In the CLEW Model – Developing an integrated tool for modelling the interrelated effects of Climate, Land use, Energy, and Water (CLEW)

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ABSTRACT

This paper introduces the prototype of a new tool which analyses the Climate-, Land-, Energy- and Water- (CLEW) re-sources and their interactions and implications associated with socio-economic development. The presented CLEW model focuses specifically on the analysis of different energy (technology) options and their impact on other resources – e.g. their contribution to climate change, land use change, and water consumption. The CLEW model systematically quantifies trade-offs associated with actions aimed at meeting development goals (specifically energy, food, and water supply) and their impact on the climate, water and environment. The model quantifies resource use with calculations based on collected data, assumptions and user-defined scenarios. Importantly, the model is not limited to internal or national effects but also includes external changes induced through energy imports or exports and land use change. Exemplarily, a first preliminary modelling exercise for the island of Mauritius has shown very strong implications on GHG emissions when switching to locally produced biofuels (bio-ethanol) through induced land-use changes and is presented in the second part of this paper.

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1. INTRODUCTION

The motivation for this paper follows a review of existing integrated resource assessment and modelling literature. This research has shown that the analysis of individual (such as energy or water) systems are undertaken routinely, but are often focused only on a single resource or have often been applied on an aggregated scale for use at regional or global levels and, typically, over long time periods. Modelling single resources is important to estimate and define resource availability, but those approaches are only of limited use for short or medium term national policy analysis and often of an academic nature.

For example, figure 1 gives an overview of worldwide available freshwater resources figure 2 illustrates global Share of Biomass Fuels in National Energy Consumption, (1999). Combining both of the approaches on a regional level and additionally including land use and/or agricultural input/output data can yield results that are much more policy relevant than water, energy or land scarcity information alone. In the case of the two illustrations presented it is obvious that there are regions in the world which heavily rely on biomass for energy production even though freshwater availabilities are amongst the lowest in the world. Combining different “layers” of information into a combined CLEW methodology may result in policy interventions that isolated modelling might approaches alone might not trigger.

Figure 1: Worldwide available freshwater resources Source: [1]
The CLEW model aims to overcome this gap in the modelling landscape and has the target of establishing a framework which is widely applicable and at the same time a useful tool for short to medium term decision making in (political) resource planning and allocation processes.

The need for integrated resource planning becomes evident as resources come under increasing pressure. Optimizing their use will be of paramount importance in the future and not only has an economic dimension (leading to increased prices for food, fuel and land) but also a significant impact on the earth’s ecosystems and their services. They are irreplaceable for survival.

Given the continuously growing human demands for the world’s natural resources - water, land and energy are under increasing stress. The use of each of these resources affects demand for the others and has an impact on the environment and climate. Today (2011) the world population is close to the 7 billion mark and according to [3] will rise to 10 billion people in 2100. Worldwide, there are about 1.1 billion people without safe water [4] and 1.6 billion without electricity. The challenges of a growing world population will without a doubt include the need for more cultivated land, increased agricultural production, higher energy production (both for electricity and fuels), and more water extraction for industry, households and irrigation.

Today, energy prices are volatile and have been steadily growing over the past decade. High energy and oil prices in turn impact the cost of production, transport, storage and packaging in the food sector. This leads to increased costs for the consumer, which out leading to increased income for the agricultural sector. Moreover, the phenomenon of “land grabbing” (were countries buy or lease large areas of agricultural land in other more fertile countries) is a trend of increasing importance indicating the growing scarcity of the CLEW resources.

Naturally, the CLEW interlinkages are prominently visible in the agricultural sector: The production of food, cash and energy crops strongly depends on water and energy for irrigation, transport and packaging and often needs input of (energy intensive) fertilizers. A change in agricultural production methods, or new and different crops produced in turn may have considerable impact on the local energy system (e.g. in the case of fuel crops) or may induce land use changes by forcing traditional farming practices to formerly marginalized land and forest areas. This in turn can increase the pressure on food crop prices. Recent years
have seen food prices to spike beyond the reach of many of the world’s poor — a trend some analysts do not see abating [5], [6].

Within the food-land-energy nexus, water plays a decisive role and is interwoven in many different ways: Water is vital for irrigation in many parts of the world, for cooling power plants, for extracting energy resources (such as coal) or for producing hydropower. On the other hand water pumping and irrigation also needs energy input and can account for large proportions of a nation’s electricity requirements.

In addition to the selected interlinkages outlined above water, land and energy resources are inseparably linked to climate and climate change. Today anthropogenic greenhouse gas emissions (GHGs) are continuing to rise with effects on global temperature levels and changed rainfall patterns. The ultimate effect can only be estimated, but climate change will have a definite impact on the availability of agricultural land and its productivity with respect to different food and energy crops. The effects will most certainly also include changes in water availability in different regions of the world.

There are many more interlinkages between the different CLEW resources, and understanding these interdependencies is of key importance for decision makers. The CLEW approach aims to systemize the inter-connections and provide tools to assess the use of all resources while at the same time taking into account the impact of climate change. Until now the CLEW interdependencies between resources have often been viewed from what could be called a ‘static perspectives’ by taking into account only one (or two) target resources (e.g. increase or optimization of electricity generation or potable water supply) while ignoring broader interdependencies with other resources – and subsequent indirect effect on the resource being analysed.

This paper argues that an isolated approach to adjust energy, water or agricultural policies without investigating their impacts on other resources may not be sufficient in many cases. The examples discussed indicate that adverse effects on the other CLEW resources are not only possible but often likely.

Better methods and models are therefore needed that consider all the feedback systems among climate, land, energy and water (CLEW). This paper illustrates the power of an integrated assessment by reporting on a CLEW case study undertaken the small island state of Mauritius and will present some underlying results of this modelling exercise.

2. STATUS QUO OF RESOURCES MODELLING

As Rogner notes in [7], “…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†,  

† MESSAGE - is software tool administered by the IAEA and provides support and detailed analyses of a country’s or region’s energy system planning - MESSAGE (Model of Energy Supply Systems 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 [8]
MARKAL$^\dagger$ and LEAP$^\S$ models. A commonly used model for water system planning is the Water Evaluation and Planning system (WEAP$^{**}$), and for water scarcity and food security planning, the Global Policy Dialogue Model (PODIUM$^{††}$) model and the AEZ$^{‡‡}$ method are well established. 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 analyse scenarios which are impractically long term.

The development of the Climate, Land, Energy and Water (CLEW) modelling framework is a response to this issue [7] and is designed to be policy focused aim to produce practical interventions and strategies. Key improvements over existing approaches should include:

a. finer geographical coverage and therefore regional applicability,
b. simplified and standardized data requirements,
c. a medium term temporal scope,
d. multi-resource representation (including their inter-linkages) and,
e. software accessible to developing country analysts.

The CLEW methodology 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 and considering externally induced effects and indirect effects. By ensuring that mass and energy balances are not violated, consistent scenarios are developed. Various costs are associated with activities (and related investments) and those in turn were also compared from one to another scenario.

3. INTRODUCING THE CLEW MAURITIUS CASE STUDY

In the second part of this paper a CLEW case study in the small island state of Mauritius is introduced and discussed. The case study will show the advantages of an integrated assessment of resources.

As a common software platform for the development of integrated CLEW modelling is still missing, an approach using different freely available software tools was used – but employing common parameterisation and using soft-linkages to enable iterations to consistent solutions. During this case study, a detailed water model (WEAP), energy model (LEAP) and land production planning model (AEZ) were applied. The models were run in an integrated fashion using common assumptions and input data. After defining a set of physical interlinkages between the different models, inputs and outputs between were exchanged between different model runs to ensure inter-responsiveness between the models.

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$^\dagger$ MARKAL - Markal is a numerical model used to carry out economic analysis of different energy related systems at the country level to represent its evolution over a period of usually of 40 – 50 years. (http://www.etsap.org/Tools/MARKAL.htm)

$^\S$ LEAP – Long Range Energy Planning model by the Stockholm Environment Institute (SEI)

$^{**}$ WEAP - The WEAP water model is maintained and supported by the Stockholm Environmental Institute: http://www.weap21.org/

$^{††}$ PODIUM - PODIUM is maintained and supported by the International Water Management Institute http://podium.iwmi.org/podium/

$^{‡‡}$ AEZ - Agro-Ecological Zoning (AEZ) is an integrative land-use model developed by IIASA (http://www.iiasa.ac.at/Research/LUC/GAEZ/index.htm)
The case study was specifically focused on the on-going national planning debate about the large scale introduction of biofuels (in particular derived from sugarcane) in Mauritius. Currently more than 75% of agricultural land of Mauritius is used for sugarcane production. Almost all of the currently produced sugar is exported, but current discussions include the option of shifting from sugar export to local ethanol production and consumption, to increase national energy security. Additionally, weather patterns in Mauritius have recently been particularly dry - concern is growing that this may be a long term climatic trend. This, in turn, raises questions about the future suitability of sugar cane – the most commonly grown crop on the island - and implications for increasing artificial irrigation (e.g. in terms of water availability and additional energy needed for pumping).

4. OVERVIEW AND CURRENT RESOURCE SITUATION IN MAURITIUS

4.1. General Overview
The Republic of Mauritius is an archipelago in the Indian Ocean, 950 km to the east of Madagascar. It has an overall land surface area of 2040 km², with more than 90% (1865 km²) attributed to the main island. The main island is volcanic in origin with a central plateau surrounded by mountain ranges and plains. The highest peak on the island has an elevation of 828 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 ([9]). Although been a relatively small island the rainfall pattern on the island is very devise depending on elevation and position relative to the prevailing winds with the result very different agricultural suitability and the need for extensive water transport towards dryer regions.

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 constructing future scenarios in this work a constant population growth of about 1% was assumed).

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%) ([10]). 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. On the other hand Mauritius is very vulnerable to rising and volatile world energy prices, as it imports 82% of its energy needs. The remaining requirements are met by domestic renewables, with bagasse accounting for 94% ([11]). 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 and naturally raise the questions of a shift from sugar to ethanol production ([12]).

4.2. Energy
Mauritius currently only uses limited amounts domestic energy resources. These include renewables, in the form of hydro and biomass, especially bagasse. Bagasse is a byproduct of sugarcane processing and is used for (co-)firing in thermal power plants or at sugar cane factories itself. Mauritius 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 from approximately 1,100 ktoe in 2002 to about 1,500 ktoe in 2010 ([13]). Gasoline and gas oil (diesel) are two main transportation fuels and the transport sector accounts for 29.6% of total oil imports ([13]. Energy represents a growing portion of total imports to the island: being 10% in 2002, 16% in 2006 and 18% (or 24,620 million Rs.) in 2010. During the period of peak oil prices in 2008 the portion of energy rose to 21.4% (or 28,352 million Rs) of total imports ([14], [13].
In 2010 2,689 GWh of electricity was generated, of which 96.2% came from thermal power plants (including the incineration of bagasse), while hydro/wind contributed the remaining 3.8%. The peak demand in 2010 was 404.1 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 778 ktoe of fuel inputs used for power generation in 2010, coal comprised (51.2%), oil products (25.4%) and bagasse (23.4%). [13]

4.3. Water
According to FAO [9], Mauritius has a very divers water systems consisting of 25 major river basins and 22 minor river basins (varying in size from 3 km$^2$ to 164 km$^2$) with the largest being 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 order to develop a WEAP model of water supply to the croplands that we consider the aspects of the island’s surface water supply, ground water supply and water usage.

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 (1,865 km$^2$), Mauritius receives an annual amount rainwater of approximately 3,900 Mm$^3$. Of the total amount of rainfall a considerable fraction is discharged to the groundwater (10% or 390 Mm$^3$) or “lost” through evapotranspiration (30% or 1,170 Mm$^3$). The remaining 60% (or 2,340 Mm$^3$) is surface runoff into rivers, stream and reservoirs and potentially used as surface water. [15] The overall hydrological structure of the Mauritius is quite complex due to its orography and diverse rainfall pattern. Rivers are generally fast flowing making their controlled use and allocation for agriculture difficult. Due to significantly different rainfall patterns across the island, an extensive canal and reservoir system has been installed to mitigate dry periods and transport water to generally dryer areas. Total dam capacity is 93 million m$^3$.

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 [9].
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. Especially, in the north of the country the amount of groundwater pumping has reached critical levels and cannot be raised substantially.[9]
Water utilization:
Total water utilization in Mauritius was 1,014 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$^3$). [16] 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 are thought to be an option for future water systems. During the last 50 years a tendency towards less and less rainfall has been observed on the island, which is used to motivate a projection of water scarcity by 2020 (this is reflected later in the modelling.)

4.4. Land use
The island of Mauritius has a total land surface area of 186,500 ha. The cultivated area is 106,000 ha, or 57 per cent of the total area of the island, of which arable land covers 100 000 ha and unmanaged crops 6 000 ha. Around 20 per cent of the island is occupied by built-up areas and 2 per cent by public roads. The remaining area consists of forests, scrub lands, grasslands and reservoirs. At present there are six sugar producing factories on the island, each with its dedicated cropland. Land management structures include large scale farming as well as small scale “family owned” farming. According to Aquastat [17] more than 95% of the irrigated land area issued for sugar cane production. Besides sugar cane a variety of vegetables and in higher altitudes tea is grown.

5. METHODOLOGY OF THE MAURITIUS CLEW CASE STUDY
This pilot study was undertaken to assess the effects and interaction of the energy, water and land-use systems in Mauritius for various strategic scenarios. A goals was to investigate induced changes in the CLEW system by changing individual parts of the system, in a manner that is not uncommon with policy decision’s today (e.g. changing the structure of energy supply (towards local resources), a changing land use on the island or supporting increased groundwater pumping or desalination etc.).

The investigations were grouped according to different scenarios. To ensure that the assessments were consistent, water, energy and land-use models were developed using the same assumptions and input data, calibrated using historic data and then integrated. Using this approach, changes in local costs (to the Mauritian economy), local water, local energy as well as local and external emissions balances can be calculated. Further, the implication or the overall GHG balance of the island was investigated.

5.5. The Scenarios
The selected policy goals that were of interest in this study relate to a number of current priorities of the Mauritius government. This includes: enhancing energy security by increasing the levels of local ethanol production; and ensuring water supplies to sustain increases in ethanol production and increased per capita demand [18]. To do this, the following dynamics and potential developments were considered:
a. Keeping the farming of sugar cane constant, one or more or all sugar processing plants were converted to produce ethanol instead of sugar. The sugar cane feedstock supply to each plant was kept constant. The land area that grows the crop for each processing factory was also kept constant.
b. A reduction in rainfall for the island was simulated, but efforts were made to maintain the yield of sugar cane cultivation (through increased irrigation). As an alternative, 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. In an extreme scenario with significantly reduced rainfall introduction of water desalination as an alternative water supply option was investigated.

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 also focuses on water scarcity in the future. Various assumptions are common to each scenario, these include:

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

5.6. Areas modelled
The boundaries modelled are conveniently delineated by the natural borders of the island. Using established energy, water and land-use models selected effects, both local and external to the island are by integrating the results. The modelling undertaken has been very detailed using high resolution GIS and local climate data for assessing the water and land use situation and detailed energy data from the period since 1995 until today plus taking into account planned power expansion as decided by the Mauritius power authority [18].
More detailed modelling takes place in the western and eastern parts of the island in two representative sugarcane factories and their associated sugar cane areas. In the west, annual rainfall is significantly lower than in the east of the island. Here, crop water must be supplemented with larger quantities of irrigation; additionally water supply in the west is further stressed due to its proximity to the densely populated area around the capital Port Luis area. The west contains crop growing fields which supply sugar cane to the “Medine” sugar cane processing facility. That facility processes sugar cane as well as using a combination of coal and bagasse to generate electricity for its own requirements and ships excess production to the grid. In the east, the “F.U.E.L” sugar processing plant is a second target area of the modelling exercise. This area is much less water stressed as rainfall is significantly higher than in the west of the island.
5.7. ENERGY MODELLING

As a first step, energy modelling was undertaken using the LEAP [Long Range Energy Alternatives Planning] tool. It is an accounting tool and set up to estimate:

- Ethanol produced and its potential to substitution gasoline on the island;
- Changes in fuel imports to the Island (affected by changes in farming, ethanol blending, and additional electricity generation from bagasse and ethanol);
- 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.

During this research selected components of the island’s energy system were modelled in detail. These included electricity generation and demand (including additional demand through increased irrigation, pumping or desalination). Demand and production were calibrated using national energy statistics and official outlooks [11, [19], [18]. 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. The model’s Reference Energy System is shown in Figure 3.

![Figure 3: Reference Energy System (RES)](image)

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 modelled 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 – after further conversion - 4.) produce ethanol via hydrolysis from a different feed.

The energy model has several links to both the AEZ land use model and the water model. For example the AEZ model delivers the amounts of crop input for the processing plants (F.U.E.L and Medine) and can potentially also supply data on additional bioenergy potentials from alternative crops (e.g. jatropha, maize or other energy crops) from marginal land on the island. The WEAP model delivers data on actual water demands from pumping and desalination for different parts of the island and is used to establish the future energy demand in the energy model. Also, 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 power station cooling and or the water “usage” in the hydropower stations of the island. Model interactions are illustrated in Figure 4 below.

5.8. LAND USE MODELING
A detailed raster based land use model of Mauritius is prepared using the Agro Ecological Zoning (AEZ) model developed by IIA SA [20]. The model can be scaled to suit regional needs but also exists at a global level (GAEZ). With help of the AEZ the production potential of crop from farmland, as well marginal land for the total land area of Mauritius can be estimated. Moreover, AEZ calculates irrigation requirements under different climate conditions as well fertilizer input required. Additionally a crop calendar is simulated showing most suitable planting seasons (e.g. depending on rainfall pattern) and possible crop rotations or crop cycles. The resolution for the model was deliberately chosen to be very fine with a raster size of 250m.

Using the AEZ, in a first step the crop productivity of the island is estimated using known local geographic conditions. Then the effect (in terms of yield and (additional) water requirement) of changing a crop type (e.g. from sugarcane to alternative food or fuels – crops) 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 on the island.

Finally, based on crop cycle requirements and a water balance, estimates of the quantity of irrigation water required (during different growth periods during the year) are made and passed on to the water model. This is done for both sugar cane and in an alternative scenario, for a different energy crop. Please refer to Figure 4 and Table 1 for an overview about the interactions of the AEZ with energy and water model. The process of selecting the alternative crop is based on AEZ methodology taking into account suitability in terms of available land type and rainfall pattern. The model can calculate the most efficient cropping cycle and is additionally capable of managing two (or more) crop-cycles in a year.

5.9. WATER MODELING
WEAP, the Water Evaluation and Planning system, was used to develop a water balance for the island, including municipal and agricultural demands. The model takes into account all river basins / catchment areas and their natural water input / out flows as well as the 5 main
aquifers of the island. The WEAP-model can simulate a broad range of natural and engineered components of these systems, including rainfall runoff, base flow, 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. For each of the catchments the land-cover classes were extracted from available GIS data sets 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 modelling 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 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 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 water bodies and rivers in the modelled area. Existing hydrological data (e.g. flow gauges, reservoirs storage data and canal flows) are furthermore used to calibrate the system.

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 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 – to meet, amongst other things, crop water requirements in a manner that matches their respective growth cycles.

Constraints on water sources (including surface and 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 vulnerable to a rainfall decrease and already experiencing water shortages. Although the agricultural sector is the main user of water today (if leaving aside water used in hydropower plants about 68% of available 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 future more detailed study.

The water model is set up to interact with the energy and land use modelling in different ways: From the Land model, water monthly requirements for different agricultural crops and cropping cycles are derived and fed into the existing model. Based on crop production volumes (also received as results from the land modelling), the water requirements for different sugar factories are estimated (as these change as a function of their activity). Increased water demand in the agricultural sector and in the sugar factories require more pumping and energy demand. These data are fed back into the energy model. 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.
Reduced water availability in rivers fuelling hydro-plants is calculated and shipped into the energy model, (which in turn simulates reduced hydro-generation and calculates increased requirements from other plant etc.)

6. MODEL INTERACTIONS AND RESULTS

As indicated in the previous sections the different models have been developed with at high resolutions and are capable of producing independent results. As indicated in the chapters for the 3 different models the development of an integrated CLEW framework necessitates that results and input data are harmonized and interlinked. As all three tools do not provide a common technical software platform, interlinkages can only be made by transporting results selectively from one model to the next. Table 3 highlights the input/output data, model interactions (and the associated flow of information) for the underlying case study. Starting with the land use modelling 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 can be calculated. These include changes in GHG emissions, energy use, costs and water requirements.

First results show very strong implications for the amount of produced GHG emissions under the investigated scenarios, with induced land-use changes (e.g. usage of marginal and or forest for agriculture) being of critical importance. Moreover, significant changes in water use, electricity and electricity demand (e.g. through increased pumping or desalination) are induced through changes in agricultural practices or crops. The investigation of scenarios of low future rainfall has shown strong impacts on the future crop and energy production and consequently strong implication for future costs of energy supply and greenhouse gas balances.

With the cost assumptions used here, the investigated shift towards local ethanol production was done at a profit. Reduced oil imports outweighed revenue loss from reduced sugar sales. (Not modelled 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 would be considered.)
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<td>Elec-Irrigation: Electricity demand for (additional) irrigation and ground water pumping</td>
<td>Tons of sugar cane: fed into LEAP as a basis for bioenergy production potentials from sugar cane</td>
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<td>Hydro PP reduction: Flow data from rivers are fed into LEAP calculate hydropower output (e.g. when more water is needed for agriculture)</td>
<td>Tons of alternative crop: fed into LEAP as a basis for bioenergy production potentials from any alternative biofuel crop</td>
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<td>Elec – desalination: Electricity demand to cater for additional water demand to be met by desalination.</td>
<td>Water – processing: LEAP will calculate the amount of biofuels and the water demand during the process. These water demands are sent to WEAP.</td>
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<td>Water – cane: Water demand of sugar cane under site-specific conditions</td>
<td>Water PP cooling: Water demand for power plant cooling, also send as demand data to WEAP.</td>
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<td>Water – alter: Crops: Water demand of any alternative biofuel crop under site-specific conditions</td>
<td>Water – alter: Water in 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 important to achieve some mix or flexibility of crops chosen to ‘hedge’ against different futures unfolding. The modelling 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 this work.</td>
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Table 1: Overview of Model interactions and input/output values between different models
7. CONCLUSIONS

In this work a CLEW framework that integrates components of energy, water and land-use modelling was presented. The approach used was a ‘systems approach’ for crop production, water as well as energy supply and demand. 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 included changing sugar production to ethanol production, as well as potential reductions in rainfall. In the first scenarios, a GHG mitigation measure and income diversification strategy, reduced petroleum imports and related emissions.

The integration of energy, water and land-use with the CLEW framework clearly demonstrated the benefits of a ‘systems approach’. For Mauritius it could be shown that based on the techno-economic assumptions used in the analyses, a shift from sugar to ethanol production yields measurable economic and climate benefits. In particular, oil import reductions through domestic ethanol production outweighed revenue losses from lower sugar sales. The CLEW model was further more applied to different climatic scenarios simulating a reduction in rainfall and the effects for crop productivity and consequently biofuel production and influence on the local energy system.
REFERENCES / ORIGINAL