treatment, fermentation and distillation equipment; and additional ancillary equipment, utilities and control systems.

An important component in this configuration is the cogeneration plant (boiler, steam turbine and auxiliary systems), burning bagasse and sugarcane straw from unburned sugarcane harvesting with 50 % straw collection (70 kg of straw per tonne of sugarcane, dry basis) and adopting high-quality live-steam conditions (65 bar/485 °C), optimised process steam consumption (350 kg steam per tonne of sugarcane processed), to assure an elevated efficiency and maximum power production (Leal *et al.*, 2016). The high specific electricity generation, 185 kWh/t of sugarcane processed, above the usual value for modern mills, is mainly a consequence of using sugarcane straw as complementary fuel to bagasse in boilers.

The USD 141.4 million investment estimated by Leal *et al.* for a plant processing 1.6 Mt per year corresponds to USD 90/t of annual sugarcane processing capacity. This is significantly below estimates for greenfield mills in west Africa, USD 212/t of annual processing capacity (BNDES, 2014). Therefore, this study adopts the investment estimate by Junqueira *et al.* (2017), USD 436.4 million, for a plant with same configuration, able to process 4.0 Mt of sugarcane per year. Assuming that economies of scale are achieved with a scaling factor of 0.6 (so total plant cost varies with the ratio of plant capacity to the 0.6 power), a final cost of USD 252.9 million is obtained for the 1.6 Mt per year plant proposed by Leal *et al.* (2016). This equates to USD 158/t of yearly sugarcane processing capacity, a more realistic value.

Table 4.5 Parameters of bioenergy production systems in sugarcane mills

PARAMETERS	EXISTING SUGAR MILL (2014)	BROWNFIELD SUGAR AND ETHANOL MILL	GREENFIELD ETHANOL MILL
Sugarcane area (kha)	16	16	16
Sugarcane processed (kt/year)	1 600	1 600	1 600
Sugar (kt/year)	200	200	0
Molasses (kt/year)	64	0	0
Bagasse (kt/year)	475	475	475
Ethanol (kL/year)	0	16 280	136 000
Electricity (GWh/year)	0	0	296
Investment (USD million)	0	4.4	252.9

kt = kilotonne; kL = kilolitre

Based on: Leal *et al.* (2016) and Junqueira *et al.* (2017)

Comparison of brownfield and greenfield ethanol plants

These two configurations represent the lower and upper bounds of investment required to produce bioenergy from sugarcane using currently available technology. The main results of this study are summarised in Table 4.5, for the original mill, for adding a distillery to the mill, and for building a greenfield mill in which all sugarcane is used to produce bioenergy.

Greenfield mills produce more ethanol than existing sugar mills can

The following technical parameters are assumed (Leal *et al.*, 2016; Rein, 2007):

- **Cane quality**: Sucrose 14 % and reducing sugars 0.6 % based on clean stalks, 5 % vegetal impurities.
- **Sugar production**: 125 kg per tonne of sugarcane.
- **Ethanol production from direct sugarcane juice**: 85.4 L/t of sugarcane.
- **Bagasse production**: 297 kg per tonne of sugarcane (moisture 50 %; 14.1 % fibre).
- **Ethanol production from molasses (with 42.1 % total sugars as sucrose and 90 % fermentation efficiency):** Yield of 260 L of ethanol per tonne of molasses. (With 40 kg or 0.04 tonnes of molasses per tonne of cane, 10.4 L of ethanol are thus obtained per tonne of sugarcane processed for sugar.)

Advanced ethanol plant combined with conventional plant

The third configuration studied is the 2G ethanol plant associated with a modern conventional 1G ethanol mill. As noted earlier, the use of lignocellulosic feedstock such as sugarcane bagasse and straw can increase bioenergy production while reducing GHG emissions. In Brazil, the adoption of 2G processes in synergy with 1G processes is expected to raise average ethanol productivity from 7.3 m^3/ha to 8.7 m^3/ha (CGEE, 2017). Research and development efforts are underway to improve 2G processes, but only a few pilot plants are operating around the world. Investment requirements, therefore, are harder to estimate than for mature, conventional technology.

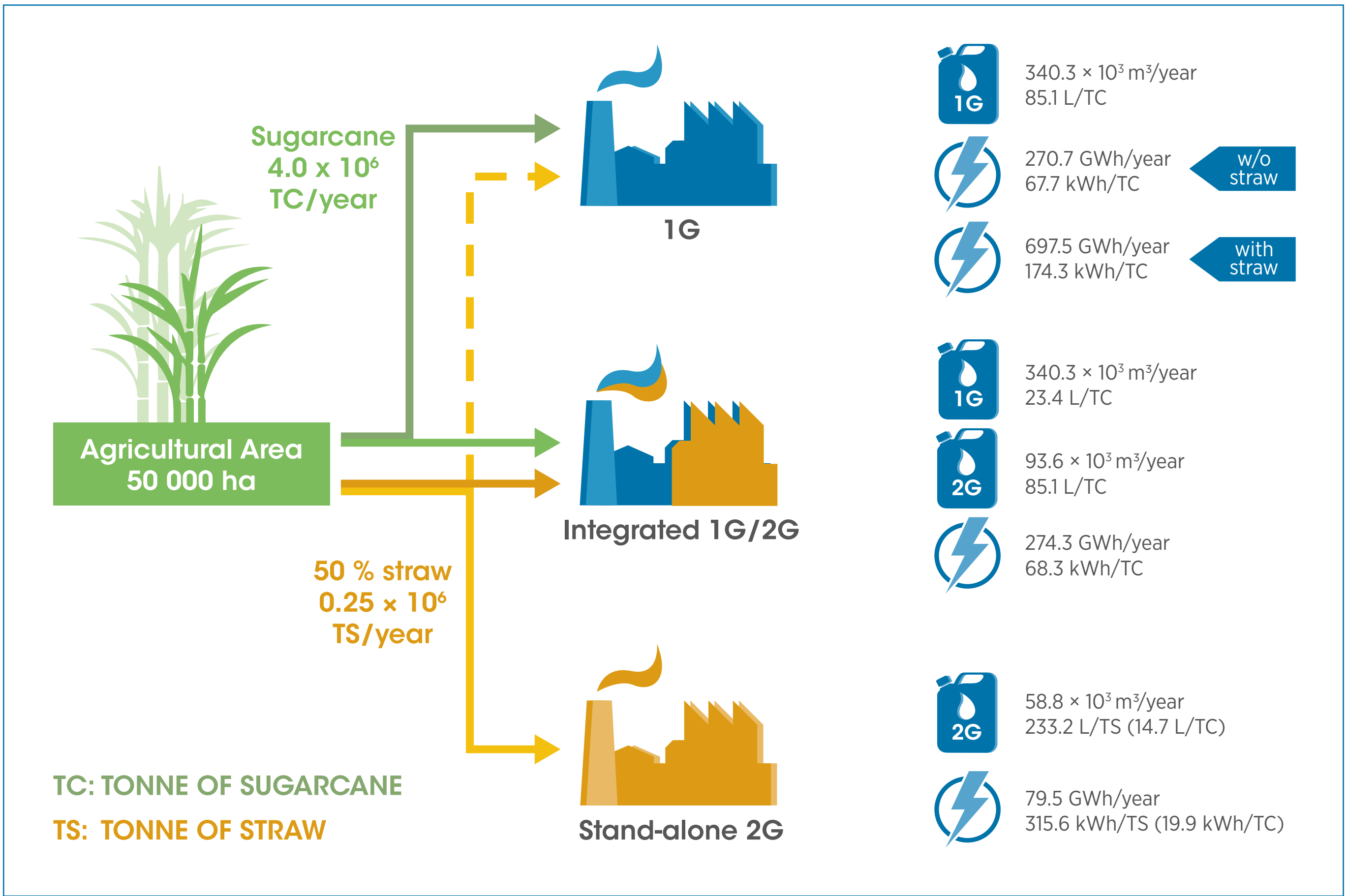
Lignoscellulosic feedstocks like sugarcane bagasse and straw can increase bioenergy production and reduce greenhouse gas emissions

One of the most active research centres in advanced technologies for sugarcane bioenergy, the Brazilian Bioethanol Science and Technology Laboratory (CTBE), has been modelling, simulating and assessing different plant configuration and 2G processes; evaluating their technical and economic feasibility; and offering references for costs and investments. According to CTBE, the most economically feasible configuration is the integration of 1G and 2G processes, sharing infrastructure (logistics, maintenance and services) and process utilities (steam, power, compressed air, etc.), and thus reducing final costs. An integrated 1G/2G facility processing 4.0 Mt of sugarcane could be expected to produce an estimated 434 ML of ethanol (78 % from the conventional 1G process and 22 % from the 2G process) and 274 GWh of electricity each year.

Such a facility would be energy self-sufficient, with power and process steam supplied by a cogeneration unit run by heat generated from the sugarcane feedstock. The advanced 2G part of the mill would use steam explosion pre-treatment of cellulosic feedstock, hexose hydrolysis (for a 36-hour fermentation, 20 % solids) and separate pentose fermentation to ethanol.

Such an innovative integrated 1G/2G mill, including all systems, would require a total investment of USD 660.8 million (Bonomi, 2015). This corresponds to USD 165/t of sugarcane processed per year – well above the capital cost of conventional 1G technology. A synthesis of inputs and outputs in this configuration, compared with 1G and 2G stand-alone options processing conventional sugarcane, is presented in Figure 4.3 (CTBE, 2015).

Figure 4.3 Sugarcane plant configurations for 1G and 2G biochemical processes



Source: CTBE (2015)

In the case of processing energy cane only, not evaluated by Bonomi (2015), the feedstock is assumed to have 20 % less sugar and 92 % more fibre (Landell *et al.*, 2010). This reduces the production of conventional ethanol and increases the output of 2G ethanol and electricity per tonne of sugarcane processed.

Adjusting the parameters presented in Figure 4.3, 434 ML of ethanol (60 % from sugar and 40 % from the 2G process) and 274 GWh of electricity would be produced. Investment needs are assumed to be the same as for conventional sugarcane.

The cogeneration plant represents an important part of the total capital investment in the mill: 44 % for an advanced conventional mill and 27 % for an integrated 1G/2G mill (Junqueira *et al.*, 2017). Thus, investment requirements can be shared between ethanol and electricity. However, cogeneration plants use bagasse from the mill to produce both low-pressure steam (used to produce ethanol) and electricity (also partially consumed in the production process).

Such common costs must be allocated between ethanol and electricity. In this study, the investment in the cogeneration plant is charged only to electricity, generated without fuel cost, assuming that the bagasse is supplied without cost by the mill, while the ethanol production assumes all other investment and the full sugarcane cost, as well.

Investment requirements for sugarcane ethanol plants

For the reference plants adopted in each technology configuration, Table 4.6 presents the main production data and Table 4.7 presents estimates for total investment and investment per unit of bioenergy produced. Capital investment is annualised assuming a 15-year useful lifetime and 10 % weighted cost of capital.

Annual operating and maintenance (O&M) costs are assumed to equal 10 % of annual capital payments on the investment for conventional processes and 15 % of annual capital charges for innovative processes. Under these hypotheses.

Table 4.8 presents the total cost of feedstock conversion in bioenergy, to be further summed with the feedstock cost to give the total final cost of sugarcane bioenergy.

Table 4.6 Reference plants for processing sugarcane for bioenergy

TECHNOLOGY	FEEDSTOCK		ETHANOL PRODUCTION	ELECTRICITY PRODUCTION
	TYPE	(kt/year)	(ML/year)	(GWh/year)
DISTILLERY IN A BROWNFIELD MILL	Molasses	64	16.3	0
ADVANCED 1G GREENFIELD MILL	Sugarcane + straw	1 600	136.0	296
INTEGRATED 1G/2G MILL	Sugarcane + straw	4 000	433.9	274
INTEGRATED 1G/2G MILL	Energy cane + straw	4 000	472.0	584

Based on: Leal *et al.* (2016) and Bonomi (2015)

Table 4.7 Investment outlay for a plant processing sugarcane to bioenergy

TECHNOLOGY	TOTAL INVESTMENT	INVESTMENT FOR ETHANOL	INVESTMENT FOR ELECTRICITY
	(USD MILLION)	(USD MILLION)	(USD MILLION)
DISTILLERY IN A BROWNFIELD MILL	4.4	4.4	0
ADVANCED 1G GREENFIELD MILL	252.9	141.6	111.3
INTEGRATED 1G/2G MILL	660.8	482.4	178.4

Based on: Leal *et al.* (2016), Junqueira *et al.* (2017) and Bonomi (2015)

Table 4.8 Conversion cost of sugarcane to bioenergy

TECHNOLOGY	FEEDSTOCK	FINAL CONVERSION COST	
		ETHANOL (USD/L)	ELECTRICITY (USD/kWh)
DISTILLERY IN A BROWNFIELD MILL	Molasses	0.039	0.000
ADVANCED 1G GREENFIELD MILL	Sugarcane + straw	0.151	0.054
INTEGRATED 1G/2G MILL	Sugarcane + straw	0.161	0.094
INTEGRATED 1G/2G MILL	Energy cane + straw	0.155	0.046

Note: Applies 10 % interest rate to investment, assumes annual O&M cost as share of annual investment cost of 10 % for conventional technologies and 15 % for Integrated 1G/2G plants

Based on these values, unit investment costs can be calculated per tonne of feedstock or product, as shown in Table 4.9. Values and costs for particular plants will vary, of course.

Feedstock and conversion costs contribute to unit investment costs

Table 4.9 Unit investment costs for plants processing sugarcane to bioenergy

TECHNOLOGY	COST PER UNIT OF FEEDSTOCK			COSTS PER UNIT OF PRODUCT	
	TOTAL (USD/t)	ETHANOL (USD/t)	ELECTRICITY (USD/t)	ETHANOL (USD/L/year)	ELECTRICITY (USD/kWh/year)
DISTILLERY IN A BROWNFIELD MILL	68.7	68.7	–	0.270	–
ADVANCED 1G GREENFIELD MILL	158.1	69.5	88.5	1.041	0.376
INTEGRATED 1G/2G MILL	165.2	44.6	120.6	1.112	0.651
INTEGRATED 1G/2G MILL WITH ENERGY CANE	165.2	44.6	120.6	1.022	0.306

5 SUPPLY CURVES FOR BIOENERGY FROM SUGARCANE IN SOUTHERN AFRICA

In considering policies to promote sustainable bioenergy from sugarcane, decision makers have to assess how much bioenergy can be produced at what cost. Based on the preceding analysis, this chapter posits scenarios for sugarcane feedstock production and processing technology. For each scenario, it develops supply curves for ethanol and electricity, showing the potential energy supply at different costs for each of the seven focus countries in southern Africa.

Six scenarios highlight different feedstock and processing options to expand sugarcane bioenergy production

5.1 SCENARIOS FOR SUGARCANE BIOENERGY

Six scenarios were chosen to cover a range of options for expanding bioenergy production from sugarcane in southern Africa, as detailed in Tables 5.1 and 5.2.

- Two "T" scenarios examine supply potential on land used to grow sugarcane today. Both assume that bioenergy is produced only from by-products of sugar production, which is held constant. One assumes current yields, the other improved yields.

- Two "E" scenarios examine supply potential with sugarcane culture expansion. Both assume expansion of sugarcane culture to all suitable rainfed areas by 2030. One assumes further expansion to areas requiring irrigation, the other does not.

- Two "F" scenarios examine supply potential with technology that could be widely adopted in future. Both assume production of sugarcane on all suitable land, with half the straw used in integrated first- and second-generation (1G/2G) ethanol plants by 2030. One assumes use of conventional sugarcane, the other use of energy cane.

Table 5.1 Agroindustry technology and land-use scenarios evaluated

SCENARIO		YEAR	SUGARCANE AREA	SUGARCANE YIELD	INDUSTRIAL PROCESS
T1	Today	2015	CU	SCC	1GM
T2	Today improved	2015	CU	SCI	1GM+1GD
E1	Expansion to rainfed land	2030	CU+RF	SCI	1GM+1GD
E2	Expansion to irrigated land	2030	CU+RF+IR	SCI	1GM+1GD
F1	Future process	2030	CU+RF+IR	SCI	1GD+2G
F2	Future process & feedstock	2030	CU+RF+IR	ENC	1GD+2G
KEY:					
SUGARCANE AREA					
• CU	Area currently cultivated, from FAOSTAT (FAO, 2018)				
• RF	Expansion in rainfed area, as indicated in the land assessment (Chapter 2)				
• IR	Expansion in irrigated area, as indicated in the land assessment (Chapter 2)				
SUGARCANE YIELD					
• SCC	Current sugarcane yield, from FAOSTAT (FAO, 2018)				
• SCI	Improved yield, from Sugarcane Yield Model in Chapter 2 (HD=0, N=80 kg N/ha)				
• ENC	Energy cane yield, 130 t/ha (per Landell *et al.*, 2010)				
INDUSTRIAL PROCESS FOR ETHANOL PRODUCTION					
• 1GM	Conventional process, from molasses				
• 1GD	Conventional process, from direct juice				
• 1GD+2G	Advanced, integrating ethanol from direct juice and lignocellulosic feedstock				

Table 5.2 Productivity parameters for sugarcane and energy cane processing

PROCESSING TECHNOLOGY	PRODUCTIVITY PARAMETERS		
	SUGAR	ETHANOL	ELECTRICITY
1GM, CONVENTIONAL FROM MOLASSES	125 kg/t cane	10.4 L/t cane	zero
1GD, CONVENTIONAL FROM SUGARCANE JUICE	zero	85 L/t cane	185 kWh/t cane
INTEGRATED 1G+2G WITH 50 % STRAW USE	zero	108.5 L/t cane	68.5 kWh/t cane
INTEGRATED 1G+2G WITH ENERGY CANE, 50 % STRAW USE	zero	111.4 L/t cane	112.2 kWh/t cane

* Except for the year 2015, for which the yield is taken from ISO (2018)

2G processes: CTBE (2015), adjusted for energy cane composition per Landell *et al.* (2010)

Source: 1G processes: Leal *et al.* (2016) and BNDES and CGEE (2008);

Projection of sugar production and consumption

As sugar production and demand are prioritised over energy production in the analysis, estimates were developed for the sugar market in 2030. Tables 5.3 and 5.4 present data on production, consumption and trade of sugar in 2015 (ISO, 2018). Based on these data, sugar demand was projected for 2030, as presented in Table 5.5, assuming that:

- Sugar consumption per capita declines by 0.1 % per annum in South Africa and grows 0.8 % per annum in other southern African countries (FAO, 2012 and IRENA analysis).

- Sugar exports and imports are held constant so that domestic sugar production in 2030 is the sum of projected sugar demand in 2030 and net sugar exports in 2015.

Table 5.3 Sugar balances by country in 2015

COUNTRY	BALANCES IN MILLION TONNES (Mt)				
	PRODUCTION	IMPORT	EXPORT	STOCK CHANGE	CONSUMPTION
ESWATINI	0.70	–	0.62	+0.03	0.05
MALAWI	0.29	0.04	0.10	–	0.23
MOZAMBIQUE	0.37	0.04	0.24	-0.03	0.19
SOUTH AFRICA	1.63	0.46	0.24	-0.02	1.87
TANZANIA*	0.32	0.21	–	-0.06	0.59
ZAMBIA	0.38	–	0.15	+0.30	0.23
ZIMBABWE	0.41	0.04	0.15	+0.22	0.30

* United Republic of Tanzania

Source: ISO (2018)

Table 5.4 Sugar demand by country in 2015

COUNTRY	CONSUMPTION (Mt)	POPULATION IN 2015 (thousands)	CONSUMPTION IN 2015 (kg/capita)
ESWATINI	0.70	1 319	40.9
MALAWI	0.29	17 574	13.3
MOZAMBIQUE	0.37	28 011	6.8
SOUTH AFRICA	1.63	55 291	33.9
TANZANIA*	0.32	53 880	10.9
ZAMBIA	0.38	16 101	14.2
ZIMBABWE	0.41	15 777	19.3

* United Republic of Tanzania

Source: ISO (2018)

Table 5.5 Sugar demand projection for 2030

COUNTRY	ANNUAL CONSUMPTION GROWTH RATE	POPULATION IN 2030 (millions)	CONSUMPTION PER CAPITA IN 2030 (kg/capita/year)	DOMESTIC SUGAR CONSUMPTION IN 2030 (Mt)	DOMESTIC SUGAR PRODUCTION IN 2030 (Mt)
ESWATINI	+0.8 %	1.7	49.7	0.08	0.70
MALAWI	+0.8 %	26.6	16.2	0.43	0.49
MOZAMBIQUE	+0.8 %	42.4	8.2	0.35	0.55
SOUTH AFRICA	-0.1 %	64.5	32.9	2.12	1.90
TANZANIA*	+0.8 %	83.7	13.2	1.11	0.90
ZAMBIA	+0.8 %	24.9	17.3	0.43	0.58
ZIMBABWE	+0.8 %	21.5	23.4	0.50	0.62

* United Republic of Tanzania

Source: ISO (2018), FAO (2012), IRENA analysis

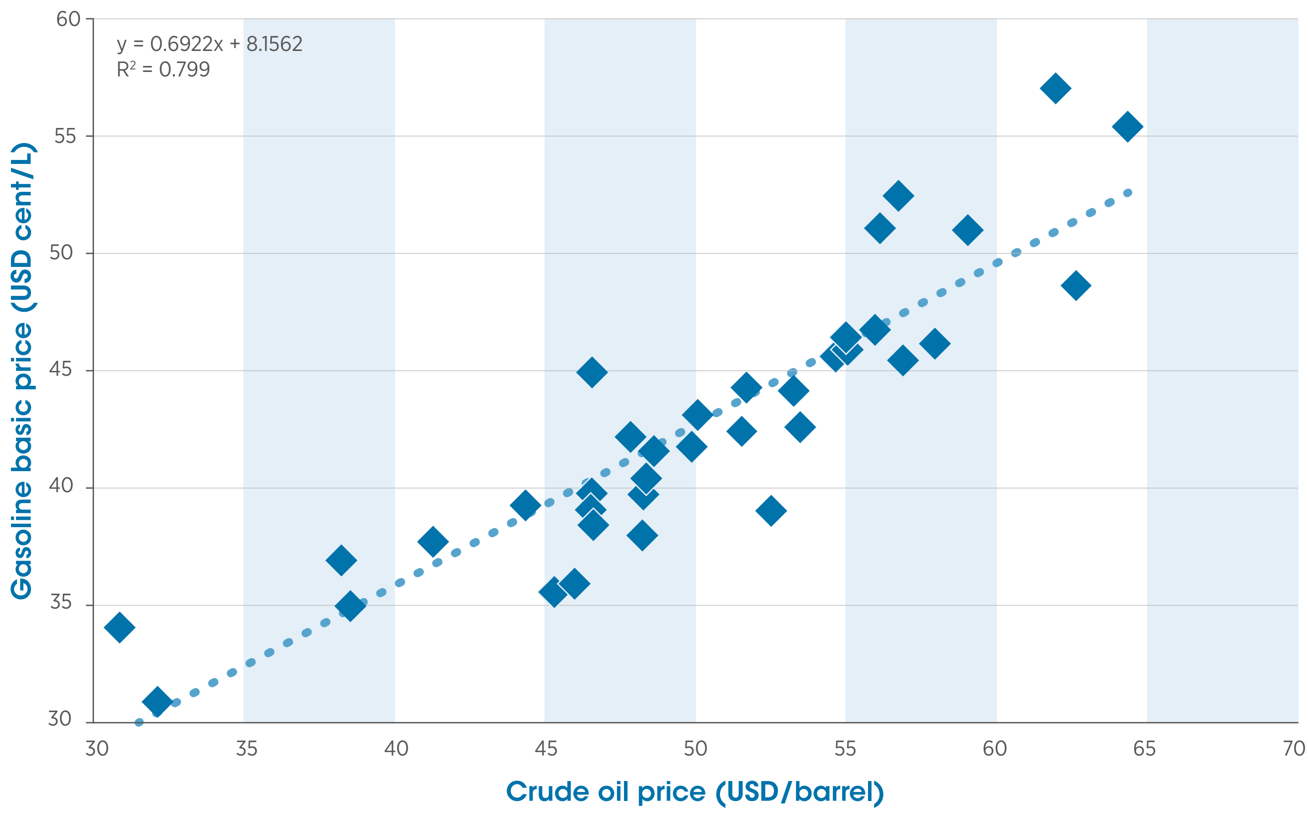
Current and prospective gasoline prices

To assess the extent to which ethanol from sugarcane could be cost-competitive for road transport, the comparative cost of gasoline (petrol) has to be assessed. There are higher-tech applications of ethanol, such as conversion to aviation fuel, and lower-tech applications, such as cooking or heating, but this report focuses on transport as an indicative market. To further simplify, the costs of ethanol and gasoline at the production plant gate are compared, assuming that the additional costs of bringing fuel to consumers will be roughly comparable.

This assessment assumes that gasoline prices are correlated with crude oil prices. Figure 5.1 presents gasoline prices (excluding taxes, at the producer gate) and crude oil prices observed in South Africa during the last decade (DOE/ZA, 2018), along with the linear correlation equation obtained from these values:

$$GP_{\text{(gasoline price)}} = 0.6922\ COP_{\text{(crude oil price)}} + 8.1562$$

Figure 5.1 Correlation between crude oil and gasoline prices



Source: DOE/ZA (2018), IRENA analysis

For illustrative purposes, a range of crude oil prices, from USD 50 to USD 100 per barrel, are considered. The lower bound is close to prices for crude oil in 2018, and the upper bound close to the US Energy Information Administration's reference case projection for 2030 (EIA, 2018). Applying the correlation, this corresponds to USD 0.43–0.77 per L of gasoline.

To convert ethanol prices to equivalent gasoline prices, a litre of ethanol was assumed to have the same energy content as 0.70 L of gasoline (BNDES and CGEE, 2008). This volumetric heating value equivalence can be considered conservative as ethanol allows greater efficiency, producing more useful power per unit of chemical energy in the fuel (Ricardo, 2017).

5.2 ETHANOL PRODUCTION POTENTIAL AND COSTS

Combining estimates of ethanol production cost and potential sugarcane yield, from previous chapters, with data on cultivated land and agroindustrial productivity for the six scenarios described in Table 5.1, ethanol supply curves for each country can be drawn. Supply curves are presented and described below for the "T" cases describing potential output today, "E" cases describing potential with sugarcane expansion, and "F" cases assuming widespread deployment of advanced conversion technologies in the future. Comparative gasoline prices for a hypothetical range of USD 50 to USD 100 per barrel of crude are shaded in grey.

Ethanol potential and cost with improved yield

Using only the land currently cultivated with sugarcane, ethanol potential is quite limited. As indicated in Table 5.6, considering all seven countries, 382 ML of ethanol could be produced yearly at an average cost of USD 0.55 per L of gasoline equivalent without sugarcane yield improvement (scenario T1, three columns of numbers on the left). With enhanced sugarcane yield, an extra 1.4 billion L of ethanol could be produced by conventional processes at an average cost of USD 0.71 per L of gasoline equivalent.

In Mozambique, South Africa, the United Republic of Tanzania and Zimbabwe, where gains in sugarcane yield are envisaged (scenario T2, three columns of numbers on the right). In both cases, the ethanol potential is surplus to current domestic sugar demand and exports. However, at a crude oil price of USD 50 per barrel (gasoline price of USD 0.43/L), only around 70 ML of low-cost ethanol from molasses, produced in Mozambique and Zambia, would be cost-competitive.

Table 5.6 Ethanol production potential and costs in 2015

COUNTRY	ETHANOL FROM MOLASSES BY-PRODUCT			1G ETHANOL DIRECT FROM SUGARCANE		
	POTENTIAL (billion litres)	COST (USD/litre-ethanol)	COST (USD/ litre-gasoline equivalent)	POTENTIAL (billion litres)	COST (USD/litre-ethanol)	COST (USD/ litre-gasoline equivalent)
ESWATINI	0.06	0.34	0.49	0.00	0.48	0.68
MALAWI	0.03	0.38	0.54	0.00	0.43	0.61
MOZAMBIQUE	0.03	0.30	0.43	0.13	0.49	0.70
SOUTH AFRICA	0.15	0.42	0.60	0.76	0.48	0.68
TANZANIA*	0.03	0.49	0.70	0.46	0.53	0.76
ZAMBIA	0.04	0.29	0.41	0.00	0.48	0.68
ZIMBABWE	0.03	0.39	0.56	0.07	0.49	0.69
TOTAL	**0.38**	**0.38**	**0.55**	**1.41**	**0.50**	**0.71**

* United Republic of Tanzania

Figure 5.2 Supply curve for ethanol from molasses, with improved agricultural practices

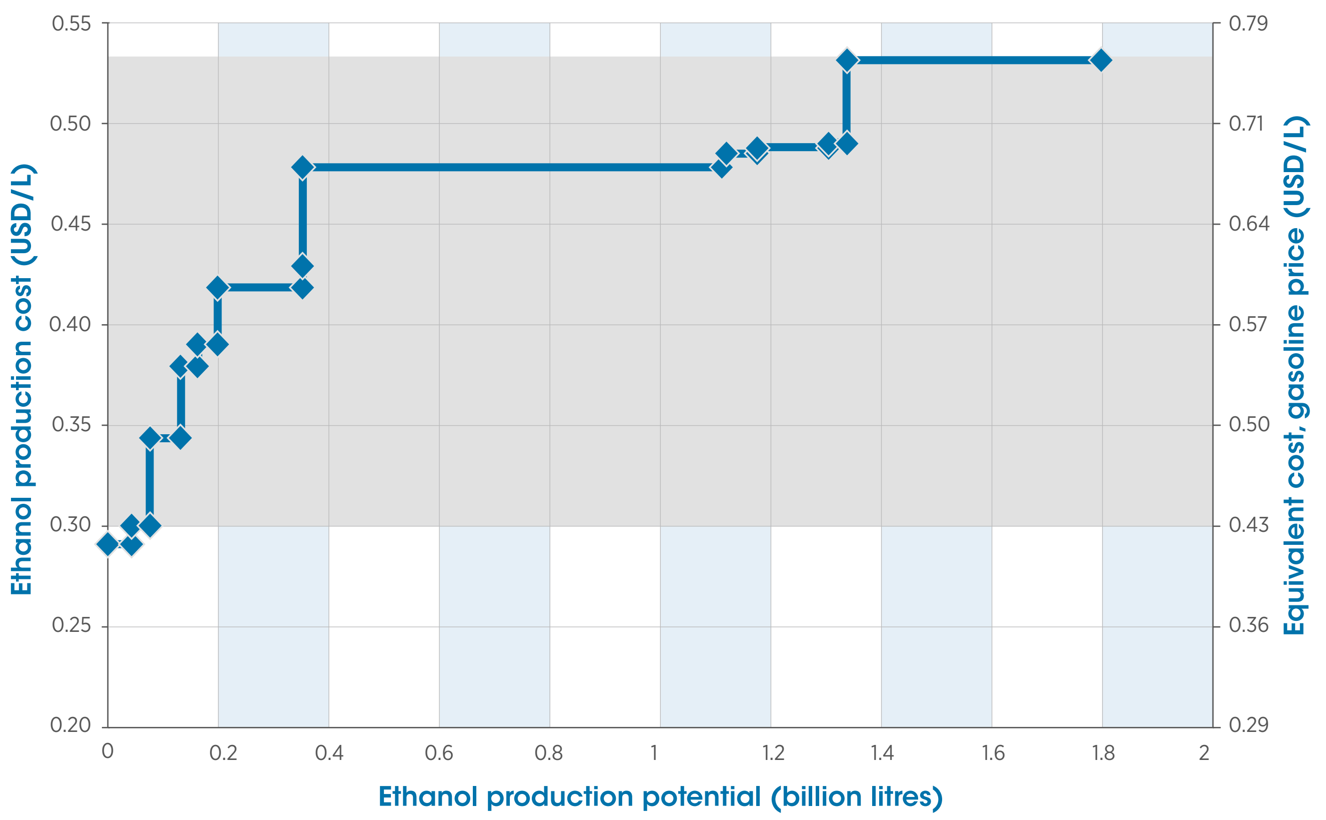


Table 5.7 Ethanol potential and cost with improved yield and land expansion by 2030

COUNTRY	ETHANOL FROM MOLASSES BY-PRODUCT			1G ETHANOL DIRECT FROM SUGARCANE				
	POTENTIAL (BILLION LITRES)	COST		POTENTIAL (BILLION LITRES)			COST	
		USD/LITRE ETHANOL	USD/LITRE GASOLINE EQUIVALENT	CL	CL+RF	CL+RF+IR	USD/LITRE ETHANOL	USD/LITRE GASOLINE EQUIVALENT
ESWATINI	0.06	0.34	0.49	0.00	0.00	0.00	0.48	0.68
MALAWI	0.04	0.38	0.54	0.00	1.56	1.56	0.43	0.61
MOZAMBIQUE	0.05	0.30	0.43	0.02	20.10	31.38	0.49	0.70
SOUTH AFRICA	0.16	0.42	0.60	0.73	0.73	5.44	0.48	0.68
TANZANIA*	0.08	0.49	0.70	0.09	3.30	4.45	0.53	0.76
ZAMBIA	0.05	0.29	0.41	0.00	9.95	21.25	0.48	0.68
ZIMBABWE	0.05	0.39	0.56	0.00	4.61	7.65	0.49	0.69
TOTAL	0.48	0.39	0.56	0.8	40.2	71.7	0.48	0.69

Note: See key from Table 5.1 for abbreviations used in this table.

* United Republic of Tanzania

Ethanol potential and cost with land expansion

With expansion of sugarcane production to all suitable rainfed and irrigated areas, ethanol production potential in the seven countries is much more substantial. As Table 5.7 shows, the potential from direct sugarcane conversion could reach 40.2 billion L with expansion to suitable rainfed land only (scenario E1, fifth column of numbers from the left) or 71.7 billion L with further expansion to very suitable irrigated land (scenario E2, sixth column) at an average cost of USD 0.69 per L of gasoline equivalent.

About another 0.5 billion L could be converted from molasses by-products of sugar production. So, with crude oil prices of USD 100 per barrel, the total amount would be cost-competitive for transport fuel, per Figure 5.3. The projected potential is surplus to sugar demand and exports for each country.

Where rainfall in deficient, irrigation can compensate

Figure 5.3 Supply curves for ethanol with improved yield and land expansion by 2030

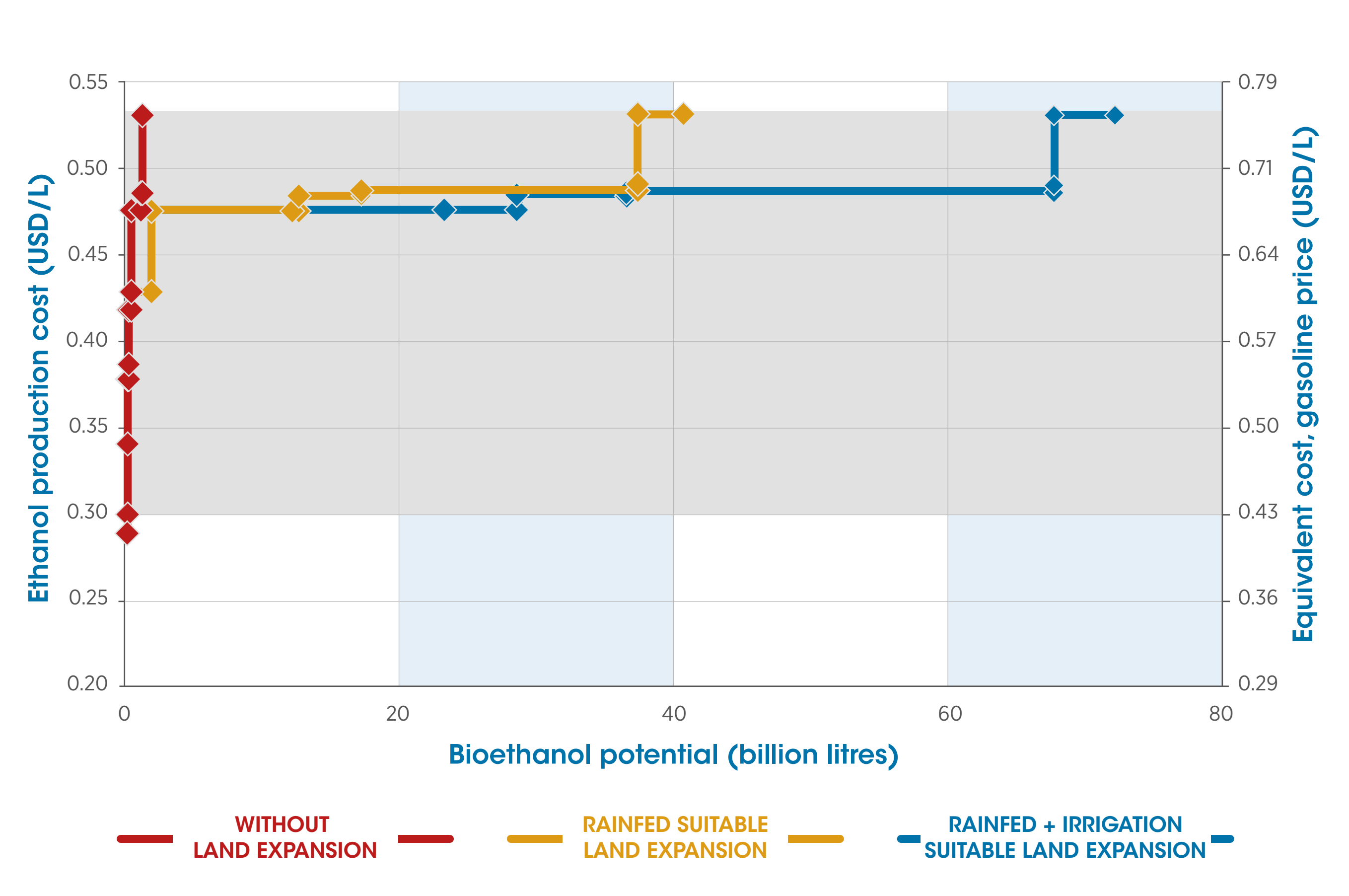


Table 5.8 Ethanol potential and cost with integrated 1G and 2G processes

COUNTRY	FEEDSTOCK	ETHANOL FROM MOLASSES BY-PRODUCT			1G/2G ETHANOL DIRECT FROM CANE		
		POTENTIAL	COST		POTENTIAL	COST	
		BILLION LITRES	USD/LITRE ETHANOL	USD/LITRE GASOLINE EQUIVALENT	BILLION LITRES	USD/LITRE ETHANOL	USD/LITRE GASOLINE EQUIVALENT
ESWATINI	SUGARCANE	0.06	0.34	0.49	0.00	0.42	0.59
MALAWI	SUGARCANE	0.04	0.38	0.54	1.99	0.38	0.54
MOZAMBIQUE	SUGARCANE	0.05	0.30	0.43	40.06	0.42	0.61
SOUTH AFRICA	SUGARCANE	0.16	0.42	0.60	6.95	0.42	0.60
TANZANIA*	SUGARCANE	0.08	0.49	0.70	5.68	0.46	0.66
ZAMBIA	SUGARCANE	0.05	0.29	0.41	27.12	0.42	0.59
ZIMBABWE	SUGARCANE	0.05	0.39	0.56	9.77	0.42	0.60
TOTAL	SUGARCANE	**0.48**	**0.39**	**0.56**	**91.6**	**0.42**	**0.60**
ESWATINI	ENERGY CANE	0.07	0.34	0.49	0.05	0.39	0.55
MALAWI	ENERGY CANE	0.05	0.38	0.54	2.58	0.35	0.51
MOZAMBIQUE	ENERGY CANE	0.06	0.30	0.43	55.04	0.40	0.57
SOUTH AFRICA	ENERGY CANE	0.20	0.42	0.60	10.98	0.39	0.56
TANZANIA*	ENERGY CANE	0.09	0.49	0.70	8.22	0.43	0.61
ZAMBIA	ENERGY CANE	0.06	0.29	0.41	37.15	0.39	0.56
ZIMBABWE	ENERGY CANE	0.06	0.39	0.56	14.54	0.40	0.56
TOTAL	ENERGY CANE	**0.60**	**0.39**	**0.56**	**128.6**	**0.39**	**0.56**

* United Republic of Tanzania

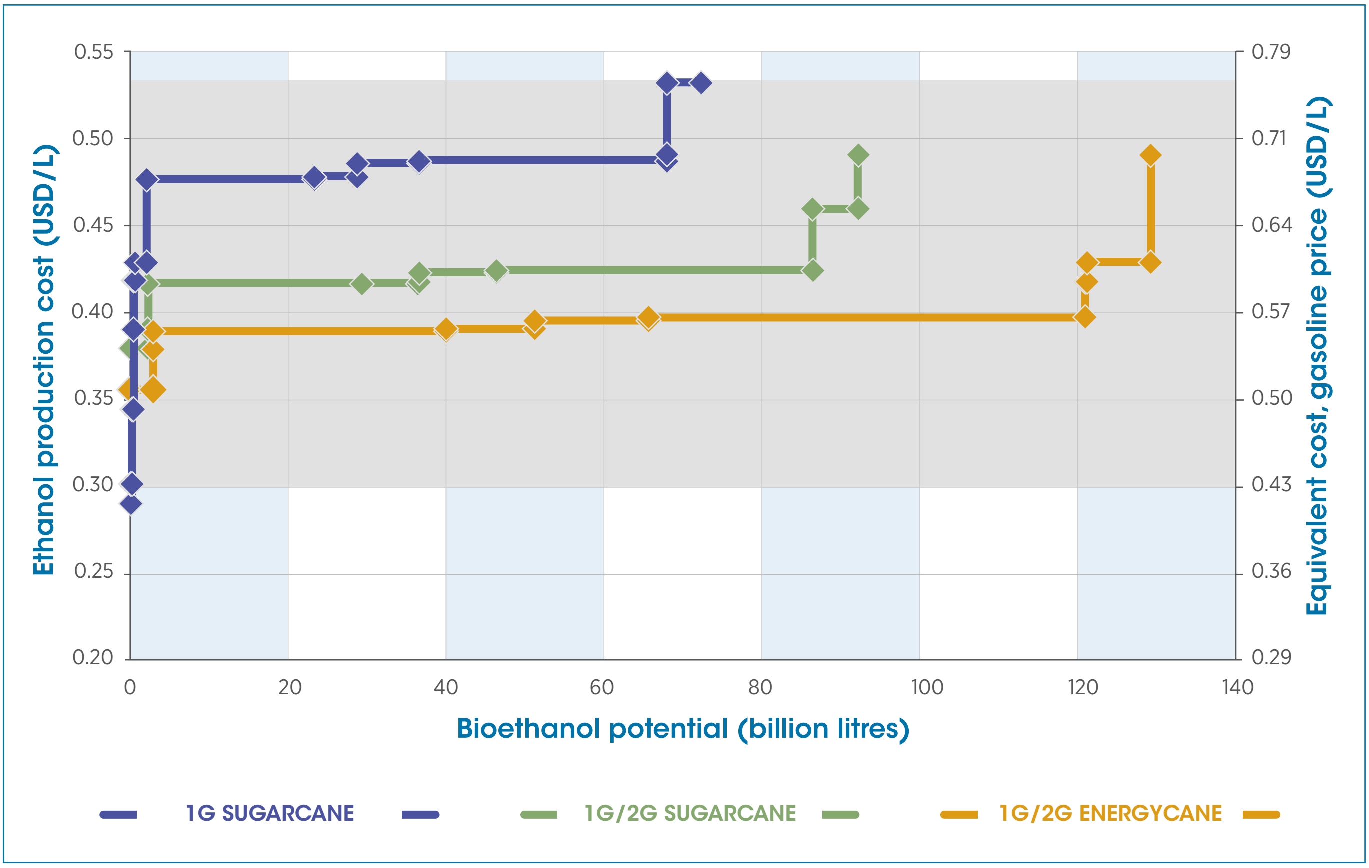
Ethanol potential and cost with advanced technology

With the future application of advanced technology for cultivation and conversion, the ethanol potential would be further enhanced. As shown in Table 5.8, the introduction of 2G technology for conversion of straw, on top of 1G processes to conversion of sugar, could increase the yearly production potential from direct conversion by nearly 20 billion L to 91.6 billion L (scenario F1, top eight rows of numbers). Furthermore, the introduction of high-yielding energy cane could boost annual production by nearly another 37 billion L to 128.6 billion L (scenario F2, bottom eight rows of numbers). Energy cane would also increase potential from molasses by-product by around 0.1 billion L.

Assuming that the development and maturation of innovative 2G processes enhance the economic viability of sugarcane bioenergy, integrated 1G/2G processes could produce ethanol from sugarcane more cheaply than gasoline in 2030 if crude oil prices increase. The introduction of energy cane would further improve bioenergy prospects in this context, raising productivity and reducing costs by around 10 %. The high-yielding energy cane would also reduce land requirements and adverse land-use change.

As can be seen in Figure 5.4, most of the potential in either case would be cost-competitive with gasoline in the middle of the postulated crude oil price range of USD 50 to USD 100 per barrel. Ethanol is even more cost-competitive with current gasoline market prices in the region, which range from USD 0.92 to USD 3.34 per litre. This is especially true in those countries with the highest gasoline prices, namely Zambia (USD 1.71/L) and Zimbabwe (USD 3.34/L) (GlobalPetrol Prices, 2019).

Figure 5.4 Supply curves for ethanol with integrated 1G and 2G processes



5.3 ELECTRICITY PRODUCTION POTENTIAL AND COSTS

Depending upon whether sugarcane feedstock is directed primarily to sugar production or ethanol production, different amounts of bagasse and straw are available for electricity generation. Table 5.9 shows the electricity potential and costs for the scenarios analysed.

If sugarcane culture were expanded to all suitable rainfed and irrigated land (scenario E2), about 156 TWh could be generated from sugarcane residues with conventional technology. If advanced conversion technology were applied, with half the straw converted to ethanol in a 2G process (scenario F1), the potential would reach some 57.8 TWh. The electricity potential decreases because the 2G unit consumes part of the straw and bagasse and requires more electricity to produce greater amounts of ethanol than the 1G unit. If energy cane were grown (scenario F2), the potential would increase to just 158.9 TWh with higher fibre content.

Generating costs associated with conventional biofuel conversion technology are similar to those associated with the full application of advanced biofuel conversion technology. The addition of a 2G conversion facility raises electricity costs from about USD 0.062 per kWh to about USD 0.102 per kWh, due to the need to amortise increased capital equipment costs. However, switching from conventional sugarcane to advanced energy cane then reduces costs again to USD 0.054 per kWh due to the lower feedstock costs allowed by higher yields.

Table 5.9 Electricity potential and costs from sugarcane and energy cane

COUNTRY	1G WITH SUGARCANE		1G/2G WITH SUGARCANE		1G/2G WITH ENERGY CANE	
	POTENTIAL (TWh)	COST (USD/kWh)	POTENTIAL (TWH/YEAR)	COST (USD/kWh)	POTENTIAL (TWh/year)	COST (USD/kWh)
ESWATINI	0.0	0.062	0.0	0.102	0.1	0.054
MALAWI	3.4	0.062	1.3	0.102	3.2	0.054
MOZAMBIQUE	68.3	0.062	25.3	0.102	68.0	0.054
SOUTH AFRICA	11.8	0.062	4.4	0.102	13.6	0.054
TANZANIA*	9.7	0.062	3.6	0.102	10.2	0.054
ZAMBIA	46.2	0.062	17.1	0.102	45.9	0.054
ZIMBABWE	16.7	0.062	6.2	0.102	18.0	0.054
TOTAL	**156.1**	**0.062**	**57.8**	**0.102**	**158.9**	**0.054**

* United Republic of Tanzania

6 CONCLUSIONS

Substantial potential exists to expand the production of bioenergy from sugarcane, including both ethanol and electricity, in the seven countries of southern Africa that were studied. Further investigation could shed light on which portions of this potential should be developed in light of prevailing and anticipated land-use patterns.

Where other crops are planted or expected to be planted, such insights could be useful to evaluate sugarcane cultivation as a possible alternative. This would also highlight where sugarcane for bioenergy would most clearly increase value addition and thereby improve the livelihood of rural communities.

Ethanol production potential

With the expansion of sugarcane cultivation and application of advanced technologies for both cultivation and conversion, the potential of ethanol would exceed projected gasoline consumption.

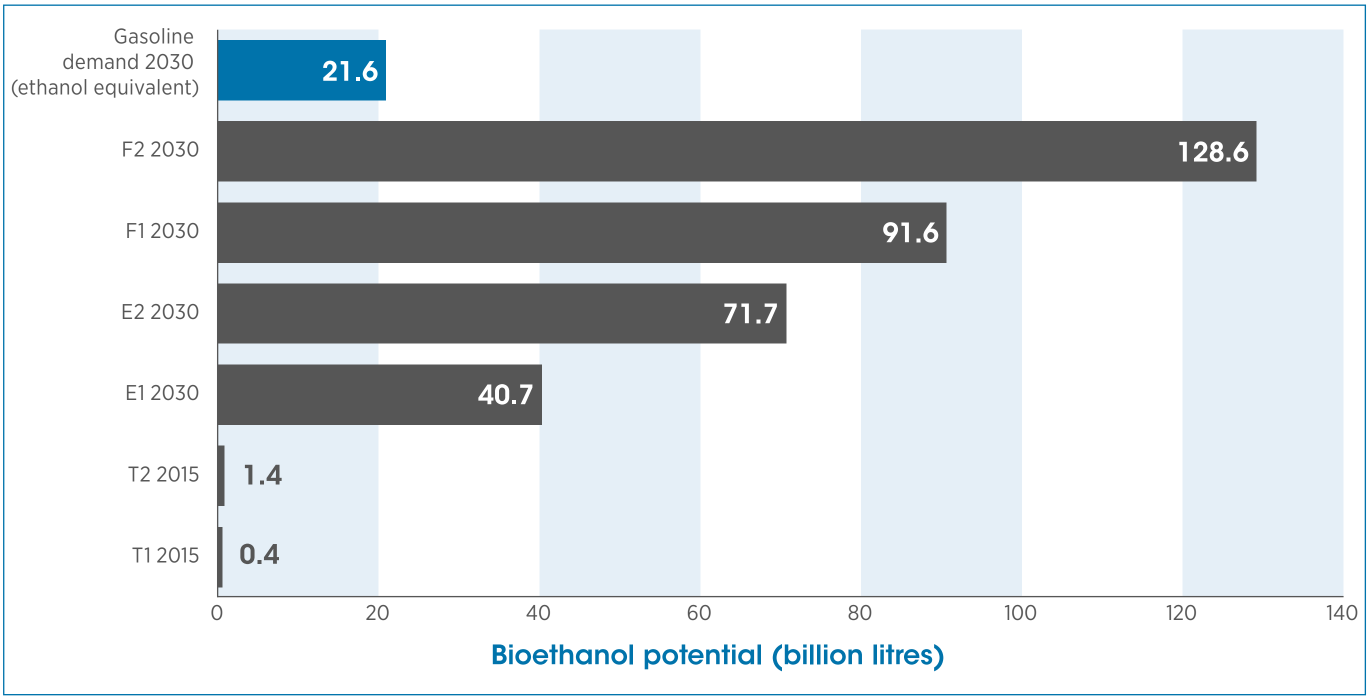
- If yields were improved on land planted with sugarcane today (case T2), some 1.4 billion litres of ethanol per year could be produced on top of domestic and export sugar needs.
- If sugarcane cultivation were expanded to all land suitable with natural rainfall (case E1), about 41 billion litres of ethanol could be produced per year, and if it were further expanded to land suitable with irrigation (case E2), some 72 billion litres per year could be produced.
- With future application of advanced sugarcane technology on this land (case F1), about 92 billion litres per year of ethanol could be produced, and with further application of advanced conversion technology as well (case F-2), about 129 billion litres per year could be produced.
- By comparison, gasoline demand projected for 2030 would equate to just about 22 billion litres, so sugarcane ethanol potential could be up to nearly six times as great.

The ability to develop this ethanol potential on a cost-effective basis as a replacement for gasoline would largely depend on the world price of oil and the market value of carbon:

- At oil prices over USD 75 per barrel, almost all the potential would be cost-effective.
- With a market value for carbon emissions, which are greater for gasoline from oil than for ethanol from energy cane, the potential would be cost-effective at lower oil prices.
- Ethanol could also be used as a clean fuel for cooking at the household level.

Further investigation could help to determine where expanded sugarcane cultivation would add the most value

Figure 6.1 Six scenarios of ethanol potential in seven countries of southern Africa



Electricity production potential

Sugarcane cultivation on all suitable lands could also provide significant amounts of electricity:

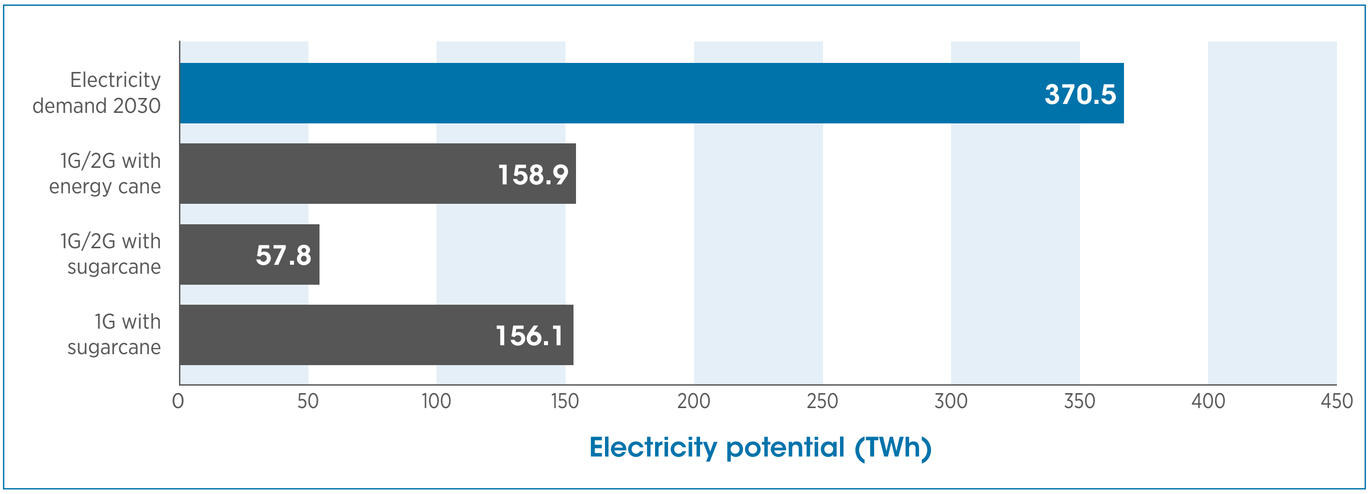
- Applying conventional conversion technology to conventional sugarcane, about 156 TWh per year, or 42 % of projected electricity demand in 2030, could be supplied.
- Applying advanced conversion technology to energy cane, only slightly more electricity could be supplied, amounting to 159 TWh per year or 43 % of projected 2030 electricity demand, since more of the cane's energy content would be needed for process heat.
- Applying advanced conversion technology to conventional sugarcane, with less energy content than energy cane, just 58 TWh, or 16 % of demand, could be provided each year.

Suggestions for further analysis

More detailed analysis could be done at the country level to identify:

- lands on which sugarcane cultivation for bioenergy is most likely to benefit farmers
- capacity-building needs to apply new sugarcane cultivation and conversion technologies
- achievable targets for sustainable expansion of bioenergy from sugarcane over time
- policy measures to help reach sugarcane bioenergy targets on a timely, efficient basis
- capacity for performance-enhancing blends with gasoline to absorb the ethanol potential
- cost-effectiveness of electricity generation from sugarcane compared with other options
- investment requirements for the scale-up of bioenergy production from sugarcane.

Figure 6.2 Electricity potential from sugarcane in seven countries of southern Africa



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