Elsevier Editorial System(tm) for Energy Policy
Manuscript Draft

Manuscript Number: JEPO-D-11-00005

Title: Seeking CLEWS - Climate-, Land-, Energy-, Water-, Strategies: A case study

Article Type: Full Length Article

Keywords: energy,
water,
land

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Abstract: Energy use is the greatest anthropogenic emitter of carbon dioxide. Water, energy and food are essential for development and their security of supply is of high importance. Yet these are inexorably linked. The agricultural sector of developing countries can use as much as 70-80% of available fresh-water supplies. Consequently energy for irrigation is a major energy user. Water is required for cooling thermal power plants. In 2006, 39% of fresh water withdrawals in the USA passed through a power plant steam turbine to produce electricity. Fertilizer, a major input to agricultural activities is highly energy intensive. And, land can be used both for producing food, or feedstock for energy carriers, such as biofuel.

Interdependencies mean that energy policies based on energy analyses alone might have adverse unanticipated effects on water resources, land resources and the climate. The same is true for water policies based only on analyses of water issues, and for land policies based only on land-use analyses.

This paper applies a prototype of a tool analyzing Climate-, Land-, Energy- and Water- (CLEW) interactions and implications associated with socio-economic development. It demonstrates tradeoffs associated with interventions aimed at meeting development goals in the context of a specific case study.

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Thus, presented and applied in this work is an integrated analytical tool that includes all CLEW aspects in a manner that may be made accessible and useful to policy analysts and planners. Given that CLEW modelling addresses four core resources, all required for socio-economic development, the case study scope could potentially be wide. The nexus bringing climate, water, energy and land systems together, implies a large number of trade-offs and interactions which may be complex in nature. Thus, in this initial case study, the scope is deliberately narrow. We choose a developing island state, such as Mauritius, which is a producer (and exporter) of food and dependant on imports for the majority of its energy needs. Further, the model that is developed (at this stage) is an "accounting tool". It quantifies relationships based on between elements of the CLEW system, which are then driven by user defined scenarios. (With these relations quantified, future work can be undertaken to formally investigate the afore mentioned trade-offs.)

Two basic sets of scenarios are applied. One in which land is used to produce (sugar cane) food and one in which it is used to produce ethanol for fuel. Each scenario set has subsets in which different land types are used: arable land, forests and grassland. Further, each scenario considers two different technology paths, one advanced and one standard production method, each with different uses of the sugarcane by-product (bagasse). Sensitivity analyses further investigate key questions and demonstrate how this model type can be used to explore the potential array of development options for the policy analyst to consider.

For each scenario, levels of local (on the island), foreign (off the island) and global (local plus foreign) emissions, energy use, water-consumption volumes are calculated. (The foreign effects reported are those assumed to be induced by changes on the island.) Further, these are categorised into direct and indirect effects. Selected economic opportunity costs for each scenario are also calculated. (All attributes are reported as costs, thus a negative value indicates "an improvement" or a cost reduction.)

Seeking CLEWS – Climate-, Land-, Energy-, Water-, Strategies: A case study

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A. Introduction

This paper applies a prototype of new tool which analyses the Climate-, Land-, Energy- and Water- (CLEW) interactions and implications associated with socio-economic development. It demonstrates tradeoffs associated with interventions aimed at meeting development goals (specifically food, fuel and water supply) in the context of a specific case study.

Energy use is the greatest anthropogenic emitter of carbon dioxide. Water energy and food are essential for development and their security of supply is of high importance. Yet these are inexorably linked. The agricultural sector of developing countries can use as much as 70-80% of available fresh-water supplies (DFID, 2001). Consequently energy for irrigation is a major energy user (Shah et al 2004). Water is required for cooling thermal power plants. In 2006, 39% of fresh water withdrawals in the USA passed through a power plant steam turbine to produce electricity[1] (NREL 2009). Fertilizer, a major input to agricultural activities is highly energy intensive. And, land can be used both for producing food, or feedstock for energy carriers, such as biofuel.

Interdependencies mean that energy policies based on energy analyses alone might have adverse unanticipated effects on water resources, land resources and the climate. The same is true for water policies based only on analyses of water issues, and for land policies based only on land-use analyses.

Thus, presented and applied in this work is an integrated analytical tool that includes all CLEW aspects in a manner that may be made accessible and useful to policy analysts and planners. Given that CLEW modelling addresses four core resources, all required for socio-economic development, the case study scope could potentially be wide. The nexus bringing climate, water, energy and land systems together, implies a large number of trade-offs and interactions which may be complex in nature. Thus, in this initial case study, the scope is deliberately narrow. We choose a developing island state, such as Mauritius, which is a producer (and exporter) of food and dependant on imports for the majority of its energy needs. Further, the model that is developed (at this stage) is an “accounting tool”. It quantifies relationships based on between elements of the CLEW system, which are then driven by user defined scenarios. (With these relations quantified, future work can be undertaken to formally investigate the afore mentioned trade-offs.)

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[1] (Given that the same water can pass through more than one turbine along the same river, much water is used for hydro-electric generation. In the US, though supplying less than 10% of electricity, more than nine times the quantity of total freshwater withdrawals pass through hydroelectric turbines! (NREL 2009))

(bagasse). Sensitivity analyses further investigate key questions and demonstrate how this model type can be used to explore the potential array of development options for the policy analyst to consider.

For each scenario, levels of local (on the island), foreign (off the island) and global (local plus foreign) emissions, energy use, water-consumption volumes are calculated. (The foreign effects reported are those assumed to be induced by changes on the island.) Further, these are categorised into direct and indirect effects. Selected economic opportunity costs for each scenario are also calculated. (All attributes are reported as costs, thus a negative value indicates "an improvement" or a cost reduction.)

B. Motivation for the development of the CLEW tool

The motivation for the model development is simple and stark. Given growing global demands, the world's resources of water, land and energy are relatively scarce; the use of each affects demand for the others; and the use of all affect the climate. There are 1.1 billion people without safe water and 1.6 billion without electricity (WB 2006). With population increases it is estimated that agricultural productivity has to increase by 56% by 2030 (FAO 2007). The need for more crops, energy services and water can drive deforestation, land degradation, water scarcity and increased fossil fuel combustion – all of which contribute GHG emissions. Increasing demands, high oil (and transport) prices as well as biofuels competing with food crops recently caused food prices to spike beyond the reach of many of the world's poor – a trend, that in the longer term, some analysts do not see reversing (Ambler-Edwards et al 2009).

Climate, land-use, energy and water are inextricably linked. Water is an essential input to energy production and energy is an essential input to water distribution (BNL, 2008). Both are required for agricultural and bio-fuels production. Weather patterns, which determine precipitation levels, are affected by the climate. The climate is affected by emissions of carbon dioxide during farming, energy use and other activities.

In the power sector, thermal power plants[2] use large amounts of water for cooling – some[3] of which is lost to evaporation. Hydropower plants use significant quantities of land[4] and interfere with existing water flows, changing silting patterns in river basins[5]. Significant quantities of water are also required for other energy processing activities, such as refining oil products or manufacturing synthetic fuels[6]. Land-use, especially cultivation of biofuel crops, is water-intensive[7].

About 7% of commercial energy production is used globally for managing the world's fresh water supply. Before use it can be extracted, purified and distributed. After use, it can be treated and recycled all of which requires energy[8].

Water combined with energy has a particularly important role to play in agriculture. In arid developing countries, irrigation can account for as much as 90% of total water use (GDI (1998) and FAO (2003)).

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[2] Some 50% of US fresh water consumption first runs through turbines for electricity production before being piped to the end-user (USGS 2004); a barrel of oil equivalent from tar sands requires three barrels of water; one kWh of coal-based electricity involves the use - on average - 95 litres of water.

[3] According to NREL (2003) approximately 2.5% of the water used for power plant cooling was evapourated.

4 The large land requirements of hydropower can require the relocation of activities and people. Over a million people, for example, had to be relocated because of the Three Gorges Dam Project (Chaudhuri, 2003).

5 Damming the Nile River, for example, caused the silt - which was deposited in the yearly floods and made the Nile floodplain fertile - to be deposited behind the dam. This lowered the water storage capacity of Lake Nasser. Poor irrigation practices further waterlog soils and bring the silt to the surface.

[6] In New Mexico, for example, refineries currently use 50–180 litres of water per barrel of crude oil and generate 30–120 litres of wastewater (Timm, 1985).

[7] A barrel of ethanol from corn requires 73,000 to 132,000 litres of water.

[8] For example, the energy required in California to treat waste water for reuse ranges between 0.1 and 4.0 kWhr per 1000 litres (CEC 2005)

Irrigation can be gravity driven but increasingly requires energy for pumping as water table goes down. For example, in India between 15-20% of electricity use is attributed to irrigation (Shah et al (2004)).

The climate is affected by releases of GHGs from anthropogenic activities[9], such as fossil fuel power production, fertilizer production and use, crude oil and biomass refining, transport and land cultivation (IPCC, 2007, Fischer et al 2005). Fossil fuel combustion accounts for the bulk of emissions[10]. Various energy technologies are low carbon emitters (such as biofuels, other renewables and nuclear). Other methods of reducing CO_2 emissions include sequestering CO_2 in forests and the future use of CO_2 capture and storage technologies. With changes in the climate come changes in weather patterns. When droughts occur, water for electricity generation is limited, irrigation demands increase and desertification can take place. Conversely flooding can damage crop land, infrastructure and human settlements.

There are clear relations and interactions between water, land-use and energy. Each affects the other in substantive ways. Ignoring effects in one can have significant effects on another. Thus, the need for a systematic, coordinated planning approach is obvious.

The analysis of individual systems such as the energy and water systems are undertaken routinely. Common tools used for energy system analysis include, for example, the MESSAGE[11], MARKAL[12] and LEAP[13] models. A commonly used model for water system planning is the Water Evaluation and Planning system (WEAP[14]), and for water scarcity and food security planning, the Global Policy Dialogue Model (PODIUM) model is well established[15]. However, these and other models are, 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; they have overly simplified spatial representations; are grand policy "*research*" rather than short term applied "*policy*"/decision support models, or analyse scenarios which are impractically long term[16].

What is presented and applied in this work is an integrated prototype accounting tool that includes essential CLEW aspects in a manner that may be made accessible and useful to policy analysts and planners. Key improvements over existing approaches include: finer geographical coverage, reduced data requirements, a medium term temporal scope, multi-resource representation (including their inter-linkages) and software accessible to developing country analysts. The aim of the tool is to help decision makers to assess: different technological options with diverse benefits and disadvantages; estimate the impacts of different development scenarios; coordinate policies and planning activities related to water, land, energy and climate; as well as analyze and evaluate policies.

The scope of the case study chosen is deliberately limited and illustrative. As it simplifies issues relating to the analysis boundary, an island state was chosen for this exercise.

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[9] Important contributors to anthropogenic releases include burning fossil fuels, land use, land use change, forestry, cement production, waste water processing, natural gas flaring and chemical processes and products.

[10] The IPCC estimates that CO_2 from energy use accounted for 56% of global GHG emissions in 2004. Power generation accounted for 30.5% of total CO_2 emissions and transport for 17% (IPCC 2007).

[11] 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)

[12] MARKAL (Market Allocation) model of the ETSAP implementing agreement of the International Energy Agency (ETSAP 2009).

[13] LEAP (Long Range Energy Alternatives Planning) model of the Stockholm Environmental Institute (SEI 2009).

[14] The WEAP energy model is maintained and supported by the Stockholm Environmental Institute: http://www.seib.org/software/weap.html

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

[16] 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 2009), IMAGE (MNP 2009), and TIAM (Loulou & Labriet 2008).

C. An Illustrative Case Study, calibrated with selected data from Mauritius

The attributes and characteristics of Mauritius offer ideal data to illustrate the use of the prototype CLEW model. The application, while based on Mauritius data, is not limited by the country situation. The Republic of Mauritius is a small island country in the Indian Ocean, 950 km to the east of Madagascar. It has a total area of 2 040 square kilometre (km^2), consisting of the island of Mauritius itself (1 865 km^2), as well as several smaller islands.

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, country's economic and social progress is potentially under threat from external shocks. These include the decision by the EU to cut its guaranteed sugar import price and hence reduce 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% energy needs. The remaining requirements are met by domestic renewables, with bagasse accounting for 94%. Imported fuels include coal (27%) 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) 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 regime. Accordingly, the government has formulated several measures to revitalise agriculture. A multi-annual Adaptation strategy and an Action plan highlighting the actions to be taken have 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 2009c)

Given the importance of agriculture, water supply is a key consideration. Mauritius has a sub-tropical climate with two seasons: the summer season from December to April, during which temperatures exceed 32 ^{0}C on a regular basis, and the winter season from May to November with a minimum temperature seldom falling below 16 ^{0}C. The average annual precipitation is 2 041 mm. The Central Plateau receives an annual average of 3 000 mm, whereas, the northern and western parts are the driest regions of the island, with an annual precipitation of 1 200 mm and 900 mm respectively.

In areas with a water-deficit, agricultural production is jeopardized by the recent occurrence of recurrent droughts. Seven out of the last twelve years have been declared drought years in the northern part of the country. Consequently, even sugar cane, which is known to be relatively drought tolerant, has suffered reduced yields. Not only does the northern part of the country supply 20% of the national sugar cane yield, but also 25% of the national food crop. It is against this background that the Government of Mauritius has approached the African Development Bank and the BADEA (Arab Bank for Economic Development in Africa) to assist in financing the installation of irrigation systems over 1,377 ha in the northern region of the country (AfDB, 2004).

According to the United Nations Development Programme (UNDP) Human Development Report, Mauritius is currently facing a situation of water stress. It has a supply of 1 083 m3 per person per year which is below the norm of 1 700 m3 per person per year. Mauritius is expected to suffer from water scarcity by 2020 with a projected supply of 974 m3 per person per year (based on a projected population of 1.34 million) (UNDP, 2006). Although the underpinning assumptions may be subject to interrogation, they provide an indication of the problems that Mauritius may face in the future regarding water supply (OECD, 2007). Some recorded statistics, which tend to substantiate this trend, show that there has been a drop of 8 per cent in available fresh water resources over the last 30 years in Mauritius.

Given its diminutive size and relatively recent industrialisation, Mauritius' contribution as an emitter of GHG emissions is negligible. However, the adverse effects of climate change and sea-level rise pose significant risks to the coastal areas of the island. Mauritius along with other small island developing States believes that they are already experiencing major adverse effects of climate change (UN, 2005).

With the various stresses observed, clear interlinkages and stresses, coupled with a relatively small CLEW system the Mauritian situation offers useful data to calibrate this application of the prototype CLEW model. In order to illustrate the model application, the scope of application is narrow, and a particular interest is to simulate the CLEW impacts of energy production (ethanol and electricity) from sugarcane.

Ethanol would reduce energy import dependence by substituting gasoline, whereas, use of bagasse for electricity generation would reduce need for coal import. However, there are interdependencies. For example, the process of ethanol production needs energy too. Increased energy independence may be earned at the expense of export earnings from sugar. Further, there are technology and process options (with different CLEW relations) which are examined. Quantifications of net impacts of these chain effects (some positive and some negative) would help policy makers to make informed decision. Following sections present some specific relevant country details and background. The total population of the country is 1.28 million (2009), of which 56% live in rural areas.

Population and economy

The annual population growth rate is 0.9% (2001-2007). In 2007, the Gross Domestic Product (GDP) was US$6.8 billion (WB 2008) Since its independence in 1968, Mauritius has had a practically continuous economic growth, averaging at a rate of 5.2%/year from 1992-2002 (CPF, 2007). It was 4.7% in 2007. Per capita annual income is approximately US$ 12 400 (ppp) (WB, 2008).

Land and agriculture

The cultivated area is 106 000 hectare (ha), or 52% of the total area of Mauritius. Of this, arable land covers 100 000 ha and permanent crops 6 000 ha[17]. Around 20% is occupied by built-up urban areas and 2% by public roads. The remaining area consists of forests, wetlands, scrub lands, grasslands and reservoirs. The agriculture sector is of strategic importance to the Mauritian economy as it employs slightly above 16% of the total working population (about 58,000 people), and is the first source of net foreign currency for the country. In 2007, agriculture accounted for about 5.3% of the GDP (WB, 2008). Sugarcane is the main crop, with an annual production in 2008 of 4.5 million tonnes (ROM, 2009a), harvested in land area of approximately 74,000 hectare. Basic foodstuffs such as rice, flour and cereals are imported as local cultivation and production of such commodities is not economical.

The potential additional land area which may be irrigated in Mauritius is estimated to be 33 000 ha. The area equipped for full control irrigation was estimated to be 21 222 ha in 2003 (FAO, 2008). Surface (or gravity fed) irrigation is practised on 2 372 ha, sprinkler irrigation on 17 028 ha and localized irrigation on 1 822 ha. About 75% is irrigated with surface water and 25% by groundwater. Around 61% of the cultivated land is power irrigated.

The use of fertilizer is rather high in Mauritius[18], and as the geology is characterised by fissured lava with relatively high permeability, the impacts of agrochemicals leaching into the groundwater reservoirs need to be

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[17] A permanent crop is one produced from plants which last for many seasons, rather than being replanted after each harvest. The term comprises land cultivated for crops like citrus, olives, coffee, and rubber; it includes land under flowering shrubs, fruit trees, nut trees, and vines, but excludes land under trees grown for wood or timber.

[18] Approximately 138kg per ha of nitrogen based fertilizer is applied for sugar cane production.

given serious consideration, as 53% of residential water stems from groundwater resources (FAO, 2008). (Amongst other options, land permeability may be decreased by increasing its organic matter content.)

Water resources and use

Total potential renewable water resources are estimated at 2.751 km^3/year[19]. Total exploitable water resources are estimated at 1.083 km^3/year. In 2006, total withdrawals were 682 Mm^3, of which about 66% (453 Mm^3) was for irrigation purposes and rest is for other sectors (domestic, industry and service). The entire population has access to potable water. Per capita consumption for domestic usage, which averaged 130 litres per capita per day (lcd) in 1991 now stands at 170 lcd.

Energy

Mauritius has limited domestic energy resources. These include renewables, in the form of hydro and biomass, especially bagasse. Bagasse is a by-product 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 are two main transportation fuels and transport sector account for 39% of the total oil import. The share of energy bill over total imports was 17.9% in 2007, compared to 16.3% in 2006.

2 465 GWh of electricity was generated in 2007, of which 96.6% was from thermal power plants and 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%) (CSO, 2007).

Climate change issues

Mauritius' economy has a high dependence on tourism and agricultural production. Given that this and irrigation levels are dependant on weather and climate patterns, impacts of changes are important.

Climate change is also important with respect to tourism, as fauna, flaura and weather are key attractors of visitors.

Further, given that the bulk of her energy use is dependent on the import of fossil fuel, increased use of renewable energy has the potential to reduce GHG emissions.

D. Case Study Assumptions

The question posed in this study to illustrate the application of the prototype CLEW model is the conversion of sugar production and export to ethanol production for local use.

Fuel import dependence can be improved, by shifting to alternatives such as locally produced ethanol from imported petrol. The production of ethanol incurs a cost which is offset by a reduced petrol import bill. The use of ethanol (a renewable fuel) in place of petrol (a fossil fuel) reduces local and greenhouse gas emissions. Reducing the amount of sugar produced for export (to produce ethanol), however reduces sugar export earnings.

Another consideration is the use of bagasse. It is assumed that bagasse can be used either for ethanol production (via hydrolysis) or for electricity production. In the first case, ethanol production is increased and petrol imports are reduced. In the second case, less electricity needs to be generated from the national grid, as locally produced bagasse is used. It is assumed that grid electricity is based on coal. Thus increase grid electricity, being fossil based, increases greenhouse gas emissions.

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[19] FAO (2008)

In all cases, fertilizer is imported and the emissions used for its manufacture (though outside the island) are calculated[20].

For the analyses, levels of local (on the island) and global (external) emissions, energy use, water-consumption volumes, and selected costs and benefits are calculated. Further, these are categorised into direct and indirect effects. Direct effects include, for example, the energy required for tilling and water required for irrigating the land. An indirect effect would, for example, include the extra energy required pump the water used for irrigation.

Further, although the model is calibrated using data from Mauritius this is for illustration only. This is useful as it allows the study to deviate and consider hypothetical scenarios that may be important in other settings. In this case (although the land available in Mauritius is almost fully utilised) we consider the effect of converting grassland into crop-land. This is an option that is faced in many developing countries, and therefore an option that would be advantageous to analyse in a CLEW tool.

E. Approach

The approach chosen in this initial phase of the CLEW modelling effort is a simple prototype accounting tool. The aim is to get a “first order” overview of the main physical inter-linkages between water-, energy-, climate- and land-systems, and the implications of exogenous change. This is a natural starting point as these physical linkages are central to any future more complex modelling. They have to be in place before the analyst attempts to determine e.g. any socio-economic inter-linkages. At this stage only limited broad assumptions on indirect land use change and selected costs are included as “socio-economic”. The remainder of the effort relies on the accounting of mass and energy. Such an approach also helps to demonstrate the relative importance of the different linkages, and will thus inform future work on the most relevant linkages.

The starting point for the model application is a homogeneous piece of land of a given size and type. This forms the building block and reference in the accounting framework. Each (land related) inter-linkage is calculated in terms of water and energy requirements as well as GHG emissions per area. (Thus to account for a “non-homogeneous” area, where n different types of land exist, one introduces n different “homogenous” areas of land.) The main rational for having land as the building block and reference is due to the physical attributes of land. As opposed to energy and water; land is difficult to move, and its characteristics are to a large extent determined by geography, i.e. location, and the characteristics are difficult to influence by direct technology interventions. Climate, terrain, altitude, insulation and weather are examples of characteristics that are difficult to change and that are specific to the location. Land type and water availability are other characteristics that can be influenced by human interventions to a limited extent only. Land is therefore thought of as a reference and building block in this application of the prototype accounting model[21].

Apart from the economic reporting across scenarios, the oil price is assumed to be 60$ per bbl over the long term, and linked to the (export) sugar price of $522/ton (ED&F Man, 2009). Ethanol is assumed to displace imported petrol. For every tonne of ethanol introduced into the system, approximately 440$ of petrol imports (EIA, 2008) are avoided. The life-cycle cost saving of using co-generated electricity from bagasse waste – rather than coal from the central grid - is: 2.7 c/kWh. The cost of coal-based grid electricity is approximately 5.2c/kWh. The production of ethanol from sugar cane only costs 211$/tonne (scenario 3SEP). Increasing the yield by supplementing sugar cane ethanol with hydrolysis based bagasse production costs 228$/tonne (in scenario 4AEP). (A description of the underpinning assumptions and justifications are given in the Appendix and are based on Toth and Barkatullah (In draft), IEA 2005, IEA 2006 and IEA 2008).

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[20] Energy used for fertilizer manufacture and transport to Mauritius is estimated by Ramjeawon (2008) as 56MJ/kg. A further 8.6 GJ used directly for land tilling, fertilizer application etc for every ha of sugar-cane cropland land annually (Khan et al. 2008).

[21] In future iterations of this model, land could be further categorised according to soil quality status. This can effect fertilizer and water needs for a given yield.

F. Scenario descriptions

Should an island with characteristics such as Mauritius start production of ethanol from sugarcane? It is with this question in mind that the following scenarios are developed.

The first scenario, 1SSM (Standard Sugar Mill), is a standard sugar mill with low energy efficiency that uses all the bagasse to produce electricity and steam needed in the production of sugar. (I.e. no excess electricity is available for supply to the national grid). The only product is thus sugar. The second scenario, 2ASM (Advanced Sugar Mill), is still a sugar mill installed with high pressure boilers, much like the process equipment installed at Mauritius today (Ramjeawon 2008). This process has a surplus of electricity that is delivered to the grid.

The third scenario, SEP (Standard Ethanol Production), introduces ethanol production from sugar cane, as opposed to sugar production in scenario 1SSM and 2ASM. The process employed is a conventional ethanol process plant, with some surplus electricity that is delivered to the grid. Our fourth and last scenario, 4AEP (Advanced Ethanol Production) represents a second generation ethanol plant, where also the bagasse (that is not used for steam) is turned into ethanol (FAO,2009), and the plant thus has to get electricity from the grid. (Note that in the last scenario, not all bagasse is converted into ethanol. Only bagasse that is not used for meeting process heat requirements is converted to liquid biofuel.)

Scenarios:

- ⇨ 1SSM - Sugar production in conventional sugar-mills (no surplus bagasse)
- ⇨ 2ASM - Sugar production with high-pressure boilers (surplus electricity from bagasse)
- ⇨ 3SEP - Ethanol production with high-pressure boilers (surplus electricity from bagasse)
- ⇨ 4AEP - Ethanol production (2. gen) with hydrolysis of bagasse (electricity deficit)

In addition to the scenarios, specific sensitivities have been undertaken on scenario 3SEP. These include:

Sensitivity (1) Converting different land types to cropland. (The analysis asks what the impacts would be as a function of what the land was used prior to its cultivation for sugar cane.) This is a focus as the carbon content of different soils plays a major role in the total GHG-balance of the island. In many developing countries, questions around what level of forest clearing etc is acceptable to increase crop production are important. This, and all subsequent, sensitivity analyses are undertaken considering standard ethanol production of scenario 3SEP. Please note that is not the intention of these sensitivities to motivate the hypothetical shift of wetlands or forest to cropland, but rather indicate how the effects of such a shift may be estimated.

Sensitivity (2) Changing irrigation methods by moving from surface to drip irrigation alters the water need and thus the energy required for pumping of marginal water.

Sensitivity (3) Considers reducing the amount of irrigation and fertilizer application. This is of interest, as changes in amount of irrigation and fertilizer use, also affect the yield.

And finally, Sensitivity (4) Applying an equal mix of biocompost and conventional fertiliser is considered. That option increases yield, the carbon stock in soil, and at the same time reduces energy used in conventional nitrogen based fertilizer production.

In all scenarios (apart from the sensitivity analyses 3 & 4), it is assumed that a conventional amount of mineral fertilizer is applied together with necessary irrigation (surface (flood) irrigation). Marginal electricity supplied from the grid is coal power, and the former land use (with the exception of the “former land use” sensitivities) is cropland for sugar production of an area of 100 ha. The focus is at the next 20 years, from 2010 to 2030.

G. Results

The initial results presented include CLEW-balances and selected economics for scenario 2ASM. This helps point out which parts of the CLEW inter-linkages that are the most important. It also acts as a useful starting point to better understand overall CLEW dynamics before moving on to a comparison between scenarios. Finally, sensitivity analyses are presented, focusing on scenario 3SEP (Standard ethanol production).

All results are reported as costs or "loadings". Thus a positive value is reported for pollution emitted, energy or water used or economic costs incurred. A negative cost implies lower pollution levels, energy use levels or profitable economics.

Results are reported in two settings:

- One is "on the island", and referred to as "local". Its reference point is the cane plantation plus sugar mill/ethanol production site. For energy and water, a positive number indicates energy and water used by the site. (And that is supplied from off-site locations, elsewhere on the island.) Negative numbers indicate that energy or water is supplied from the site to the rest of the island. For GHGs, negative numbers indicate a sequestration of carbon or a substitution of emitters (such as ethanol fuel for petrol). Positive numbers indicate increased emissions.
- The other setting is "foreign", and as implied, takes place outside of the island. The latter is assumed to be affected by changes on the island. An example includes the upstream emissions associated with fertilizer manufacture and transport[22], coal or oil supply for example.

G.1. Sugar production with advanced sugar mills (2ASM)

CLEW-balances from 100 ha used for sugar production in advanced mills are shown below. This use of the land results in around 900 tonne of sugar production on a yearly basis. Almost 500 MWh of electricity is generated from the waste bagasse. The local results show the loading of the plantation-sugar-mill/ethanol-plant system. Recall that electricity is supplied *to* the grid *from* the system. The system is therefore incurring a "negative" loading. The annual energy is shown in Figure 1[23]. The water use for scenario 2ASM is shown in Figure 2. It is clear that water use by the system is dominated by irrigation, followed by water use for sugar production. Finally local GHG-emissions are shown in Figure 3.

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[22] While nitrous emissions associated with fertilizer application on the island are included as local emissions.

[23] In order to ease comparison, energy numbers are reported in terms of their primary energy equivalent, which in this case is petrol and coal delivered to the Island, we thereby for simplicity ignore the fuel chain of oil refining and coal extraction.

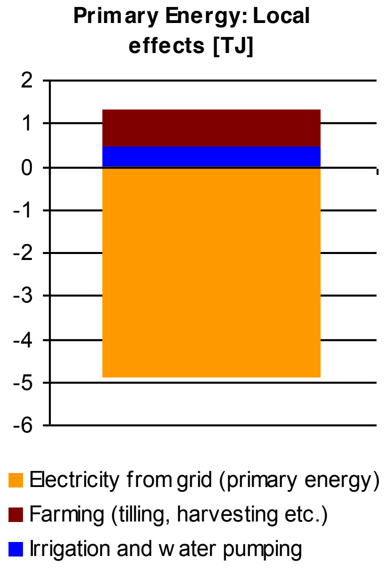

Figure 1: Local Energy balance

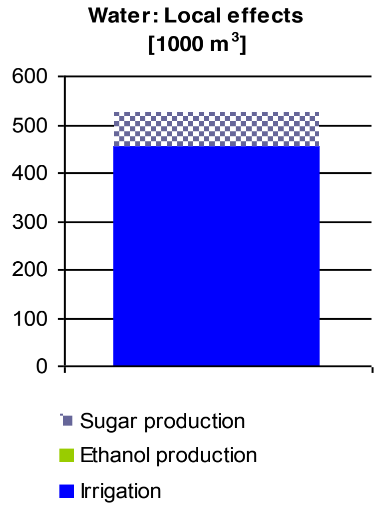

Figure 2: Local Water balance

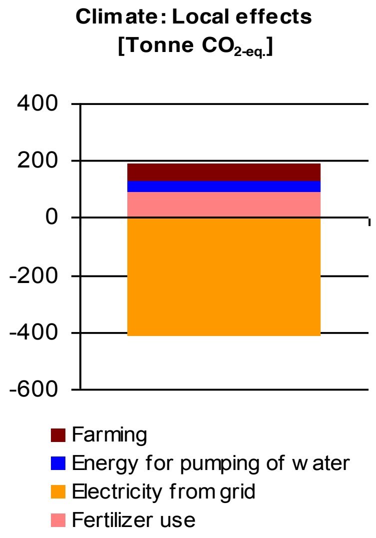

Figure 3: Local GHG balance

GHG-emissions accounted for are emitted primarily by farming activities (tilling, ploughing, harvesting etc.), field emissions of N_2O[24], and energy used for pumping of water[25]. The electricity from bagasse displaces an equal amount of electricity that would have otherwise been generated from coal, thus emissions here are considered negative. These outweigh the GHG-emissions caused by the sugarcane farming (the total local GHG-balance is -234 tonne $CO_{2\ \mathrm{eq}}$).

As shown above, farming and water pumping for irrigation are the major energy users for sugar production, but external to the island is the production of imported fertilizer. Fertilizer production uses considerable amounts of energy; around 0.6 TJ in total for production of the 7500 tonne of sugar cane[26]. Thus, the climate accounting also has a foreign component that is dominated by fertilizer production. Another foreign component accounted for are the "up-stream" fuel chain emissions from imported fuels. In this case, this is negative as bagasse effectively replaces coal imports for power generation and thus less coal has to be extracted, with associated "up-stream" effects. Foreign (external) GHG emissions and energy use changes are shown in the figure below.

The GHG emissions reduced, due to coal displacement (by bagasse), nearly out-weight the emissions caused by fertilizer production, both for the external energy- and GHG-balance. Primary energy and external GHG emissions are reported in figure 4.

In this scenario approximately 900 tonnes of sugar are produced and exported at a total income of $473 000. All liquid fuel requirements are imported. The 500 MWh generated from bagasse saves the system $12 000.

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[24] These emissions are associated with the use of nitrogen based fertilizer on the sugar cane plantation.

[25] It is assumed that approximately 2500m^3/ha of additional irrigation water is supplied for a yield of 75.5ton.

[26] Note that the emissions estimate used includes fertilizer transport to the field and are taken from Ramjeawon (2008). Local emissions from fertilizer application are estimated as 6.7 kg CO_2eq per kilogram of N-based fertilizer. This is the median value given by the IPCC (1996).

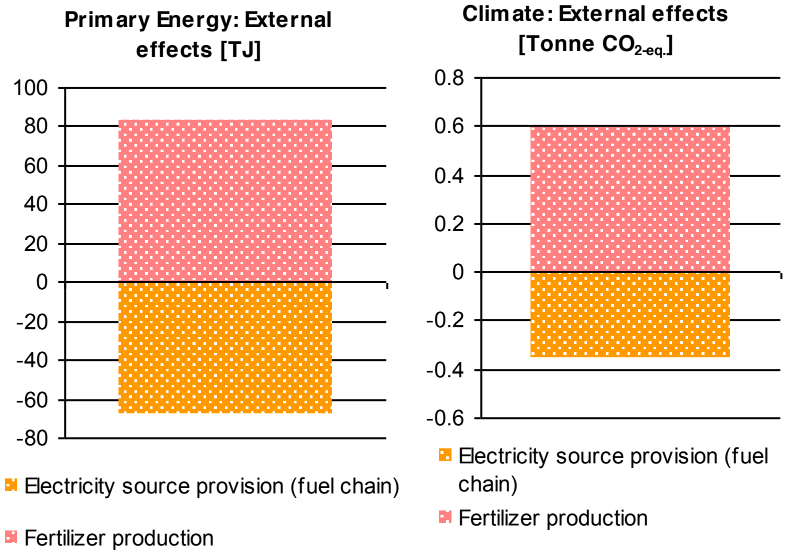

Figure 4: Foreign energy and GHG-balance

G.2. Scenario comparisons

The following section compares scenarios in terms of their water balance, energy balance, economics and GHG emissions. Where results change over time, cumulative values are used, and where the balance does not change over time, the composition of the different balances is shown for a single year.

In scenarios 3SEP and 4AEP sugar production is replaced by ethanol (and food replaced by fuel). Less sugar is produced and exported to the world market (compared to scenarios 1SSM and 2ASM). Ceteris paribus, this raises the price of sugar, which in turn provides global incentives to produce more sugar elsewhere. Foreign sugar production, leads to land use change outside of Mauritius. (The underpinning assumption details and justifications are found in the appendix.) (It is noteworthy to remember that the sugar that is produced is not given any local energy credit. Ethanol production and use is given energy credit. This is because ethanol replaced petrol imports and local use, while sugar is a food product rather than an energy source.)

G.2.1. Scenario water balances

The water balances is shown in Figure 5 below.

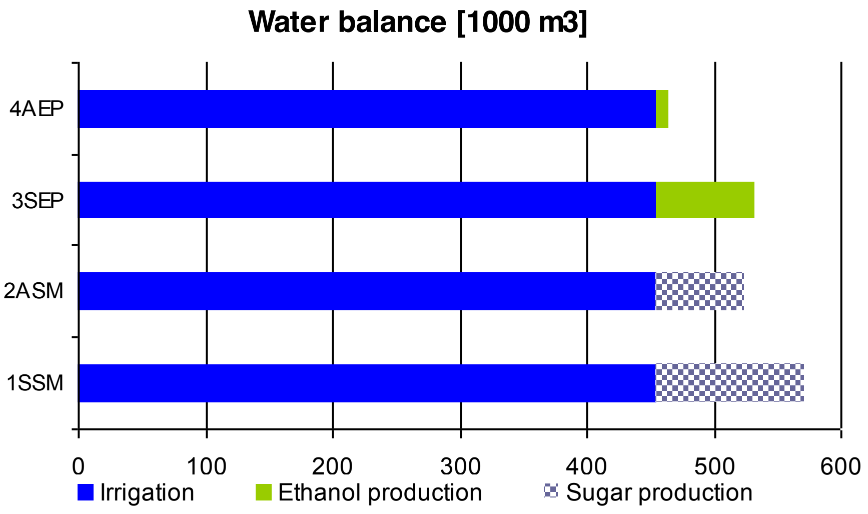

Figure 5: Water balances for the four scenarios

Irrigation is the main water user in all scenarios. The quantity of water used is also equal for all, since there are no differences in the farming activities. However, there are differences associated with water used in the process of either sugar or ethanol production.

G.2.2. Scenario energy balances

Though the energy used for irrigation and farming is equal between all the scenarios, there are very small changes associated with water pumping to the sugar mill / ethanol plant. Larger differences include changes in electricity production (indicated in orange). In scenario 4AEP bagasse is converted to ethanol (and some process heat) but not to electricity. Thus electricity is supplied from the local grid to the plant (indicated by the positive top-right bar in the graphic). In scenarios 3SEP and 2ASM excess bagasse based electricity is exported to the grid (as indicated by positive bars in Figure 6). While in both 4AEP and 3SEP scenarios imported petrol is displaced by local ethanol production and use. These results are summarised in the graph below.

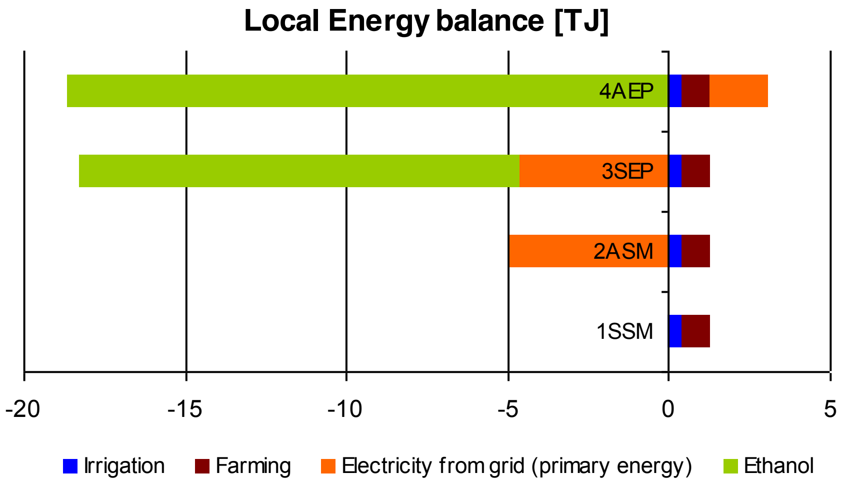

Figure 6: Local energy balance for the four scenarios

It is interesting to note that the energy balance is better for standard ethanol production (3SEP) compared to a ‘second generation’ ethanol production process (4AEP) (i.e. more net energy is produced by the site (left-negative) than being used by site (right-positive)). From a pure primary energy perspective it is thus more efficient to convert bagasse to electricity than to ethanol. If the foreign effects were included, the difference is amplified as “up-stream” energy requirements are accounted for. The total balance including foreign energy is shown in the appendix.

G.2.3. Scenario economics

A transition to produce ethanol from sugar cane has significant cost implications. A simple analysis was therefore undertaken to show the relative ease with which a cost-benefit analysis can be undertaken using a prototype CLEW tool. This was done by varying the oil price. Further, the sugar and coal price are modelled as functions of the oil price, due to an observed recent correlation, however, in one sensitivity analysis the sugar price is assumed to be decoupled. (It is intended that these costs are purely illustrative and used in order to demonstrate the usefulness of the CLEWS accounting framework applied in the case study. More details on the economic assumptions are provided in appendix A.)

The total economic cost, relative to scenario 1SSM, for the different scenarios for 60 and 120 $/barrel is shown in Table 1 below, where negative numbers means cost-benefit. The table should be read as the cost of moving from scenario 1SSM to one of the other scenarios, for different price regimes.

Table 1: Levelised cost of a shift from standard sugar mill to one of the other scenarios, for different price regimes

[1000 $]	Oil: 60 $/barrel, Sugar: 522$/tonne	Oil: 120 $/barrel, Sugar: 1044$/tonne	Oil: 120 $/barrel, Sugar: 522$/tonne	Oil: 180 $/barrel, Sugar: 522$/tonne
1SSM	0	0	0	0
2ASM	-12	-20	-20	-28
3SEP	328	579	106	-116
4AEP	334	518	45	-245

Advanced sugar mill (2ASM) is economic for all price-regimes. It is observed that higher oil prices impute a higher value to the electricity produced from bagasse. Relative to scenario 1SSM, it is only at higher oil prices (120+ $/barrel) that ethanol production becomes economic. Due to of larger volumes produced by 4AEP compared to 3SEP, the advanced ethanol production becomes economic at slightly lower oil prices than the standard ethanol plant.

Figure 7 below shows the main economic effects of a transition from a standard sugar mill to standard ethanol production (1SSM to 3SEP) for different oil prices. Positive values represent opportunity costs, and the negative numbers shows income. However, since higher oil price also mean higher sugar-prices, the opportunity cost of diverting from sugar production is higher than the income from petrol substitution for all the scenarios and for all oil-prices.

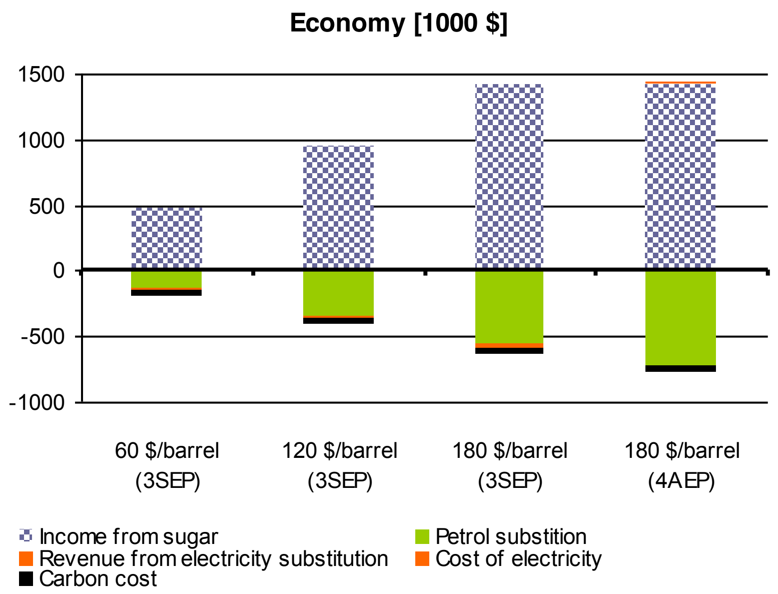

Figure 7: Economy of a transition from 1SSM to 3SEP for different oil-prices

The opportunity cost is shown as positive (and therefore income is indicated as a negative cost.) The option to the far right is the shift from 1SSM to the 4AEP scenario which produces more ethanol but has to import electricity from the grid. It is clear from a comparison between the third and fourth column, that from an economic view, the bagasse has a much higher net value as input for ethanol production compared to as an input for electricity production. However, the latter option (3SEP) has better energy and climate balance than 4AEP, but as these numbers indicate: the economic incentives does not coincide with the energy and climate balance (as will be shown below). The sugar price is held constant at 522 $/ton, as the oil price again is varied. The resulting economics for a transition from 1SSM to either 3SEP or 4AEP are shown in Figure 8.

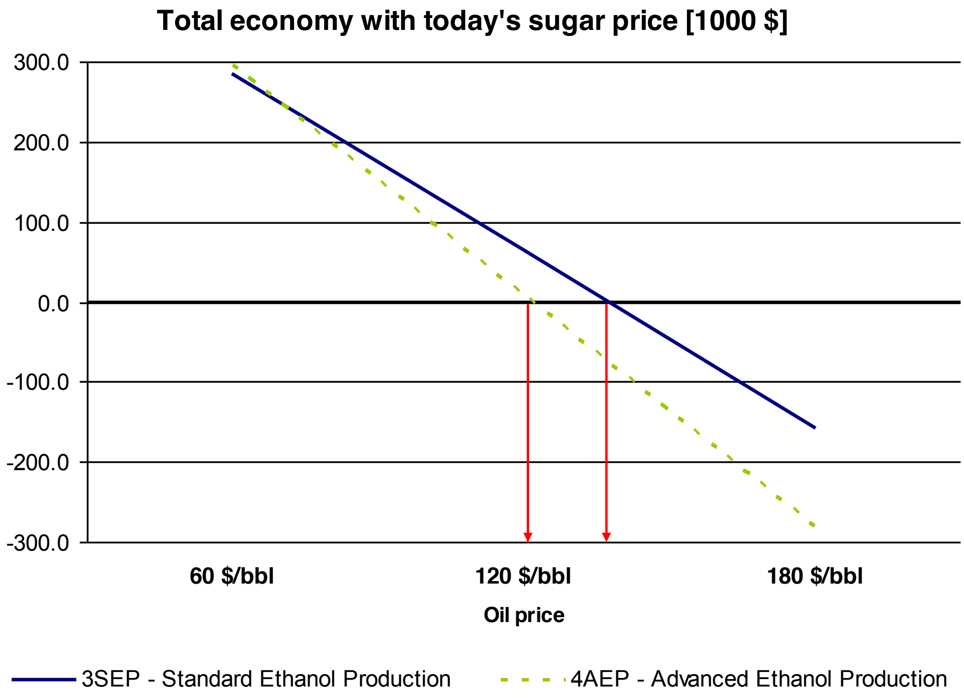

Figure 8: Economic results for a transition from 1SSM to either 3SEP or 4AEP

The second generation ethanol plant becomes economic at around 120 $/bbl, and the standard ethanol plant at around 135 $/bbl.

G.2.4. Scenario GHG balance

Figure 9 shows the local GHG-balance of the four scenarios, with emissions as positive bars to the right, and emissions substitution as negative values to the left. The local GHG-balance follows the same pattern as the local energy balance, which is not surprising as most of the GHG emissions stems from energy use, except from the field emissions from fertiliser use. The substitution of coal electricity in scenario 2ASM leads to a net reduction of GHG-emissions of 255 tonne a year. Again it is noted that the balance is actually better for standard ethanol production (3SEP) compared to a 'second generation' (4AEP). The 3SEP scenario reduces local GHG-emissions by 1420 tonnes each year compared to a standard sugar mill (1SSM). The 4AEP scenario reduces 1256 tonnes per year indicated by the positive and negative bars shown in Figure 9). Importantly, for the climate balance the foreign effects are considerable, and they vary over time, as the soil that undergoes land use change (as it is assumed that foreign production of sugar takes partly place on previously uncultivated land) reaches its new steady state. External fuel chain and fertilizer production emissions are constant over the whole period, but are insignificant compared to the assumed foreign land use change. The local GHG-balances for the four scenarios are shown bin Figure 10 as bold lines, (which are the sums of the bars in Figure 9), while the foreign emissions from scenario 3SEP and 4AEP are shown as dotted lines. Initial "external emissions" are many times larger than any gain provided by petrol substitution.

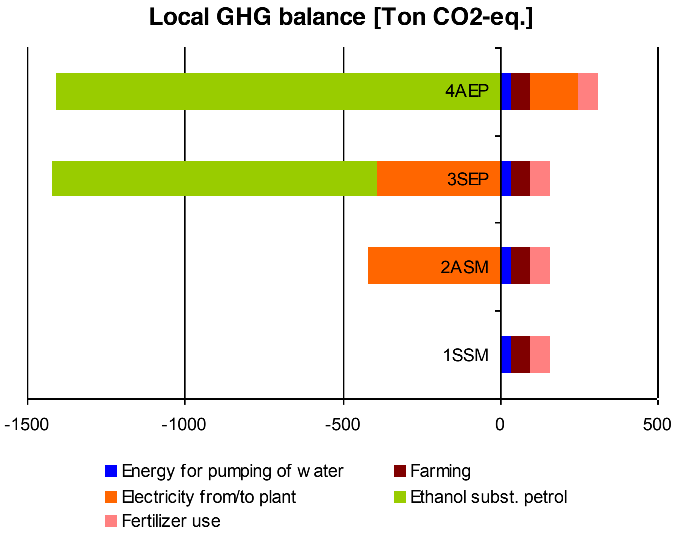

Figure 9: Local GHG balance for the four scenarios

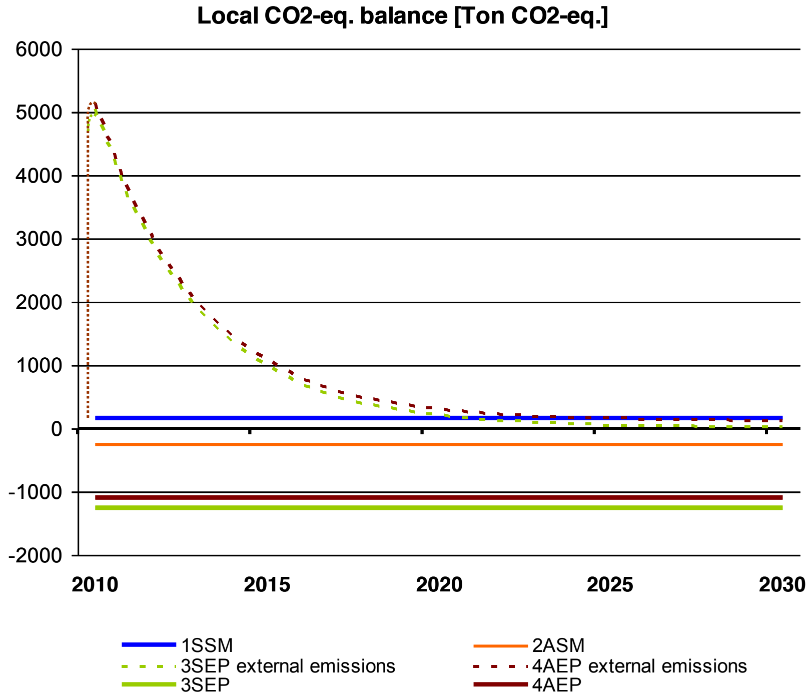

Figure 10: Local GHG balance, together with external emissions for 3SEP and 4AEP

The initial emissions from foreign land use change from the two scenarios (3SEP and 4AEP) that produces ethanol, are considerable[27] but decay at an exponential rate, as seen as the dotted lines in the figure above. The net total emissions reach 0 and become negative from around 2023 onwards for the two ethanol-producing scenarios. The two sugar mills (in scenarios 1SSM and 2ASM) do not induce increased foreign sugar production and associated land use change, since they continue to produce sugar, just as before. Their external emissions are related to fertilizer production and electricity fuel chain, they are 90 tonne for 1SSM and 16 for 2ASM, and thus insignificant compared to 3SEP and 4AEP. The standard sugar mill emits a total of around 250 tonne $CO_{2\text{-eq.}}$ each year, while the advanced one is substituting coal electricity and thus has a net annual emissions reduction of around -255 tonne $CO_{2\text{-eq.}}$.

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[27] Recall that when sugar cane on the island is converted to ethanol, it is assumed that cane for sugar production is grown elsewhere.

Comparing accumulated total emissions with accumulated local emissions, the importance of possible indirect land use change becomes clear. Thus, the increased production of ethanol from sugarcane is promising on a local accounting level, however, it may be less clear when foreign effects are accounted for. The total emissions are shown as dotted lines, while the local direct emissions on the island are shown as bold lines in Figure 11. The differences in accumulated emissions are indicated with arrows. The total net accumulated emissions reaches zero in 2023 for 3SEP and in 2027 for 4AEP.

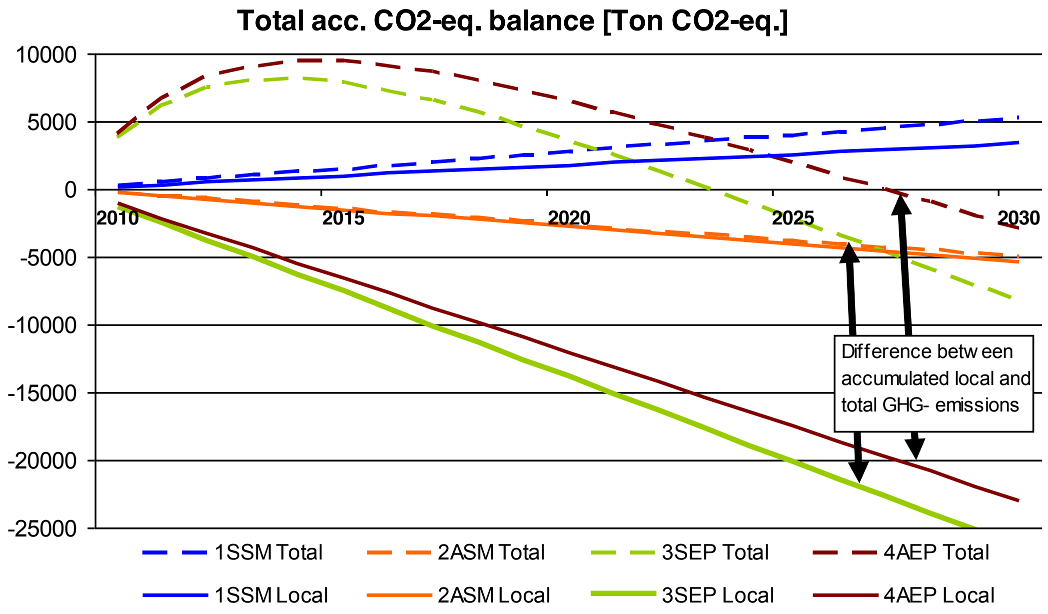

Figure 11: Economic results for a transition from 1SSM to either 3SEP or 4AEP

G.3. Sensitivity 1: Converting different land types to cropland

The carbon content of different soils varies significantly and a land use change may have severe consequences for GHG-emissions. (The details behind the assumptions used are placed in appendix A.) Figure 12 shows the total GHG-balance with both local and foreign emissions included. The magnitude of the emissions from land use change makes the foreign emissions (coal fuel chain and fertilizer production) diminish in comparison. Note again that the results for this sensitivity are based on standard ethanol production (3SEP).

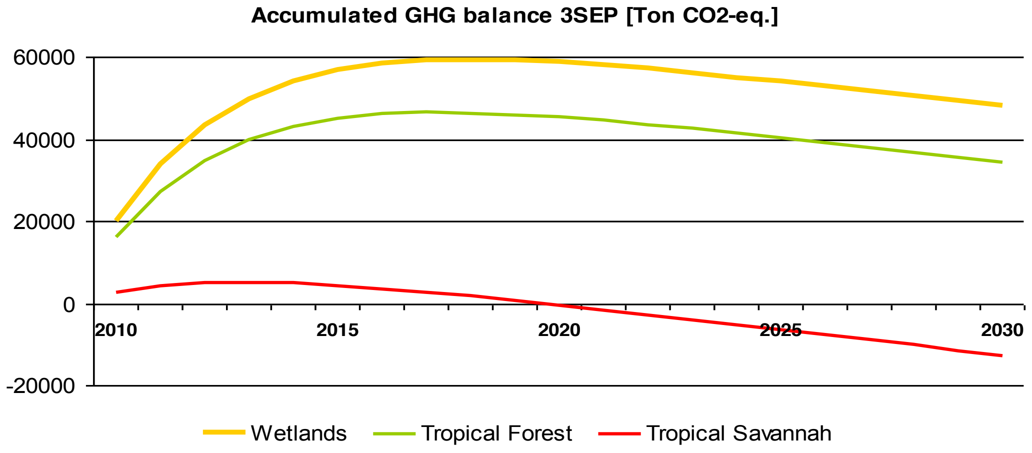

Figure 12: Accumulated GHG balance from ethanol production on wetlands, grassland or forests

From the figure it is clear that ethanol production from land that was formerly tropical forest or wetland is a poor option if GHG-emissions reduction is a goal. Land that was once “Deserts and semi-desert” with low carbon soils would gain carbon content from cropping. (It is assumed fertiliser application, water provision, tilling and other cropping aspects are appropriately carried out so as to enrich the organic matter in the soil.). This is especially true for perennial crops, where much of the residues are left in the field after harvest. Converting tropical savannah would result in a net emissions reduction around 2020. For wetland or tropical forest the net accumulated emissions reach zero in around 100 years from now. The carbon content of the land that is turned into cropland is therefore crucial for the total GHG balance[28]. Assuming an essentially zero value for unused land, may yield significant local economic gains[29].

It is plausible to think that the former state of the land – prior to conversion to crop land - influences aspects like: yield, fertilizer need, and irrigation need for the cropland that is situated there after the land use change. As these aspects have high local specificity, general assumptions made here are only for illustrative purposes *only*[30]. Input assumptions related to the land that was converted are included in Table 2. That table indicates the yield as well as irrigation and fertilizer needs relative to standard cropland. For a cropland that was formerly a wetland, it is assumed that irrigation is not needed (hence a value of zero in the table); the high carbon content in the soil increases yield by 8%; and only 50% of fertilizer is needed compared to standard cropland. Tropical forest that is cleared is assumed to have the same characteristics as cropland. Tropical savannah that is turned into cropland is assumed to increase yield by 2%, and need 90% of the fertilizer needed for standard cropland.

Table 2: Assumptions regarding irrigation, yield and fertilizer use after land use change

Factors **Land converted**	***Irrigation need:***	***Yield:***	***Fertilizer need:***
Tropical forest	100%	100%	100%
Wetlands	0%	108%	50%
Tropical savannah	100%	102%	90%

The resulting energy consequences for 100ha of converted wetlands and savannah are shown in Figure 13. There are net gains for both, mainly due to the higher yield. The former wetland has both a higher yield and no irrigation need; the latter reduces energy for pumping by around 0.4 TJ[31].

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[28] GHG emissions form methane and nitrous oxide formed in the wetland are not estimated in this analysis, but depending on the situation may be significant.

[29] Recall that for sugar production only 100ha of land, 900 tons of sugar could be produced and exported at a total income of 473 000$. All liquid fuel requirements are imported. Also, the 500 MWh generated from bagasse saves the system 12 000 $.

[30] An actual application of the tool would have to focus on dynamics such as changes in soil water and soil fertility status, with the shift from wetland/forests and savannahs to cropland. Similarly irrigation needs will be a function of the specific water table and rainfall patterns, as well as specific soil fertility quality. Both of which may change over time with the associated effects of long term cropping.

[31] Again, note that these assumptions are illustrative, and a site-specific application would require site specific data. For example, the conversion of wetlands to crop land may not increase yield. In fact the conversion can potentially reduce the yield unless lime is applied to neutralise changes in soil pH. In some cases phosphorus fertiliser may need to be applied to address phosphorus deficiency. In addition wetland conversion may stimulate soil organic matter decomposition/mineralisation and the sudden flush of carbon dioxide and the release of nitrate. (Nitrate in the presence of anaerobic sites (e.g., inadequate draining) can cause a gigh flush of nitrous oxide, a potent GHG.)

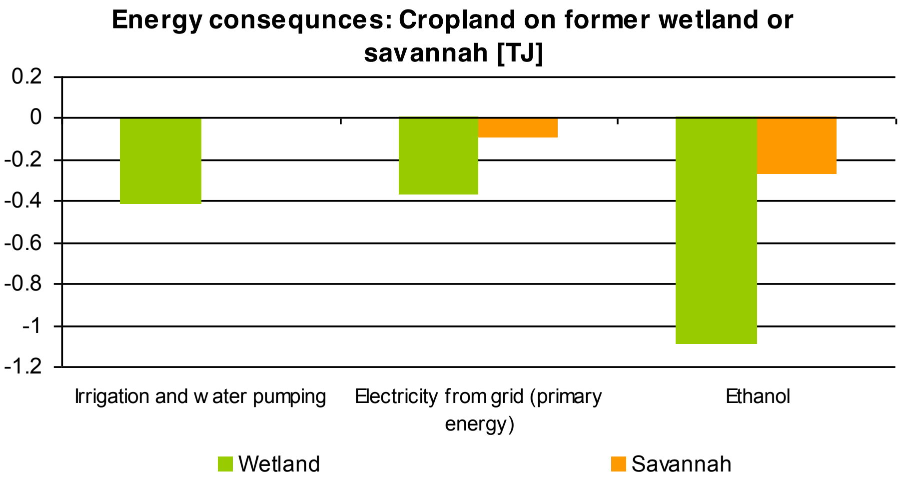

Figure 13: Reduced energy use because of land use change

Focusing on water: as the cropping of sugarcane on the wetland required no irrigation, water needs are reduced by about 450 000 m^3. (Here only direct effects are accounted for[32].) The net water consequences are shown in Figure 14. There is an increase in water consumption due to increased ethanol production from higher yields incurred, but is insignificant and not visible.

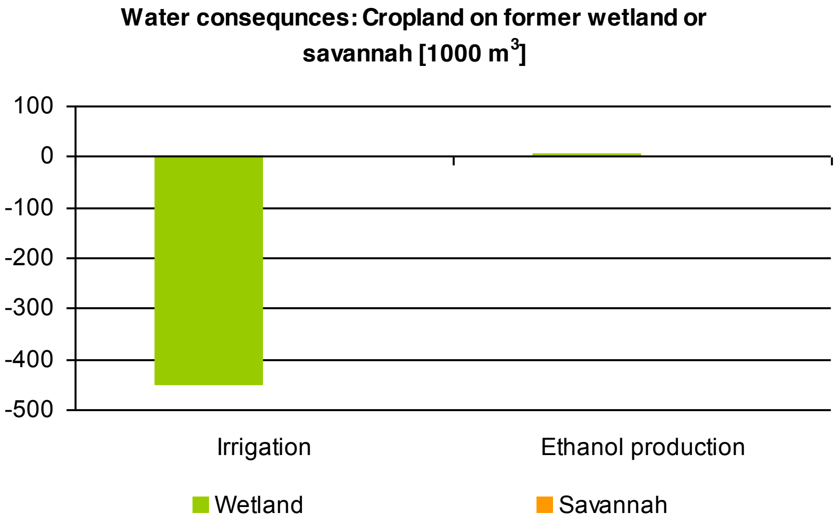

Figure 14: Changed water use because of land use change

G.4. Sensitivity (2): Changes in irrigation type from flood to drip for 3SEP

Changing irrigation methods leads to considerable water savings, which in turn leads to reduced energy use and cost savings. This is due to lower pumping requirements. Lower coal quantities used for electricity production in turn reduces GHG emissions. Direct water savings are estimated to be 177 000 m3, which represents 33% of all water consumption for the system considered. The energy use reductions are 162 GJ, or 12.7% of all energy used in the agricultural steps. This in turn mitigates 13.7 tonne of GHG-emissions (8.6% of all farm related local emissions). It is thus clear that the implications of changing irrigation system are considerable in all CLEW-systems.

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[32] Note that the energy required for wetland draining and conversion to cropland is not included. Note also that this conversion will change the soil hydrology and actual irrigation requirements (if any) will be a function of local water table, precipitation and other conditions.

G.5. Sensitivity (3) Lowering the amount of irrigation and fertilizer use for the 3SEP scenario

A change from high input agriculture to low input (no fertilizer and only rain fed) agriculture has an impact in all the CLEW elements. However, it is not trivial to determine whether the balance turns positive or negative[33]. Low input agriculture results in a lower yield (from 75 ton/ha to 57 ton/ha), which implies less substitution of petrol and electricity, but at the same time it implies as well less pumping of water (no irrigation) and no fertilizer use or production.

Figure 15 shows the changes in the energy-system for low input agriculture, including the foreign production of fertilizer, which is saved with low input.

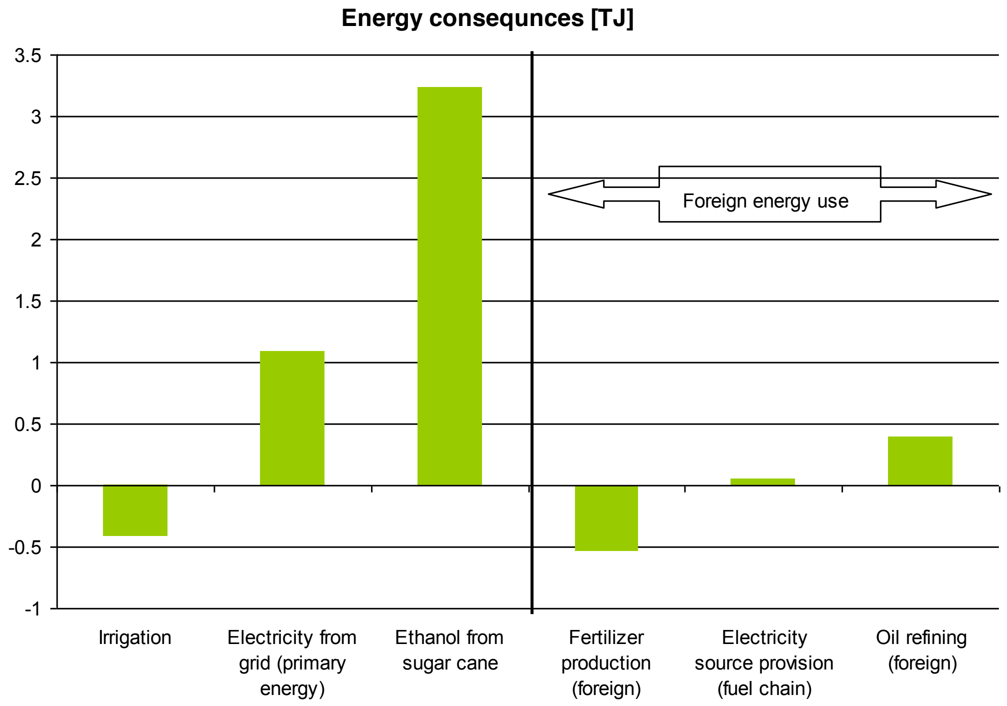

Figure 15: Energy consequences from a change from high-input to no-input agriculture

Less energy is used for water pumping to the ethanol plant (minimal) and no pumping for irrigation purposes is required. Also, less energy is used for foreign fertilizer production. But the loss in yield is more significant. In total 3.3 TJ less energy is coming out from the system. The water balance in contrast is purely positive, as shown in Figure 16.

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[33] In fact, certain potentially negative consequences are not included in this analysis, and are a function of the specific farming practice applied. Without mitigating measures, lower inputs can lower soil quality resulting in losses of organic soil matter with a consequent decline in yield. In addition rainwater may fail to be retained in soil system with the decline in soil fertility and soil organic matter etc.

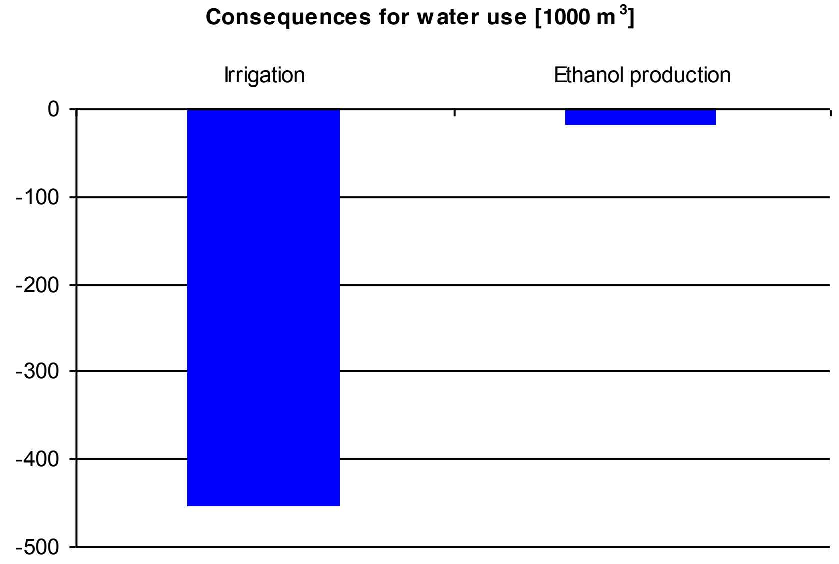

Figure 16: Water consequences from a change from high-input to no-input agriculture

A total of 473 000 m^3 of water is saved through the low-input agriculture. In the climate account foreign effects for the coal fuel chain, oil refining and fertilizer production are included.

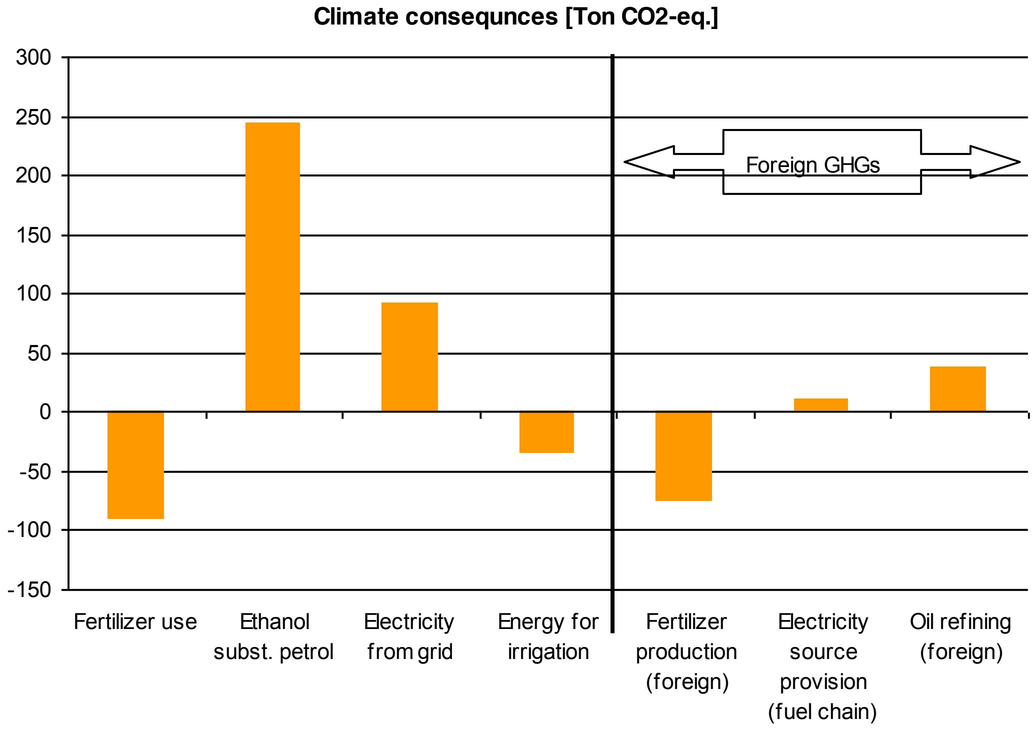

Figure 17: GHG emission consequences from a change from high-input to no-input agriculture

GHG emissions increase as a lower yield reduces the substitution of petrol and coal (electricity generation). While, GHGs are mitigated as no fertilizer is used and to lesser extent less water is pumped. The foreign emissions are reduced because no fertilizer is used or produced, but more oil has to be refined, and more coal provided, since the no-input alternative produces less sugarcane, and thus less ethanol and electricity. The total effect is an increase of 181 tonne GHG-emissions from a shift from high input to low input agriculture in the 3SEP scenario). Results are illustrated in figure 17.

G.6. Use of 50% bio-compost as fertilizer in the 3SEP scenario

Chauhan *et.al.* (2008), in the "Sugar Technology Journal" investigates the consequences of the partial use of bio-compost on sugar cane fields in India. Based on this study a this sensitivity considers the introduction of a 50% bio-compost alternative, boosting yield with the same percentage (14.8%) as reported by Chauhan *et.al.* (2008). This alternative requires full irrigation and yields 87.0 tonne of sugar cane per ha (compared to a normal yield of 75.5 tonne per ha). Further, the method increases the carbon content of the top-soil by 11,6% in the first season. It is assumed that N_2O-field emissions are independent of use of biocompost and thus equal. It is also assumed that fossil energy input to produce biocompost increases the "farming" energy use by 50% compared to mineral fertilizer. Note again that these assumptions are employed for illustrative purposes. This analysis does not include estimates of the relative costs of bio-compost provision, it ignores possible availability constrains, does not estimate possible upstream effects (such as emissions and energy) associated with its manufacture, nor does it account for potential N_2O emissions differences associated with changes in fertilizer application, irrigation and the decomposition of soil organics.

The energy consequences of such a shift towards 50% bio-compost in scenario 3SEP is shown in Figure 18 below.

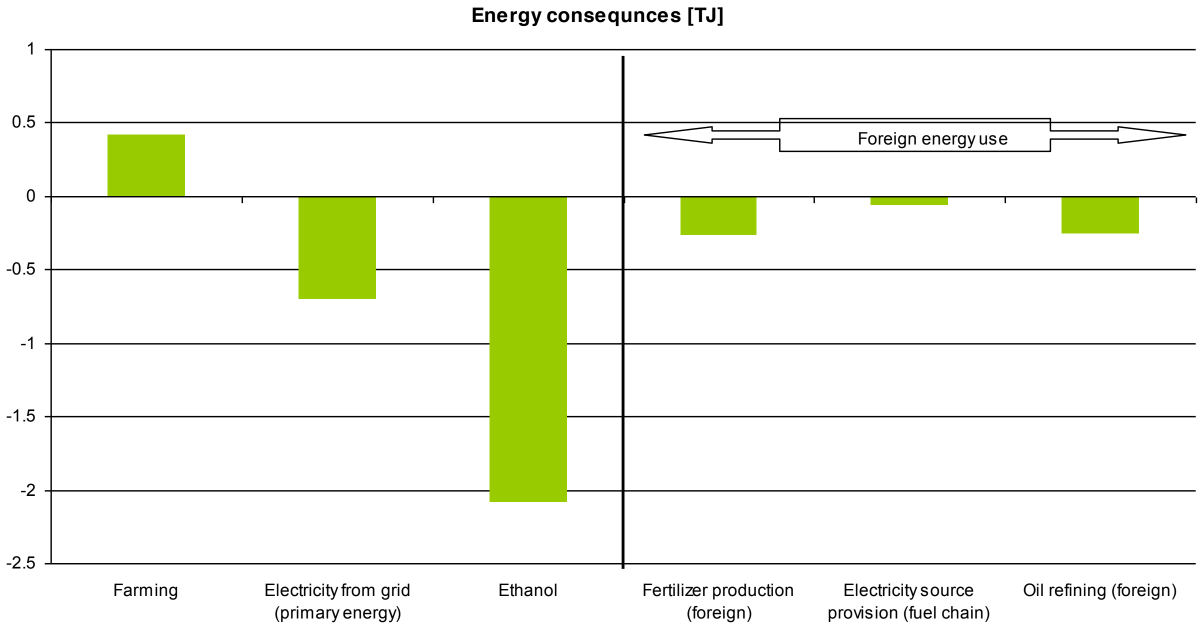

Figure 18: Energy consequences from a change from 100% mineral- to 50% of bio-compost-fertilizer

In summary, marginally more energy has to be used to pump more water (12 000 m^3) to the ethanol plant as more ethanol is produced (though this is negligible). More energy is used during farming in order to produce and collect the biocompost. The remaining changes are net gains, where the increased production of ethanol and electricity are predominant. The total energy balance reduced by 2.9 TJ. This is significant compared to the 15.7 TJ of ethanol produced with 100% mineral fertilizer. The GHG-emissions results follow a similar trend.

The total GHG-mitigation amounts to 552 tonne of $CO_{2\text{-eq.}}$ To capture the increase in the carbon content of the topsoil, the system dynamics over the next 20 years are considered. Figure 19 shows the total GHG-balance shown for 2010 – 2030. (Note that this is the difference between a 100% mineral fertilizer and a 50% bio-compost alternative – emissions related to bio-compost manufacture are not included, but may be significant, depending on the production of the bio-compost.)

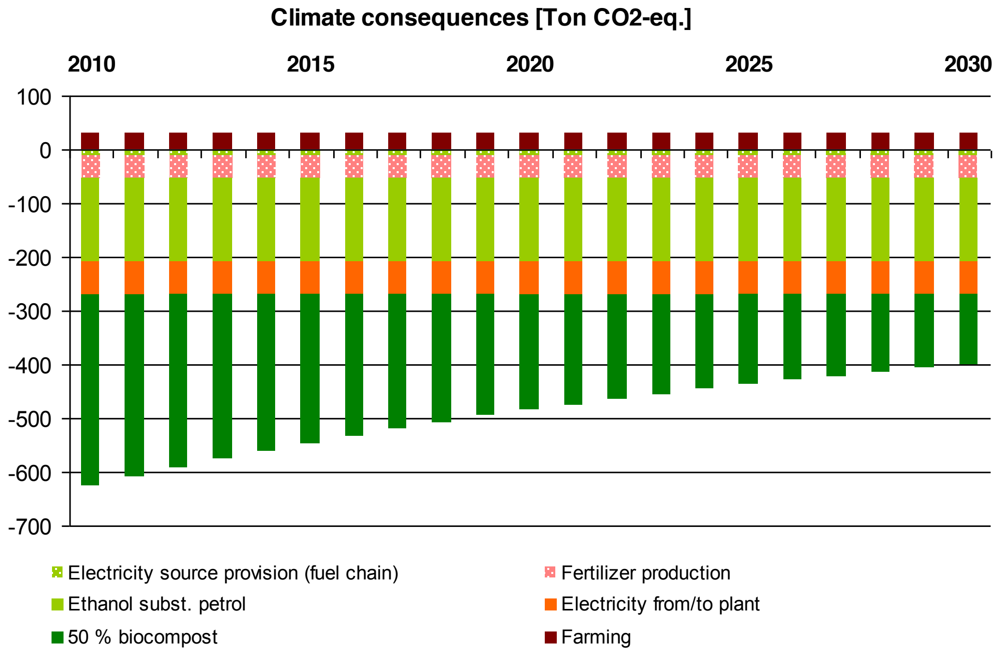

Figure 19: GHG emission consequences from a change from 100% mineral- to 50% of bio-compost-fertilizer

The improved performance through higher yield and more carbon sequestrated in soil leads to a considerably shorter carbon period required to reach a cumulative net carbon emission level of zero for ethanol production, as shown below. (Recall that the in-direct land use change happening outside the island, that incurs a large "carbon debt" for both alternatives). The net positive cumulative emissions occur in 2019, instead of in 2024 compared to the 100% mineral fertilizer case.

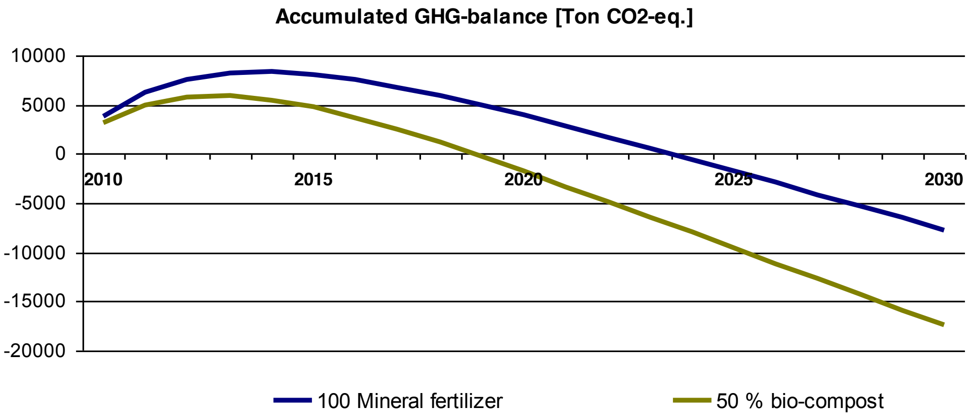

Figure 20: Cumulative emissions from a 100 % mineral-, and 50 % bio-compost-fertilizer alternative

Further studies could look into the economics of such a transition, as there is a trade-off between mineral fertilizer cost on the one hand, and cost of producing bio-compost, combined with increased yield.

H. Conclusions

This study demonstrates the application of a simple accounting model that takes into account aspects of the Climate, Land, Energy and Water (CLEW) system of a case study. This application illustrated two main sets of conclusions.

The first relates to the model itself and the second to policy insights gained. The case study of an island similar to Mauritius showed that an integrated accounting framework adds value. Several insights would have been missed were only a single resource considered. It was shown that if current sugar prices are decoupled from oil prices, ethanol production is viable at prices over $120 per barrel. It was noted that increased ethanol production using second generation processes is more economically efficient (less costly) than producing ethanol from current practice. However, at the same time, this increases net emissions and fuel use. That is because less bagasse is used to generate electricity as it is diverted to liquid fuels, disproportionably increasing the need for coal fired-generation. Finally, the effects of land use change may have important GHG emissions associated, after approximately ten years. Savannah can be converted to ethanol production with an eventual net reduction in carbon emissions (as carbon lost from the soil is displaced by increased ethanol fuel usage). However, wetlands and forest conversion may increase GHG emissions. Finally it is shown that increased investigation into the costs and benefits of bio-fertilizer production may be useful.

I. Next steps

Having demonstrated there are several natural steps which will shape the evolution of the CLEW tool. These include:

(1) Explicitly including local food provision as well as other CLEW services as “exogenous” drivers. This is of particular importance to LDC’s where food security is a key issue.

(2) Increase the number of case studies and practical application as well as interactions with stakeholders and policy makers to ensure that appropriate boundaries and policy questions are addressed.

(3) To include a variety of crops and connect the model with a database that keep track on site-specific issues related to climate, soil, water availability

(4) Include generic crop yield calculator, for initial scanning of CLEW land strategies. (With that in place the accounting model could play a role as a first-order assessment model at the local/regional scale. A possibility includes merging the CLEW-accounting model with the IIASA/FAO model called AEZ (Agro-Ecological Zones)).

(5) Develop a detailed function specification of the CLEW model based on a pragmatic set of considerations related to: target user, policy questions to be answered, existing modelling communities (such as LEAP and WEAP) etc.

(6) Allow for linkages to other models where higher resolution of CLEW representation is needed, than is envisaged in this tool.

(7) Having demonstrated that CLEW relations can be quantified, the development of a formal framework for undertaking economic, social and environmental trade-offs should be undertaken.

J. References

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K. Appendix

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