Seeking CLEWS - Climate, Land, Energy and Water Strategies - A pilot case study in Mauritius

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Abstract

Governments' are faced with ensuring the security of water, energy and food supplies. This applies both to countries using these commodities as well as exporters. Further, in order to underpin socioeconomic development, the provision of inputs should be at low cost, environmentally benign and entail consistent policy making. The aim of this effort is to illustrate the practical 'achievability' of multi-resource planning as well as illustrate its benefits.

This paper demonstrates the integration of a water, energy and land-use model to quantify greenhouse gas emissions and costs associated with meeting energy, water and food security goals in an island state. The illustrative case study is for the Island of Mauritius, for which a WEAP, LEAP and a land production planning model (AEZ) were developed and run in an integrated fashion to determine (a) potentials of bio-fuel production targets, (b) the consequence of crop changes and (c) measures to ensure adequate water supplies in the face of decreasing rainfall.

Introduction

The approach

As Rogner (2009) notes, "…most water, energy and land-use planning, decision and policy making occurs in separate and disconnected institutional entities." Likewise, the analytical tools used to support decision-making are equally fragmented, though undertaken routinely. Common tools used for energy system analysis include, for example, the MESSAGE[1], MARKAL[2] and LEAP[3] models. A commonly used model for water system planning is the Water Evaluation and Planning system (WEAP[4]), and for water scarcity and food security planning, the Global Policy Dialogue Model (PODIUM) model is well

[1] MESSAGE (Model of Energy Supply Strategy Alternatives and their General Environmental Impacts) is a systems engineering optimization model which can be used for medium to long term energy system planning, energy policy analysis and scenario development. The model provides a framework for representing an energy system with its internal interdependencies. (IIASA 2001)
[2] MARKAL (Market Allocation) model of the ETSAP implementing agreement of the International Energy Agency (ETSAP 2011).
[3] LEAP (Long Range Energy Alternatives Planning) model of the Stockholm Environmental Institute (SEI 2011).
[4] The WEAP (Water Evaluation and Planning) model is maintained and supported by the Stockholm Environmental Institute: http://www.seib.org/software/weap.html

established[5]. However, these and other models, in one way or another, lack the components required to conduct an integrated policy assessment especially where these may be needed in a developing country policy context. Generally, they focus on one resource and ignore the interconnections with other resources; have overly simplified spatial representations; are grand policy "*research*" rather than short term applied "*policy*"/decision support models, or analyze scenarios which are impractically long term[6].

The development of the Climate, Land, Energy and Water (CLEW) modeling framework is a response to this issue (IAEA, 2009[7]). Key improvements over existing approaches should include: finer geographical coverage, simplified data requirements, a medium term temporal scope, multi-resource representation (including their inter-linkages) and software accessible to developing country analysts. Also, it uses a systems approach, which refers to physical accounting of resource, technology and other requirements to meet certain needs and services, with the accounting extended far upstream. By ensuring that mass and energy balances are not violated, consistent scenarios were developed. Various costs are associated with activities and those in turn were also compared from one to another scenario. As an initial step, a detailed water (WEAP), energy (LEAP) and land production planning (AEZ[8]) method were applied. The models were run in an integrated fashion with common assumptions and soft-linkages. In order to demonstrate their usefulness, they were applied to a case study – the production of food (exports in the form of sugar) and fuel, under various water stresses on the island of Mauritius.

Background to the case study - Mauritius

The Republic of Mauritius is an island country in the Indian Ocean, 950 km to the east of Madagascar. It has a land surface area of 1865 km^2 and is volcanic in origin with a central plateau surrounded by mountain ranges and plains. The highest peak on the island has an elevation of828 m.a.s.l. The island has a tropical maritime climate consisting of two seasons: summer, which lasts from November to April and is the rainier season, and winter, which is cooler and relatively dry. Average annual temperatures range from 20 to 25 °C and rainfall ranges from 600 mm to 4000 mm depending on elevation and position relative to the prevailing winds.

Mauritius has made considerable progress in transforming its economy from a low-income country to a middle-income country based primarily on: services (68% of GDP) including tourism; industry (27%) including sugar processing and textiles and agriculture (5%) (ROM 2009a). However, the country's economic and social progress is potentially under threat from external shocks. These include the decision (that came into effect in October 2009) by the EU to cut its guaranteed sugar import price and hence reduced the price of sugar imported from Mauritius by 36 per cent over the four year period 2006–09. Another important shock is the recent rise and volatility experienced in world energy prices. Mauritius imports 82% of its energy needs. The remaining requirements are met by domestic renewables, with bagasse accounting for 94%. Imported fuels include coal (27% of imports) used for electricity generation, as well as liquid fuels, such as petrol for transport. Thus, increased energy security and diversifying income from sugar exports are key concerns.

Sugar production has been of strategic importance for the country for decades. Since 1975, Mauritius has had an export quota of about 500,000 tons per year under the Sugar Protocol of the Lomé Convention. The convention links European Union imports to the African, Caribbean and Pacific (ACP)

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[5] The Podium model is maintained and supported by the International Water Management Institute http://podium.iwmi.org/podium/

[6] Examples of models which tackle some of the integrated nature of the CLEW system, but are impractical for local short-to-medium term policy making include, amongst others: MINICAM (PNL 2011), IMAGE (EMN 2011), and TIAM (Loulou & Labriet 2008).

[7] A full case study using CLEWS can be found in Rogner et al (Submitted).

[8] AEZ (Agro Ecological Zoning) model developed by IIASA

countries' exports. Currently over 95% of the sugar produced in the country is exported to the European Union (EC, 2009). During the 2007 agricultural exports, of which 55% were sugar represented 34% of total domestic exports (ROM, 2008). However, it is likely that this sector will undergo substantial changes in the wake of the reform of the EU sugar import regime. Accordingly, the government has formulated several measures to refocus agriculture. A multi-annual adaptation strategy and action plan highlighting the steps to be taken has been prepared. As a consequence of the government's "diversification" policy, many planters with access to irrigation have diversified from sugar cane to food crops and vegetables; others are assessing a shift towards ethanol production from sugarcane (CPF, 2007). One national strategy document specifically commits Mauritius to producing a target of 30 million litres of ethanol annually by 2015 (ROM 2009b) either for domestic blending with gasoline or export.

Energy

Mauritius has limited domestic energy resources. These include renewables, in the form of hydro and biomass, especially bagasse. Bagasse is a byproduct of sugarcane processing. It imports all of its petroleum products. Coal, which is used by the manufacturing industries and for power generation, is also imported. Over the past decade, demand for imported energy products has grown on average 6% per annum. Gasoline and gas oil (diesel) are two main transportation fuels and the transport sector accounts for 39% of total oil imports. Energy represents a growing portion of total imports to the island: 16.3 % in 2006 and 17.9% in 2007.

2 465 GWh of electricity was generated in 2007, of which 96.6% was from thermal power plants while hydro/wind contributed the remaining 3.4%. The peak demand in 2007 was 367.6 MW. The generation fuel mix has been evolving over time with a major shift from fuel oil to coal and an increasing share of bagasse. Of the 708 ktoe of fuel inputs used for power generation in 2007, coal comprised (48.4%), oil products (27.9%) and bagasse (23.8%).

Water

According to Aquastat (2010), Mauritius consists of 25 major river basins and the largest are the Grand River South East and the Grand River North West. Most rivers are perennial, originating from the central plateau and leading towards the sea. In addition to the 25 main river basins, there are 22 minor river basins. River basins vary in size from 3 km^2 to 164 km^2.

Surface Water*:*

The calculation of the amount of available surface water is based on the average rainfall of 2,100 mm per year. Given the area of the island (1865 km^2), an annual amount of approximately 3,900 Mm^3 of rainwater falls on Mauritius. Only a certain percentage of this water is utilizable as large fractions are discharged to groundwater (10% or 390 Mm^3) or "lost" through evapotranspiration (30% or 1,170 Mm^3). The remaining 70% (or 2,340 Mm3) is surface runoff into rivers, stream and reservoirs and potentially used as surface water.

Ground Water:

Groundwater resources contribute significantly to meeting the island's water demand. Mauritius has five main aquifers and the annual groundwater recharge (from rainfall) has been estimated to be around 390 Mm^3. Presently about 150 Mm^3/y of groundwater are pumped for domestic, industrial and agricultural needs. Groundwater resources contribute approximately 50% of the municipal water supply (including industrial and household supply), but only 5% of the water supply in the agricultural sector. Overall, 15% of the water supply is extracted from ground water sources.

An increased use of ground water in Mauritius is problematic as all the aquifers in Mauritius are open to the sea and are exposed to saline intrusion. Increased pumping of ground water may lead to undesirable seawater (saline) intrusion and deterioration of groundwater quality.

Water utilization:

Total water utilization in Mauritius was 1014 million m^3/year (2005), of which agriculture accounts for 490 Mm^3, municipalities (including domestic demand and tourism) for 224 million m^3, industry for 11 million m^3 and hydropower plants for an additional 289 million m^3. The abstraction of groundwater resources amounts to 150 million m^3/year from 360 boreholes, and the remaining abstractions come from surface water (537 million m^3) and from existing reservoirs (327 million m^3).

Due to concerns about water security (and regular water rationing occurring in the dry season) water desalination is increasing in popularity amongst the islands tourist hotels, which present one of the main sources of income for the country. Given the above mentioned restrictions to groundwater pumping, desalination can potentially be an option for future water systems.

Table 1: Selected water characteristics of Mauritius

Purpose	*Surface water & River-run offtakes*	*Storage reservoirs*	*Groundwater*	*Total*
	Mm^3/year	*Mm^3/year*	*Mm^3/year*	*Mm^3/year*
Domestic, industrial, tourism	38	72	114	224
Industrial *(private boreholes, only ground water)*	-	-	11	11
Agricultural	370	95	25	490
Hydropower	129	160	-	289
Overall utilisation	537	327	150	1014

Source: SADC.2005

The total water utilisation (1,014 Mm^3) represents 26 % of the total precipitation of 3,900 Mm^3 (as calculated above) and is equivalent to 37 % of the all potentially utilisable fresh water (including surface water (2,300 Mm^3) and ground water (390 Mm^3) summing up 2,730 Mm^3).

A country is water stressed when its potential supply of water is less than 1,700 m^3/person/year and water scarce when the supply is lower than 1,000 m^3/person/year (UNDP, 1998). The present usable fresh water potential for Mauritius is 1,300 Mm^3/year which is equivalent to 1,083 m^3/person/year. Thus, as per UNDP's definition, Mauritius is already close already water scarce.

The future water demand in Mauritius is expected to increase with population growth and per capita usage. There are also concerns that rainfall is decreasing.

Based on data from the last censuses the population on the island has increased by 94,000 inhabitants between 2000 and 2009 (this represents an increase of 8.2% in total or 1.1% annually). For the future, a constant population growth of about 1% is expected. Since 2005, treated water waste was reduced by about 25% but at the same time the water demand per capita has risen to 217 l/capita/day (according to the Statistics office of Mauritius).

Overall, a growing water demand seems unavoidable for Mauritius, especially when considering a growing demand for irrigation. During the last 50 years a tendency towards less and less rainfall has been observed on the island, which has been identified as one of the main causes for projected water scarcity by 2020.

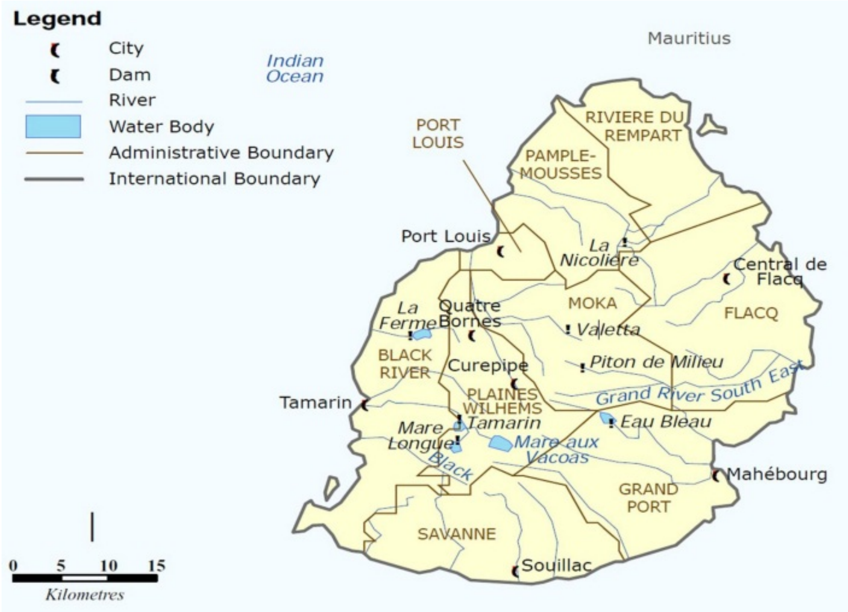

Figure 1: Rivers and basins in Mauritius. Source: Aquastat, 2010

Land use

Mauritius is a small island state with a total land surface area of 186,500 ha. The cultivated area is 106 000 ha, or 57 percent of the total area of the island, of which arable land covers 100 000 ha and regular crops 6 000 ha. Around 20 percent is occupied by built-up areas and 2 percent by public roads. The remaining area consists of forests, scrub lands, grasslands and reservoirs (GisDevelopment.net, 2010).

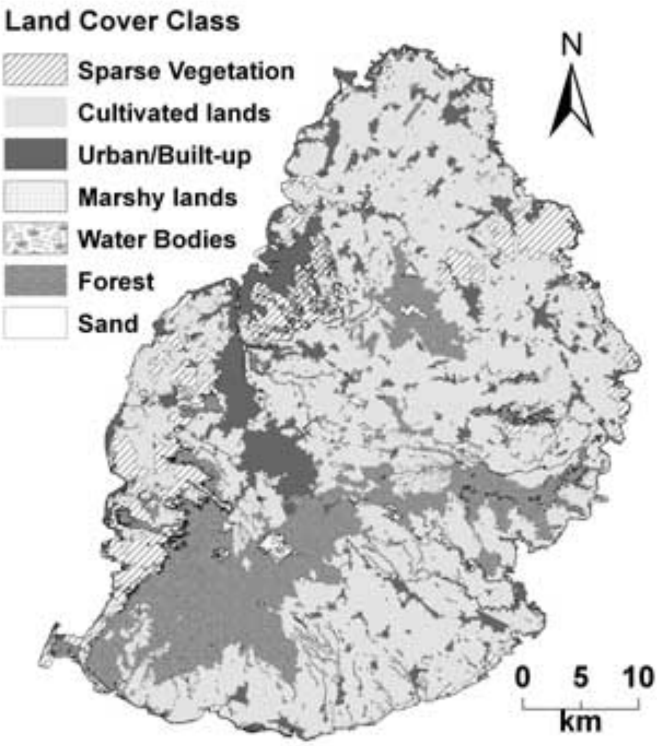

Figure 2: Land coverage in Mauritius. Source: (GisDevelopment.net, 2010)

At present there are six sugar producing factories on the island, each with its dedicated cropland.

Methodology

The pilot study was undertaken by assessing the effects and interaction of aspects of the energy, water and land-use systems in Mauritius. These assessments were made in the context of different scenarios. To ensure that the assessments were consistent, water, energy and land-use models were developed, calibrated and then selectively integrated. Using this approach, changes in local costs (to the Mauritian economy), local water, local energy as well as local and external emissions balances were calculated.

Scenarios

The selected policy goals that were of interest in this study relate to ensuring that energy security is enhanced by increasing the levels of ethanol production; ensuring water supplies to sustain increases in ethanol production - while maintaining the stability of sugar exports. To do this, the following dynamics were considered:

- Keeping the farming of sugar cane constant, one or more sugar processing plants were converted to produce ethanol. The sugar cane feedstock supply to each plant was kept constant. The land area that grows the crop for each processing factory was kept constant also[9].
- A reduction in rainfall for the island was experienced, but efforts were made to maintain the yield of sugar cane cultivation, or sugar cane was substituted by a high yield alternative crop (that requires less water). It was assumed that the cropland associated with each processing plant was kept constant, and shortfall in water supply was met using various water management techniques as well as introducing desalination as an alternative water supply option.

The dynamics are accounted for and arranged into two families of scenarios: one which focuses on increasing ethanol production from available sugar cane and another which focuses on water scarcity in the future.

Various assumptions are common to each scenario, these include:

- A long-term oil price of 80$ per barrel, and a proportionally related sugar market price of *0.42 $/kg.*
- All costs are expressed in constant 2005 USD ($)
- A discount rate of 5%
- The base year is 2005 and all scenarios are modeled to 2030.
- Each month of the year is represented for the water and land use modeling; an average day (for each month) is further split into three representative time slices for the electricity modeling.

Other assumptions, grouped by energy and water, land-use are detailed in the appendix.

Reference (BAU) Scenario

In this scenario, sugar production (and electricity production from Bagasse) is maintained at expected levels and electricity, as well as gasoline demand growth, follows national projections, based on historical trends. Electricity generation from bagasse continues at current levels through thermal incineration but no ethanol is produced. Sugar cane growth throughout the island is accounted for in terms of the national water, energy and emissions balances. Subsequent scenarios focus on the changes in two processing plants and associated crop changes. Rainfall patterns of the last ten years are expected to continue.

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[9] It is assumed that the ethanol can be absorbed by the local transport fleet - as a first pass assumption. (Almost equivalently, it is assumed that production excesses could be exported at the marginal benefit of otherwise reduced gasoline imports. In that case emissions benefits would accrue outside the island, where the ethanol is used.)

Scenario family 1:

Given targets set by the government for increased ethanol production for domestic use, as well as potential export opportunities, the first family of scenarios considers the implications of changing sugar production to ethanol production. These changes are modeled to take place in 2015, and focus on two of the four processing plants on the island.

Case 1: Sugar cane production levels are kept constant, however sugar production is changed to (so called 'generation one' (Gen1)) ethanol production in the two selected processing plants. Ethanol is blended with gasoline to meet domestic transportation fuel demand. By-product bagasse is used to produce electricity and heat at the sugar processing plants. Excess electricity is sent to the national grid.

Case 2: In this scenario, sugar cane is again used to produce ethanol, however, excess bagasse is not used to produce electricity for the national grid, but also converted to ethanol using so called 'generation two' (Gen2) technology.

The government of Mauritius is concerned about changing weather patterns and decreasing rainfall, as the island has been faced with several 'drought years' in the last decade. In these scenarios the implications of maintaining either the output of sugar or ethanol under drier conditions are tested. The potential of an alternative crop such as ethanol feedstock is also tested.

Scenario family 2:

In each of the following scenario sets, rainfall is decreased a fixed percentage starting in 2015, compared to historical values.[10]

Case A (BAU, Water Stress): This scenario builds on BAU. Sugar output is kept constant and efforts are made meet crop (and other) water requirements.

Case B (Ethanol - 1st Generation, Water Stress): Builds on Scenario 1 where ethanol output is constant with increasing efforts required to provide water (The same desalination and related assumptions are adopted in this set of scenarios.)

Case C: **(Ethanol - 2st Generation, New Crop, Water Stress)** An alternative crop is considered for producing ethanol and subject to the same water stresses as A and B above.

Table 2: Scenario summary

Characteristic:	Cane - sugar	Cane - ethanol (Gen1)	Cane - ethanol (Gen 2)	Alternative crop - ethanol
Scenarios	**BAU**	**1**	**2**	
Models used	All	Energy	Energy	
Water stress scenarios	**A**	**B**		**C**
Models used	All	All		All

Areas modeled

The boundaries modeled are conveniently delineated by the natural borders of the island. Selected effects, both local and external to the island are modeled. Detailed modeling takes place in the western and eastern parts of the island. In the west, annual rainfall is lower than in the east. As crop water must

[10] In these scenarios, rainfall is reduced until and including situations where significant levels of seawater desalination is required. It is assumed that this desalinated water will be used to meet commercial demand, displacing fresh-water for agricultural purposes. The displaced fresh-water is available for irrigation, via supply management. (Note that the increase in electricity required for desalination via reverse osmosis is accounted for.))

be supplemented with larger quantities of irrigation, water supply is stressed and further linked with high water demand (especially the in the Port Luis area) in the north of the country. The west contains crop growing fields which supply sugar cane to the "Medine" processing facility. That facility supplies generates electricity for its own requirements and ships excess production to the grid, burning waste bagasse to do so. In the east, the "F.U.E.L" sugar processing plant is a second target area of the modeling exercise. It also supplies a relatively stable quantity of co-generated power to the electrical grid.

Energy modelling

As a first step, energy modeling was undertaken using the LEAP [Long Range Energy Alternatives Planning] tool. It is an accounting tool and set up to estimate: ethanol produced (and substitution with gasoline); changes in fuel imports to the Island (affected by changes in farming, ethanol blending, electricity generation); changes in electricity generation (in terms of power plant operation and capacity adjustments) as well as account for GHG emissions both on the Island, as well as external emissions associated with fuel and fertilizer supply to the Island. (For example, external emissions would include those associated with crude extraction, refining and oil product transport to Mauritius). While on the island, emissions associated with the direct use of gasoline and diesel would be accounted for (together with other local emissions related to electricity generation and farming etc.). The on-island and external emissions are accounted for separately.

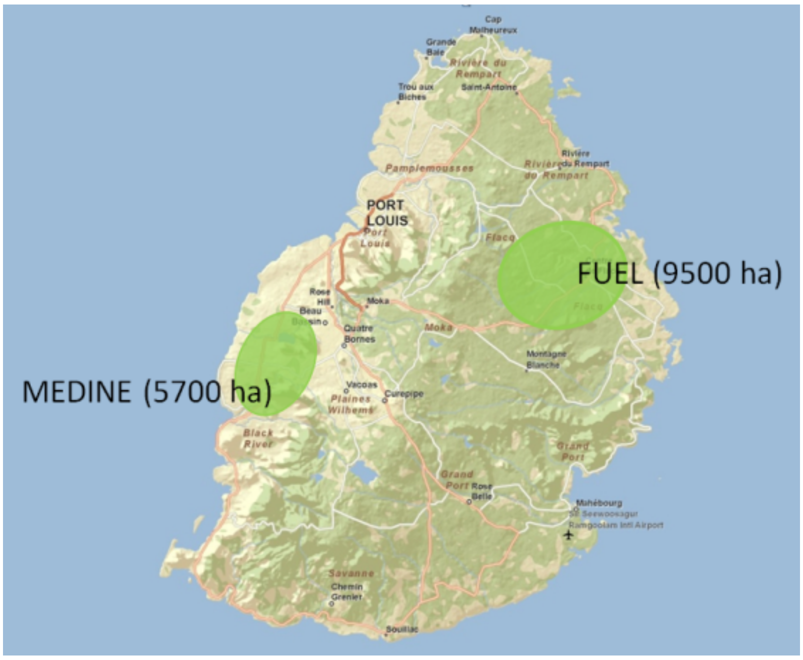


Figure 3: Areas considered for detailed modelling

To do this, selected components of the island's energy system were modeled. These included electricity generation and demand, including irrigation, pumping and desalination demands. Demand and production were calibrated using national energy statistics and official outlooks (ROM 2009c, CEB 2008 & CEB 2003). The production of ethanol and electricity generation from each processing plant considered was represented, as well as the usage of gasoline and - when introduced - its substitution by ethanol. A detailed description of the energy model, its input data and assumptions can be found in Appendix 2, and the model's Reference Energy System is shown in Figure 4.

All existing power plants and co-generating processing plants are included in the model with the F.U.E.L and Medine plants separated out for special analysis. In both cases they are modeled to: 1.) continue producing sugar and electricity (from bagasse mixed with coal), 2.) produce ethanol and electricity, 3.) produce ethanol converting waste bagasse via hydrolysis to ethanol, and 4.) produce ethanol via hydrolysis from a different feed.

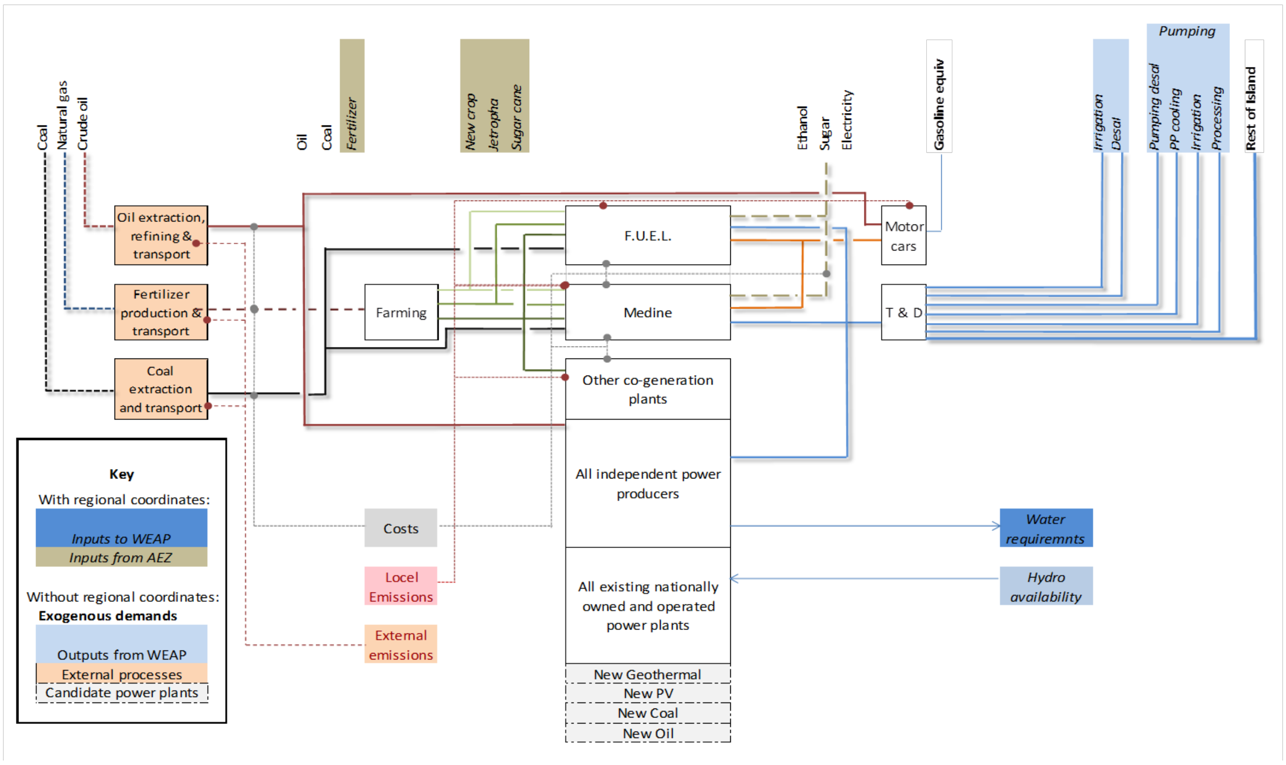


Figure 4: The energy model Reference Energy System [RES]

The energy model has several links to both the AEZ land use model and the water model. The production of crop for the processing plants from both the dedicated fields currently supplying the F.U.E.L and Medine processing plants, as well as jatropha contributions from marginal land, are outputs from the AEZ model. Demands for pumping (driven by increases in the transport of water from desalination, power station cooling, irrigation requirements and processing) as well as the need for increased desalination and irrigation are supplied from the water model. As water may be diverted from hydro generation in times of shortage, changes in hydro availability are provided by the water model. In turn the energy model provides water demand data for changes in power station cooling and (ethanol or sugar) processing requirements.

Land use modeling

The production potential of crop from farmland, as well marginal land is estimated and calibrated using Agro-Ecological Zoning (AEZ) techniques. First the crop productivity of the island is estimated using known output values. Then the effect (in terms of yield and water requirement) of changing crop type from one biofuel feedstock (sugar cane) to an alternative is estimated. Further, the potential production (and water usage) of feedstock crops, such as jatropha, on marginal land are to be estimated.

Thus the tonnage of crop produced by cropland for each scenario is estimated and serves as inputs to the energy model (which estimates sugar, ethanol or electricity production), the tonnage of fertilizer required is estimated in order to account for GHG emissions used in its production and transport to the island – as well as its use.

Finally, based on crop cycle requirements and a water balance, estimates of the quantity of irrigation water required are made and passed on to the water model. This is done for both sugar cane and in scenario C, an alternative crop. The alternative crop is modeled on a popular biofuel feed. It is assumed there are two cycles in a year, and associated with this is a water demand. The demand is different to sugar cane which is assumed to have a single cropping cycle per year. This is illustrated in Figure 5. That figure also indicates typical rainfall for the year.

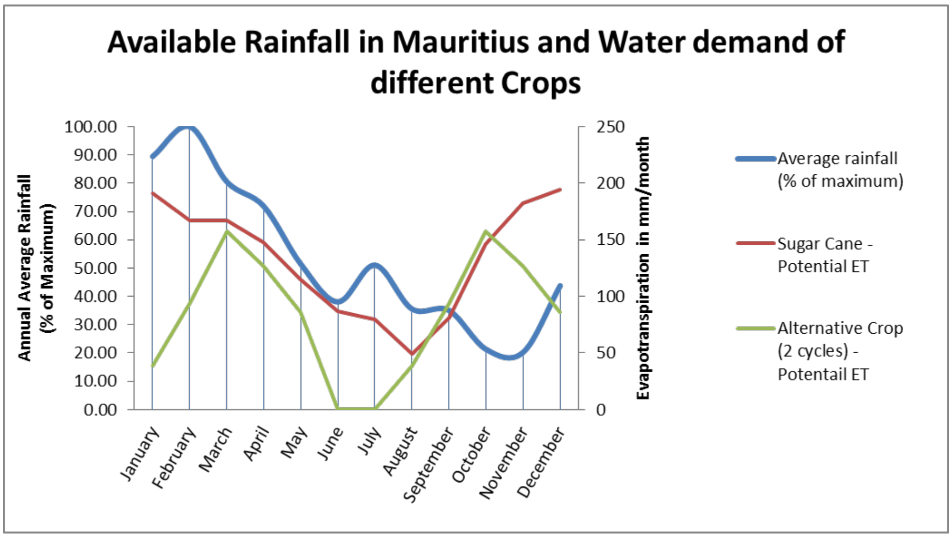


Figure 5: Monthly rainfall and crop requirements

Water modeling

WEAP, the Water Evaluation and Planning system, was used to develop a water balance for the island, including municipal and agricultural systems as well as its watersheds. The WEAP-model can simulate a broad range of natural and engineered components of these systems, including rainfall runoff, baseflow, and groundwater recharge from precipitation; sectoral demand analyses and allocation priorities, reservoir operations; and hydropower generation.

In order to obtain a detailed model of the water system of Mauritius, the island was split up into about 60 catchment areas with specific hydrological characteristics and with specific climatic data assigned[11]. For each of the catchments the land-cover classes were extracted from a number of available GIS files and other maps. The main land cover classes identified include urban areas, forest, scrub land, sugar cane growing areas and marginal land. The land cover classes influence the hydraulic characteristics that are important for modeling the surface runoff and groundwater recharge of a region. As a result the model calculates water availability in each of the regions and assigns amounts of water (headflow) to the main rivers for each catchment area.

In a next step water demand data for all different areas were collected and future demand projections (based on GDP and population growth projections) were made. After assigning the water demand sites to its specific sources (rivers, canals, reservoirs or ground water extraction) the model was balanced to match demand and supply for the available data sets (1997-2005)

The resulting WEAP model is able to calculate stream flows and water levels for all main waterbodies and rivers in the modeled area. Existing hydrological data (e.g. flow gauges, reservoirs storage data and canal flows) are furthermore used to calibrate the system.

Note, that available data sets, together with other detailed assumptions and inputs are included in the appendix.

The WEAP model is set up in such a way that decreased rainfall can be simulated; reduced groundwater abstraction potential; as well as the introduction of new water sources such as desalination plants. A set of scenarios was created to show the effects for decreased rainfall on the island. The main effect of

[11] An extensive set of climatic data was used to calibrate the model, including historical data of several stations around the island measuring precipitation, temperature, humidity, wind, and evaporation.

decreased rainfall is an increased groundwater pumping demand to cater for the "demand-gap" created. The model is able to calculate and project the pumping requirements for different rainfall scenarios.

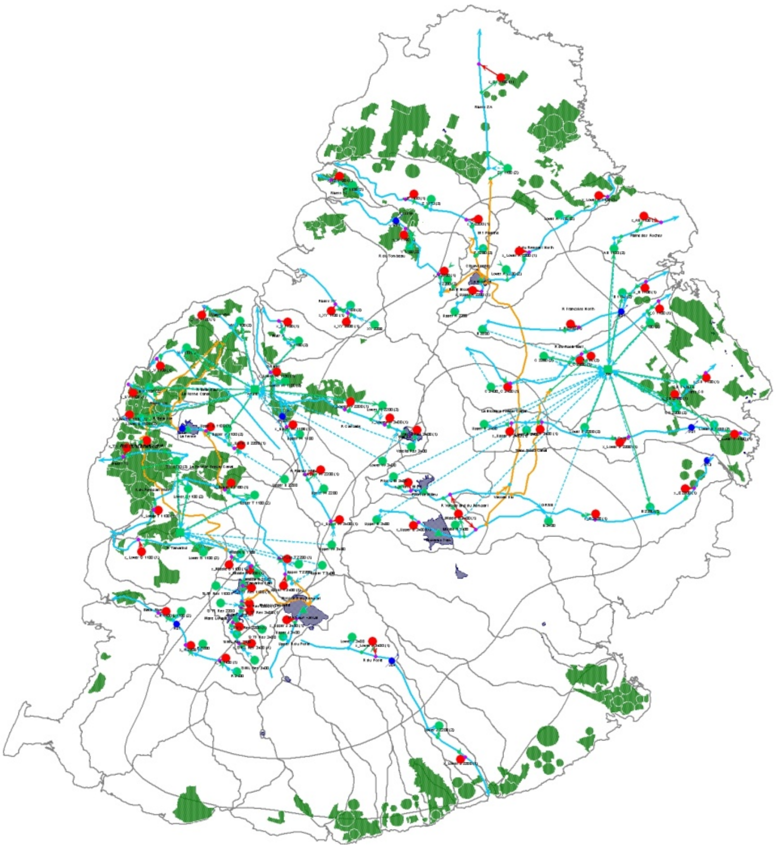


Figure 6: Mauritius water model overview – including Catchments, simplified rivers, canals and reservoirs, as well as demand sites[12].

Constraints on water sources (e.g. groundwater supply) were assessed and estimates were made of how far into the future operations would be maintained before shortages would be expected. Importantly, water availability is heterogeneous on Mauritius with the west side of the island (including the capital Port Luis) being very vulnerable to a rainfall decrease and already experiencing water shortages. Although the agricultural sector is the main user of water today (about 50% of all water is used in agriculture), population growth and growing urban water demand are a key concern. The concurrent implications of crop water demand and growing demand for municipal water supply due population increase are considered in the model and will be the topic for further studies in the future.[13]

The water model is set up to interact with the energy and land use modelling in different ways: From the Land model, water requirements for different agricultural crops are derived and fed into the existing model. Based on crop production volumes (also received as results from the land modeling), the water requirements for different sugar factories can be estimated (as these change as a function of their activity and output). Increased water demand in the agricultural sector and in the sugar factories implies more pumping and energy demand. These data are fed back into the energy model.

[12] The illustration gives an overview about the general outline of the water systems and its representation in the WEAP modeling software.

[13] Specifically, the analysis explores the implications of this increase in demand on the water delivery system that transports water from the Midlands Dam – Nicoliere Reservoir system. In scenarios in which rainfall decreases, the yield of this system will decrease. The resulting increase in groundwater pumping with its associated energy implications is modelled. We model the situation in which water is diverted from municipal demand to meet agricultural demand - requiring the increased use of desalinated water in the commercial sector.

One additional interaction between the water and energy models is the production of hydropower – as the generation of electricity there is directly linked to water availability.

Model interactions

Starting with the land use modeling focusing on the croplands (that feed the F.U.E.L and Medine processing plants) together with links to the water and energy models, various effects are calculated. These include changes in GHG emissions, energy use, costs and water requirements. An indicative flow of information between the models used is given in Figure 7 below.

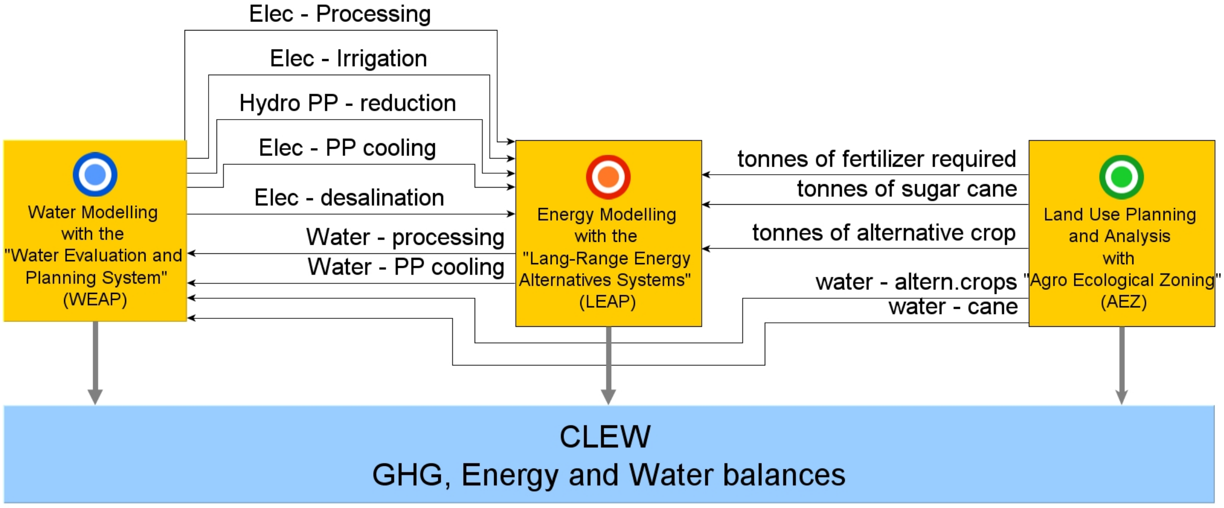


Figure 7: Model interactions

Results

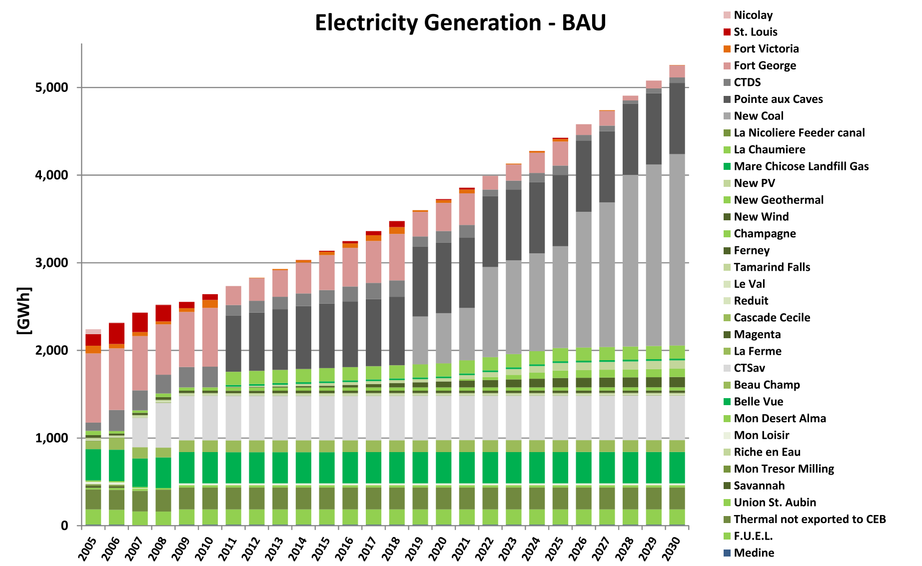
The models were all first calibrated to replicate the current electricity production, water balance and land-use patterns as well as project changes into the future. These formed the basis of the Business as Usual scenario, which is used as a reference.

Business as usual

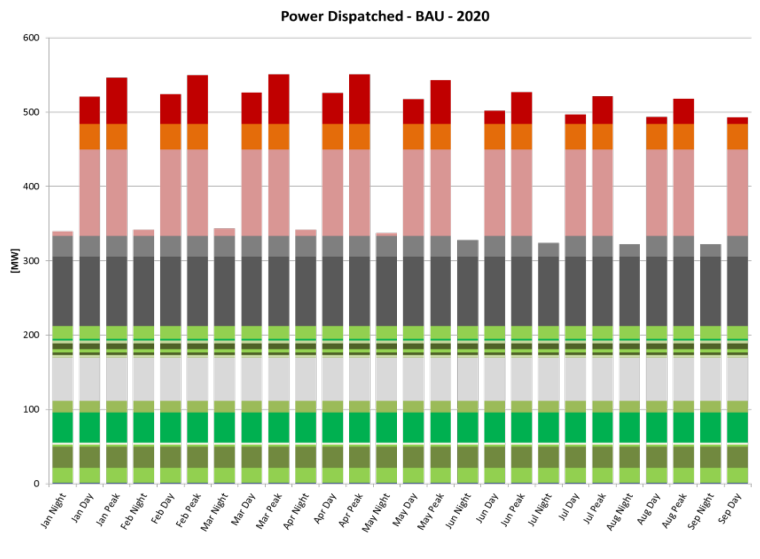
The figures below indicate calibration results for the energy system and subsequently the water system described in the previous sections. Renewables (bagasse fired co-generating power plants and hydro) together with coal provide base-load power. While, expensive (to operate) oil power plants provide peak requirements. Both the demand for electricity and gasoline for transport grow steadily. Off-island emissions from fertilizer production stays constant, while oil refining and coal processing increase over time as on island demands increase. On island emissions accounted for include those from the electricity system, selected agriculture and gasoline based transport.

Power generated by plant

(note that reds indicate oil, grey's coal and green renewable (hydro or bagasse) generation.



Power dispatched by plant in 2020



Selected GHG emissions calculated in the energy model

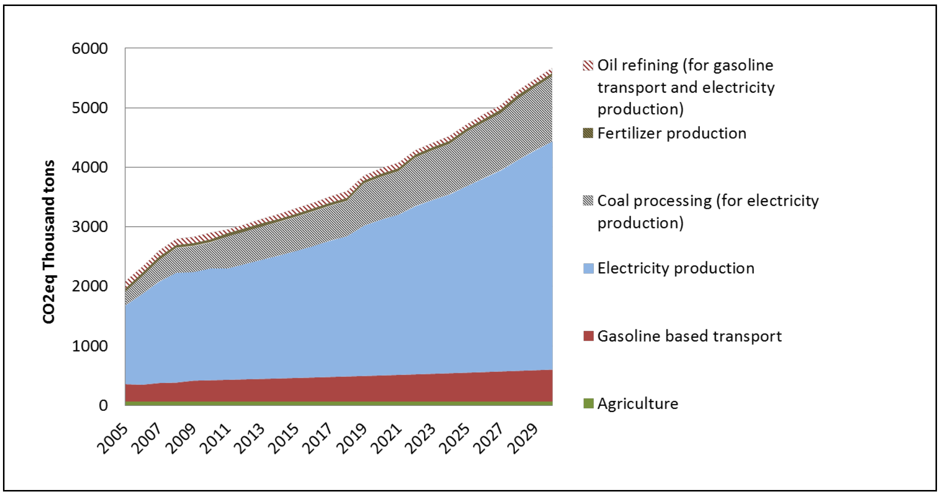


Figure 8: Selected BAU energy system model results

The illustrations in Figure 9 below give an overview of the details of the water systems modeling in the BAU scenario. As explained in the section about water modeling methodology the island was divided into its main catchment areas with real rainfall data series from 1997-2005 providing the water input data. Other metrological data as well as land cover data were used to model the water characteristics of the different parts of the island. As a result the water model can provide a detailed analysis of water flows and storage volumes in the island. The following four graphs give insight into the results in the BAU scenario:

a) Gives the water balance for the years 1997 to 2005. Especially interesting is year 1999 were the annual rainfall was exceptionally low and temperature high. This will also be illustrated in the graphs b, c, and d;
b) Gives an overview of water consumers in the years 1997 – 2005. Water demand in the year 1999 was high due to high demand in agriculture (high temperatures, low rainfall);
c) Shows the storage volumes of the 8 main reservoirs in Mauritius. Interesting are the high fluctuations and the low volumes (partly empty reservoirs in the dry season); and
d) Shows the water demand (not covered by rain or surface water from rivers) for different months - while during the rainy season all water demands are covered by rain and surface water from rivers, the dry season see a high demand needs from reservoirs and groundwater pumping which often leads to water rationing in the dry season.

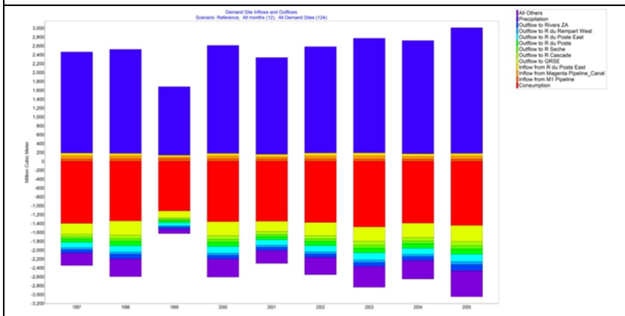
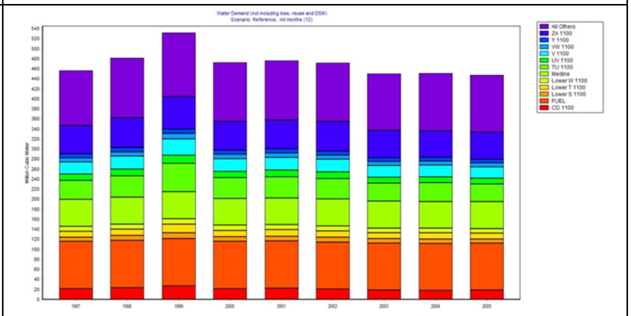
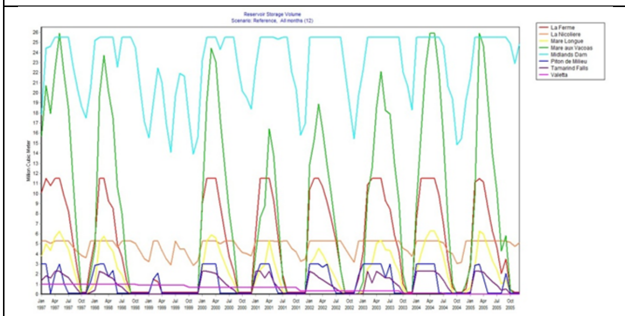
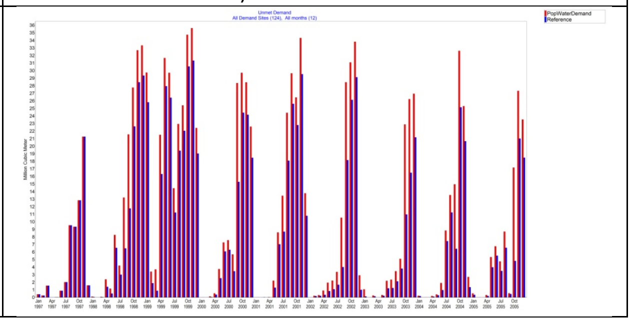
a) Inflow – Outflow: Illustrating were the water is coming from (precipitation, groundwater) and were it is going to (consumption, sea, evaporation)	b) Structure of water demand according to region or consumer
	
c) Storage volumes of reservoirs	d) Unmet demand from surface water: remaining demand to be covered from storage reservoirs and ground water pumping (especially from September to December)
	

Figure 9: BAU calibration and related water system simulations Ethanol production (Cases 1 and 2)

Next we consider the effect of converting a sugar production to ethanol production. Comparing the BAU scenario, the most significant change that results is the reduction in gasoline imports. Small changes in generation are also observed (primarily due to small increases in electricity demand for ethanol over sugar production). Note that water requirements are very similar between these scenarios (with only small differences again, due to process change.)

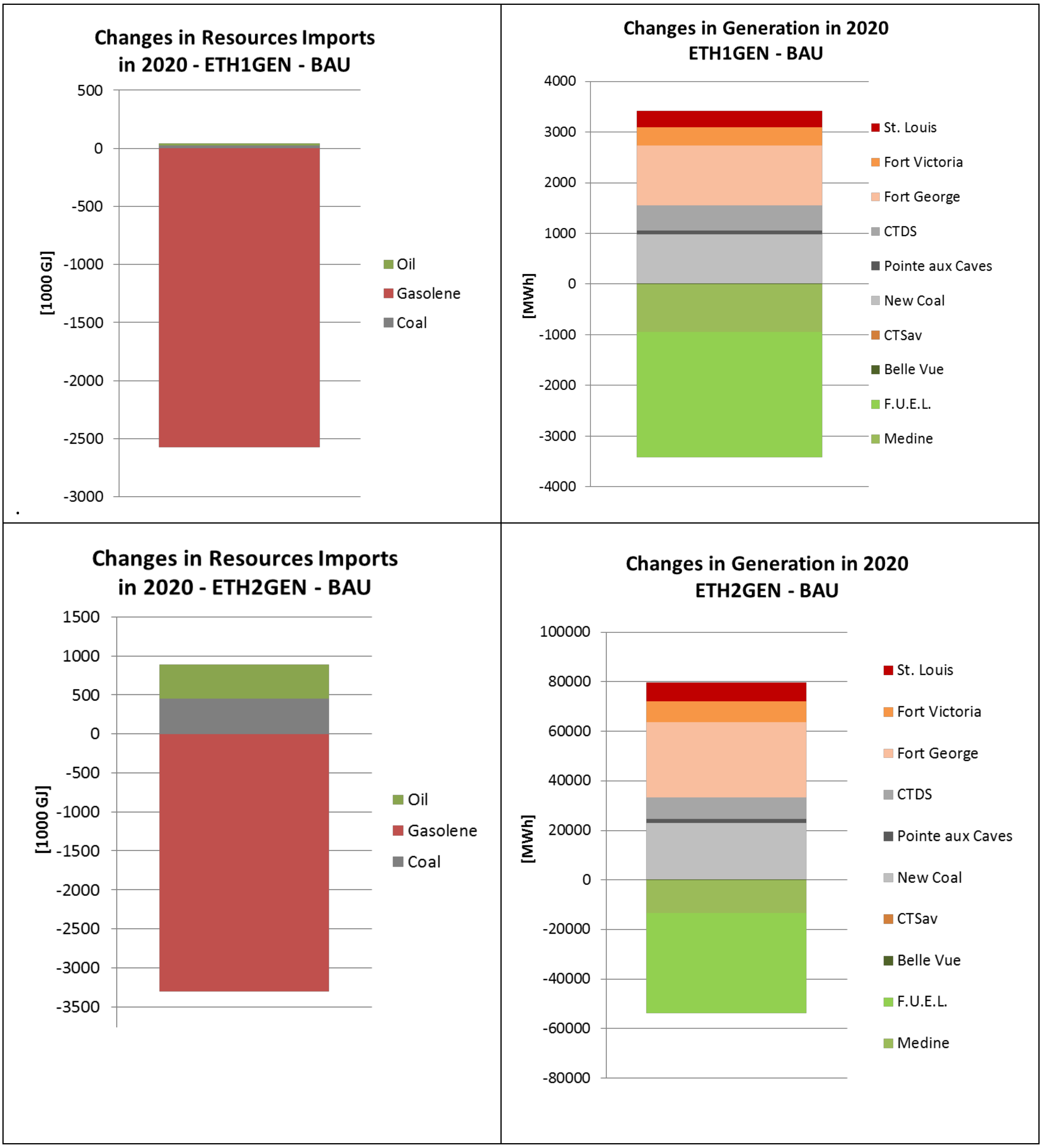


Figure 10: Changes in selected energy dynamics for cases 1 and 2 compared to (BAU)

As indicated in Figure 11, GHG reductions are significant. This is due to reduced imports of gasoline as well as associated refining and extraction emissions. For GEN2 ethanol production however, while more imported gasoline is displaced, more power plant fuel is imported. (This is because excess bagasse is not used for electricity production in this scenario. It is used for ethanol production.)

Accordingly GHG emissions increase slightly in the GEN2 scenario, as higher quantities of coal are burned for electricity generation. Similarly (with the increased cost of power station fuel and second generation ethanol production) the overall economics of GEN2 are less favourable.

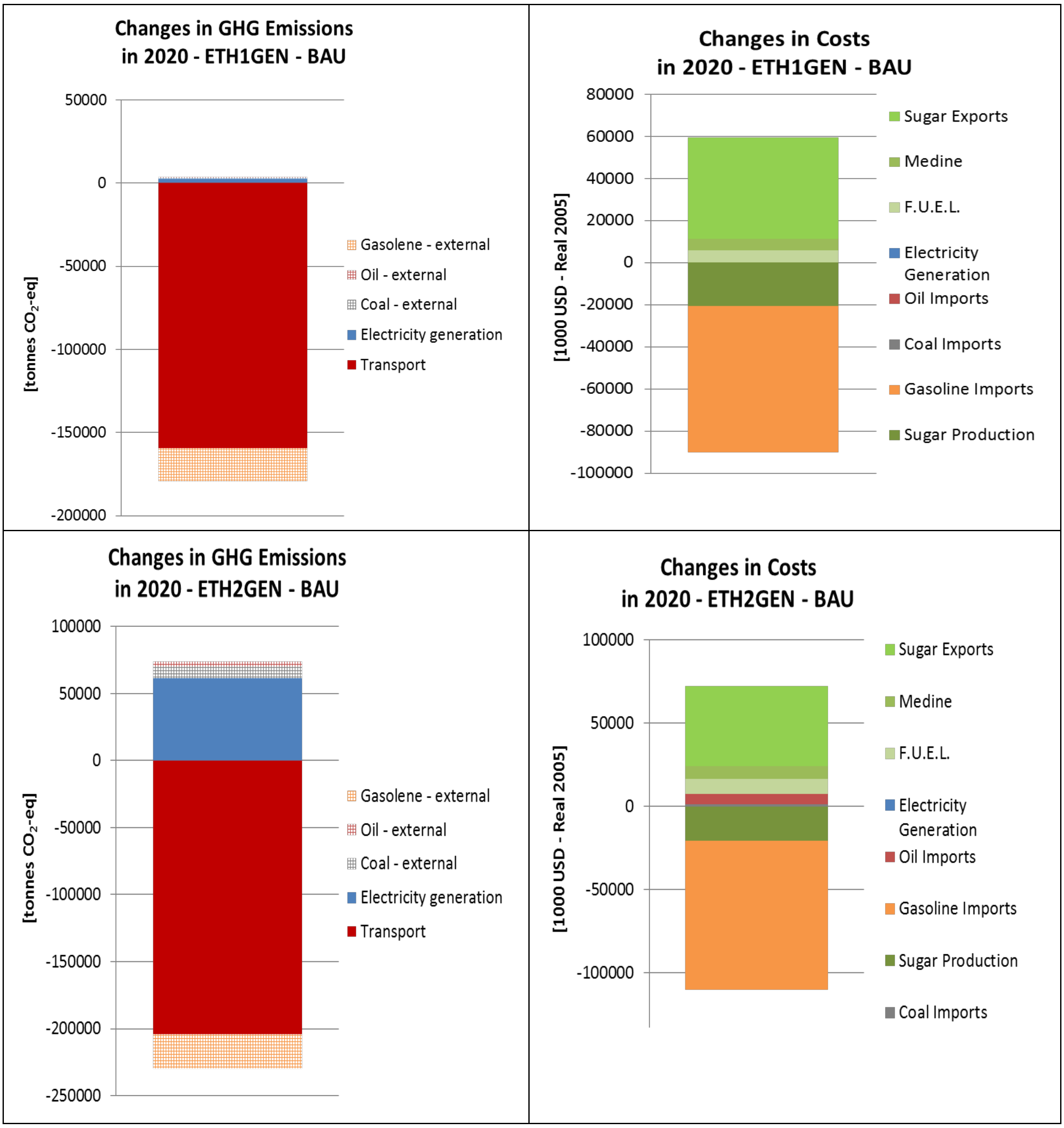


Figure 11: Changes in GHG emissions and costs for cases 1 and 2 compared to Business as Usual (BAU)

Water stress cases A, B and C

In these scenarios rainfall is reduced from 2015 on. We report the case of a 40% drop in rainfall compared to historical (1995-2005) levels and investigate the implications of keeping sugar cane – or alternative - crop production constant.

Figure 12 below shows the eight existing water storage reservoirs on Mauritius and their respective water storage volumes from 2005 – 2030 (each line represents the water volume of one reservoir). The years 2005-2015 represent "normal" rainfall years with an average yearly rainfall of 2100mm for the island. After simulating a 40% drop of rainfall from 2015 onwards reservoir storage constantly decreases until 2021 at which time it stabilizes at a low level. While before 2015 the reservoirs always recovered to full storage volume during the rainy season in the reduced rainfall scenario all of the reservoirs do run completely refill and lose up to approximately 80% of their yearly storage capacity.

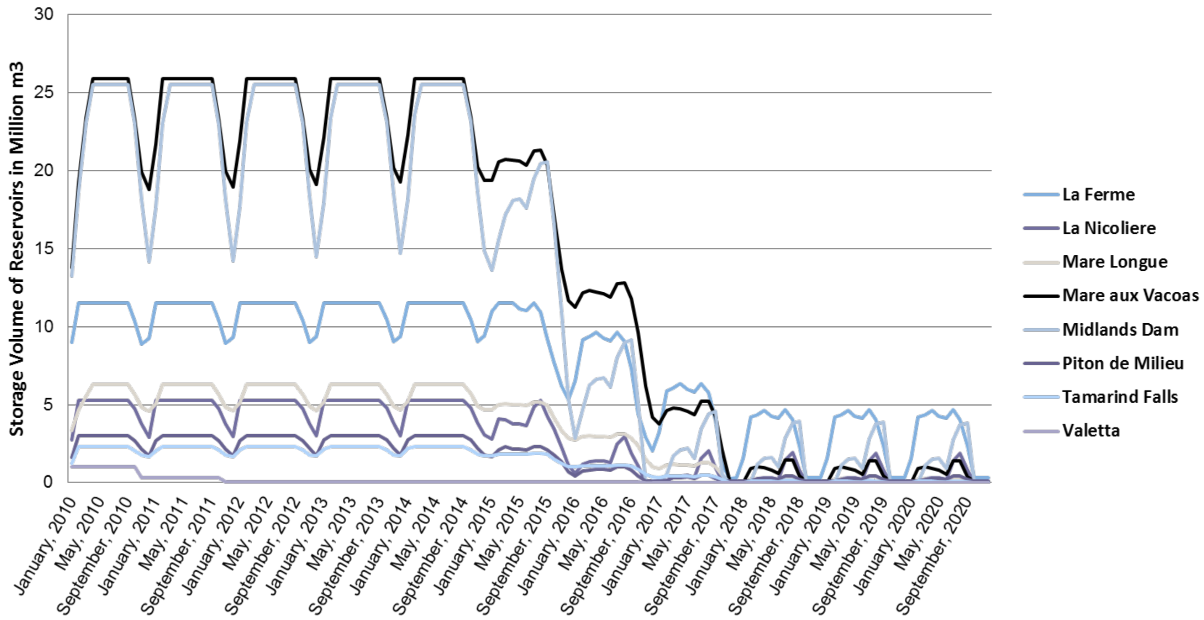


Figure 12: Changes in reservoir levels through the scenario period (reduced rainfall scenario).

The modeling of the reservoirs storage volumes under the reduced rainfall scenario illustrates the sensitivity of the Mauritius island water system to changes in rainfall and shows the necessity to investigate other sources and methods of water extraction. Figure 13 further emphasizes this statement: here the pumping requirement for agriculture was modeled for the period between 2010 and 2030 – again with a drop in rainfall of 40% after 2015 onwards. The pumping requirement in the agricultural sector of Mauritius covers the water demand which not covered by rainfall and surface water. At the moment groundwater pumping plays a minor role in agriculture providing only less than 10% of the agricultural water. In the scenario of reduced rainfall this percentage will grow as illustrated in the figure below. As pumping cannot indefinitely be increased to ensure stable groundwater levels and avoid seawater intrusions into the ground water aquifers, water desalination is investigated at a later stage.

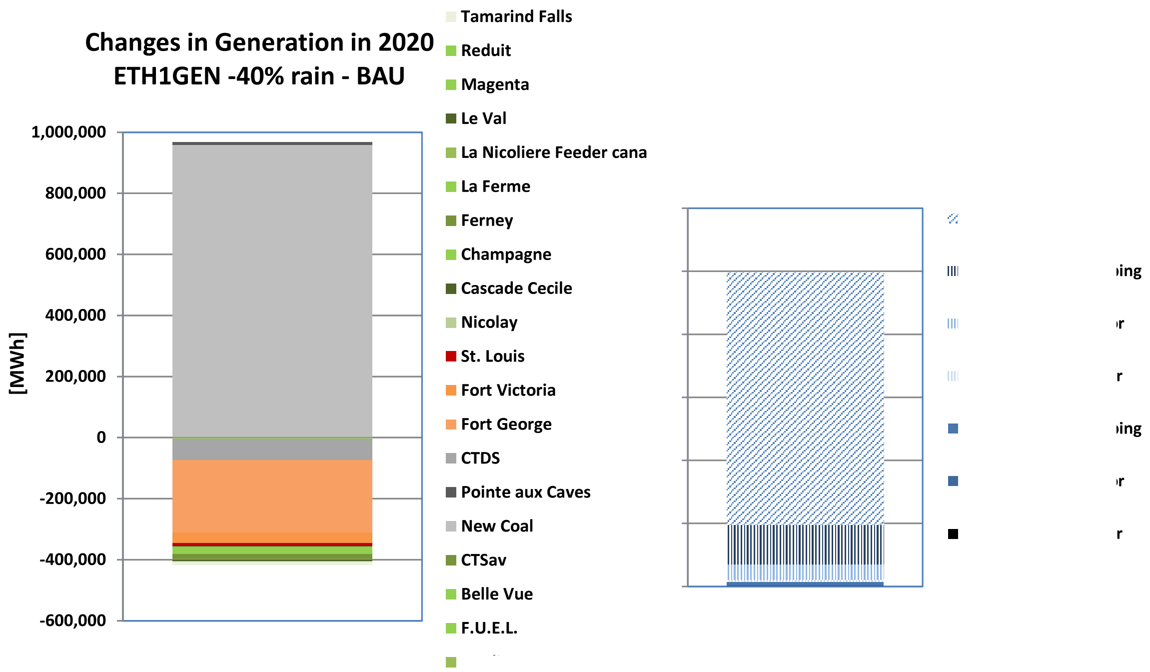
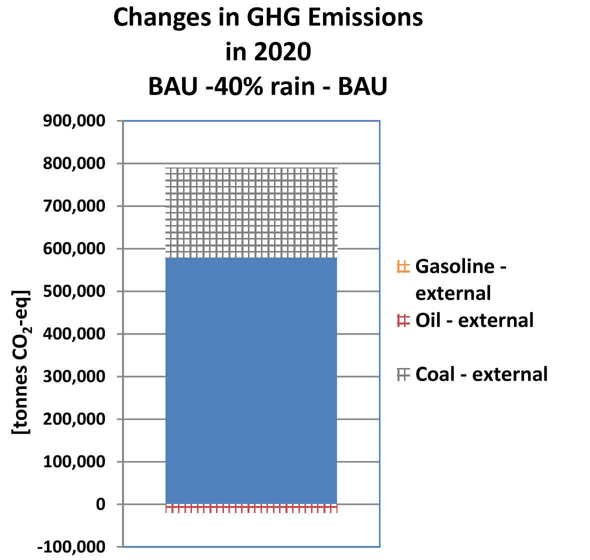


Figure 13: Increases in water-related electricity requirements and generation compared to BAU for 2020 for case B.

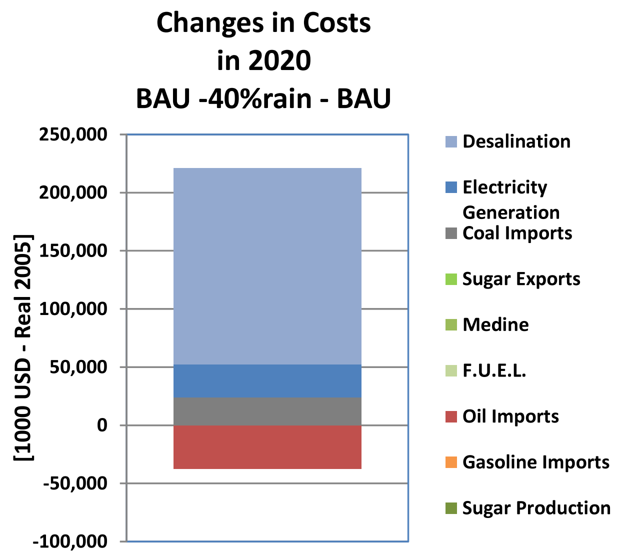
Figure 13 shows increases in energy demands and generation changes for Gen1 ethanol production under water stress compared to business as usual under no stress. Requirements for desalination are significant, followed by increases in pumping for irrigation. Small quantities of pumping are required to supply water for other needs. The bulk of new generation requirements are taken up by new coal fired power plants. (The changes in energy demand and generation are similar for cases A and B).

To adapt to this water stress scenario there are increases in costs for desalination, for increased generation and associated increases in power plant fuel imports. If we compare these costs to BAU, the increase is significant in 2020. While GHG emissions increase due to higher electricity demands, they are partially offset by the use of ethanol in place of gasoline. Thus the cost of adapting this mitigation measure to this climate change scenario is measured. These results are summarized in Figure 14. Interestingly, it is the cost of desalination that accounts for the bulk of this increase. The increased cost of generation needed for the desalination and pumping is still offset by gains made from reduced gasoline imports.

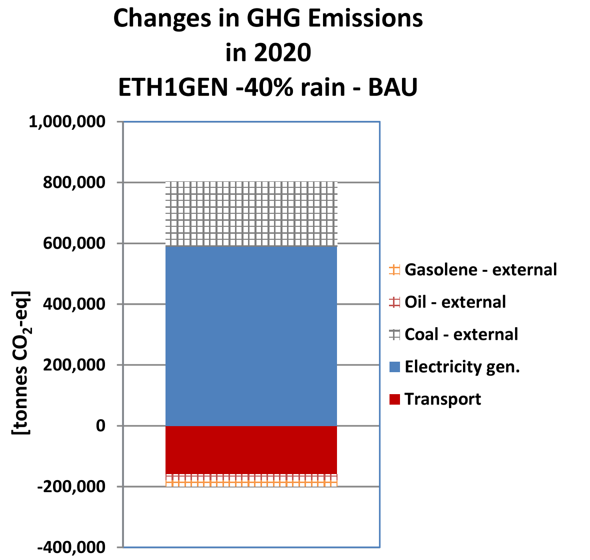
Changes in GHG emissions for case A



Changes in GHG emissions for case A



Changes in GHG emissions for case B



Changes in GHG emissions for case B.

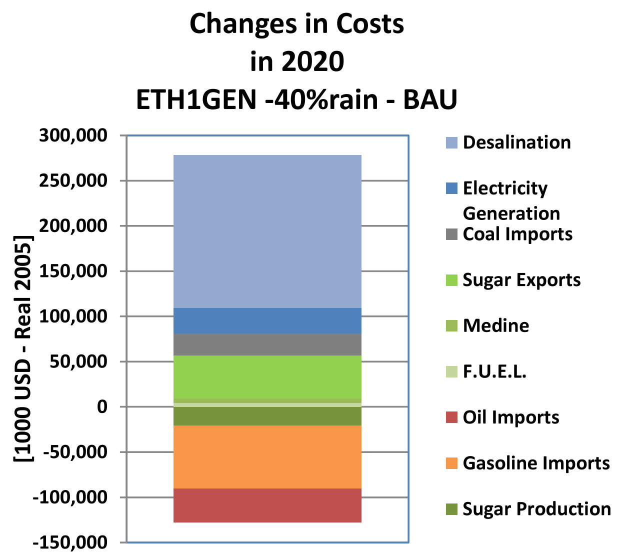


Figure 14: Changes in GHG emissions and costs for cases A and B compared to (BAU).

To mitigate the requirements for water, when rainfall is reduced, an alternative biofuel feedstock is grown on the Island. Were all sugar cane production to be converted to the alternative crop, desalination demand would drop as shown in Figure 15.

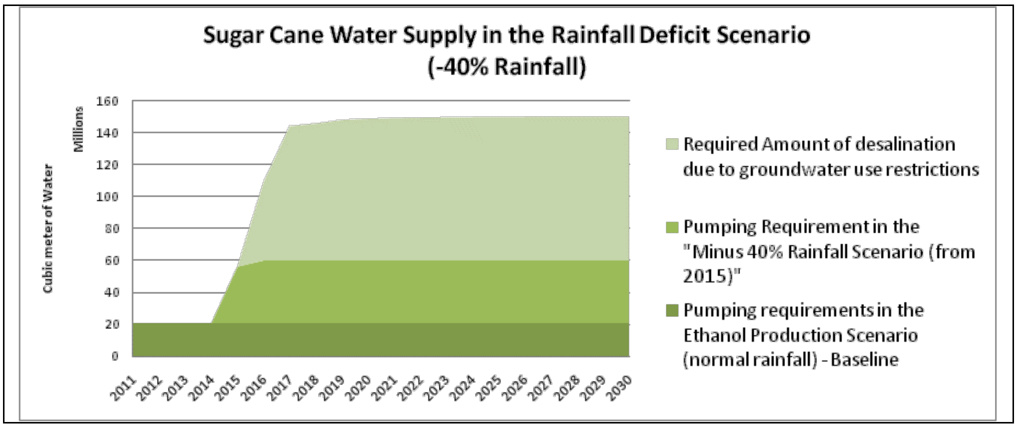


Figure 15: Water requirements for Mauritius if sugar cane production is kept constant or an alternative crop is planted.

In case C, we consider a change in crop production and processing only for the Medine and F.U.E.L facilities and dedicated fields. (For comparative purposes, the rest of the island, it is assumed, continues growing sugar cane, and its water requirements are met to maintain BAU production figures.)

Changing the crop when there is no change in rainfall requires increased pumping. This is so even though the alternative crop (1) requires less water per ha and (2) has a lower yield. However, when rainfall decreases, pumping requirements for the alternative crop are lower and production of ethanol less costly (i.e. more economic). The implications are most interesting. It is clear that sugar cane is a good match for the rainfall patterns at present. According to Figure 5, the year is divided up such that the bulk of sugar cane's water requirements are in the first half of the year. Thus introducing a cope cycle in the second half of the year when rainfall is reduced is onerous on the present system. However, under future dyer conditions others may be better. Both have important energy and GHG implications. Note also that, requiring more fertilizer per ton of production, the alternative crop increases off island emissions further.

It is important to note how sensitive the results are to assumptions relating to ethanol, sugar and oil prices and their potential linkage.

Conclusions

In this work a CLEW framework that integrates components of energy, water and land-use modeling is presented. The approach used was a 'systems approach'. Each system was represented in terms of physical quantities imported, produced, transformed and used. By ensuring that mass and energy balances were not violated, consistent scenarios were developed. Various costs were associated with activities and those in turn were also compared from one to another scenario.

The approach was applied to study CLEW scenarios for Mauritius. Scenarios changing sugar production to ethanol production, as well as reductions in future rainfall were considered. The first scenarios, a GHG mitigation measure and income diversification strategy, reduced petroleum imports and related emissions. With the cost assumptions used here, this was done at a profit. Reduced oil imports outweighed revenue loss from reduced sugar sales. (Not modeled here, but a clear risk management strategy would be to consider the conditions under which high flexibility would be desirable. By high flexibility, the ability to carry the extra cost and switch from sugar to ethanol production, based on changes in fuel and sugar prices is considered.)

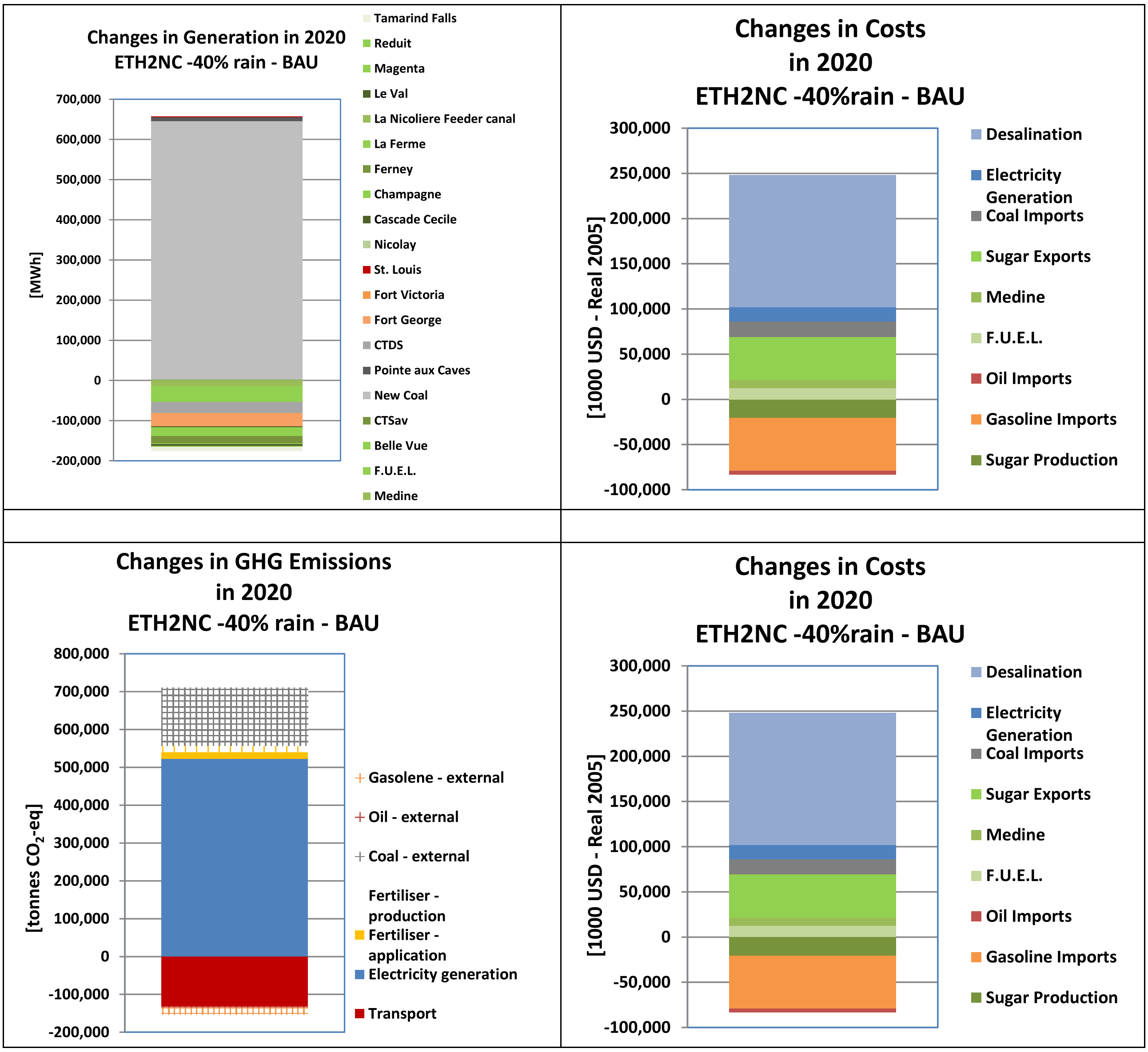


Figure 16: Changes in generation, energy demand for water, GHG emissions and costs for case C compared to Business as Usual (BAU)

The second set of scenarios analyzes the effect of lower rainfall. Initially affecting the West and then to a lesser extent the East of the island, increases in irrigation and water movement lead to the need to supplement natural supplies with desalinated seawater. The latter with increased costs and GHG emissions due to increased desalination and associated increases in electricity generation. Increased costs outweighed the gains made by switching to ethanol (under no rainfall shortage), however emissions were still significantly lower.

This yielded important outputs and demonstrated key findings. The first is that it is clear that CLEW systems are strongly interwoven. This work showed a change in climate (expressed here as a simple rainfall reduction scenario) would change the energy system (directly reducing hydro-production and indirectly require more water desalination and pumping) as well as affect crop production. A change in the energy system (moving from sugar to ethanol production) would reduce climate related GHG emissions, and depending on crop choice or rainfall changes, affect water requirements etc. Crop selection for changing weather conditions (in our case, lower rainfall) is important. Crops that are suitable for current conditions may not be so for future conditions and vice versa. It may be be important to achieve some mix or flexibility of crops chosen to 'hedge' against different futures unfolding.

The modeling developed was also complex to the extent that initial simplified approaches may be misleading. Aspects such as land suitability, rainfall, water transport and demand are strongly spatial and localized, while the energy system has links (such as through the above mentioned hydro) that limited the accuracy of the 'first pass assessment' undertaken in that work.

While relatively complex, an observation is that this type of integrated analysis is clearly achievable. That is not to support the specific outputs of observations of this project, as there are high levels of data uncertainty and it is ongoing. However, it is clear that such physical systems can be interlinked and parallel assessments can be made. A weakness of this approach is that, though represented, the integration could be stronger.

Finally, this approach provided a lens through which individual technologies and policies might be assessed in an integrated manner. It allowed for a GHG mitigation measure (moving to bio-ethanol) to be assessed in the same framework as an adaptation measure (increased seawater desalination). This was done in the same framework, allowing potentially vulnerable countries, such as Small Island Developing States (SIDS), to appropriately plan their transition to the green economy, but robust to climate change. Similarly insights into co-benefits (or costs) of selected climate, energy, water and land-use policies might be gleaned. Further in terms of long term sustainability information on national cleaner production and consumption for different hypothetical futures can be, to some extent, considered.

Recommendations

Following this exercise - which is still ongoing - there are some clear next steps. These relate to this case study, to development of the analytical approach and to application elsewhere.

The case study is still underway, and a clear set of issues have been identified to carry out further analysis. These include detailed sensitivity analysis as well as review. Various refinements are needed. At present ethanol is assumed to be used in the local transport fleet (or equivalently exported at the marginal cost saving associated with displacing gasoline imports). It would be useful to consider the practicalities and limits of changing the local transport fleet to absorb ethanol. It would also be useful to consider the benefits of flexible sugar/ethanol production into the future, changing with fluctuations in international sugar and oil prices. Various different scenario configurations should be considered. These would include - for example - the potential for introducing high quantities of intermittent renewables to meet water requirements. An interesting observation and strong advantage of the detailed water model is that the potential for storing water is well represented. This opens the door to assess the potential for intermittent desalination and pumping. Water can be pumped and stored when the intermittent resource is available. This may further reduce the need for 'backup' generation. (The latter is often needed to supply essential power when the renewable resource is not available.). Scenarios of mixed crop to mitigate against weather changes would be interesting to investigate. Further, there are important water and energy efficiency options, such as changing irrigation and land tillage systems to be looked at in more detail.

Essentially three separate tools were run and soft linked in this exercise. Were a single tool used, perhaps with some goal programmed, 'unintuitive' but effective policy insights may be revealed. Further, as many different attributes of the CLEW system are being modeled, it would be of importance to policy makers and analysis to consider the effects of different attribute weightings. Further work should thus consider what may be the most useful multi-criteria or objective analysis and how these may be combined to help set up the input and output for future analysis.

Finally it is clear that the development objectives and climate vulnerabilities identified here exist in many islands and countries. A strength of this work is that, by using the tools chosen powerful insights may be gained. These insights will be country specific as the tools used are highly customizable. These would be useful both for assessing international assistance options, as well as honing national policy. Further, while the human resource to undertake these analysis is available in key organizations there is an urgent need to disseminate tools and training to the member states of the UN system.

References

Aquastat, 2010, http://www.fao.org/nr/water/aquastat/countries/mauritius/index.stm, Food and Agriculture Organisaion (FAO), Accessed 2010.

CEB (Central Electricity Board). 2003. Integrated Electricity Plan 2003-2012. November

CEB (Central Electricity Board). 2008. 2008 Annual Report.

CPF (Country Programme Framework) 2007. Country Program Framework: 2007-2012 Republic of Mauritius and IAEA.

EC (European Commission). 2009. The Lomé Convention http://ec.europa.eu/development/geographical/cotonou/lomegen/lomeitoiv_en.cfm . Accessed 2009.

ETSAP (Energy Technologies Systems Analysis Program). 2011. http://www.fao.org/nr/water/aquastat/countries/mauritius/index.stm Accessed April.

GisDevelopment.net, 2010, http://www.gisdevelopment.net/application/natural_hazards/landslides/mwf09_rody.htm, Accessed 2010.

IAEA [International Atomic Energy Agency] (2009). Annex VI: Seeking Sustainable Climate Land Energy and Water (CLEW) strategies, Nuclear Technology Review 2009. http://www.iaea.org/Publications/Reports/ntr2009.pdf

IIASA (International Institute for Applied Systems Analysis). 2001. Model MESSAGE, http://www.iiasa.ac.at/Research/ECS/docs/MESSAGE_man018.pdf

Rogner, H.; Vessia; Ø., Howells, M.; Aggarwal, P.; Brent, N.; Nguyen, M., Fischer, G.; Purkey, D., Heaps, C., Heng, L. (Submitted), Seeking CLEWS - Climate-, Land-, Energy-, Water-, Strategies: A case study, Energy Policy.

Rogner, H.H. (2009) Climate, Land, Energy and Water Strategies. CSD 17. IAEA

ROM (Republic of Mauritius). 2008. Digest of External Trade. Central Statistics Office. http://www.gov.mu/portal/goc/cso/report/natacc/trade07/trade07.pdf

ROM (Republic of Mauritius). 2009a. Agricultural and fish production 2008 – Highlights. http://www.gov.mu/portal/goc/cso/ei751/toc.htm . Accessed 2009.

ROM (Republic of Mauritius). 2009b. National Accounts Estimates (2006-2009), March 2009 Issue. http://www.gov.mu/portal/goc/cso/ei757/natacc.pdf

ROM (Republic of Mauritius). 2009c, Long-Term Energy Strategy (2009-2025), October 2009. www.gov.mu/portal/goc/mpu/file/finalLTES.pdf

ROM (Republic of Mauritius). 2010, A roamap for the sugarcane industry in the 21st centuary, http://www.gov.mu/portal/sites/moasite/download/roadmap.pdf, Accessed 2010.

SADC (South African Development Comunity). 2005, SADC –Development of a Mauritius Country Framework For Action within the Sounthern African Vision for Water, Life, and Environment in the 21 centrury.“ – Conference Proceedings

SEI (Stockhom Environment Institute). 2011. Software, http://www.seib.org/software/index.html , Accessed April.