Land, energy and water resource management and its impact on GHG emissions, electricity supply and food production- Insights from a Ugandan case study

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Abstract

Despite the excitement around the nexus between land, energy and water resource systems, policies enacted to govern and use these resources are still formulated in isolation, without considering the interdependencies. Using a Ugandan case study, we highlight the impact that one policy change in the energy system will have on other resource systems. We focus on deforestation, long term electricity supply planning, crop production, water consumption, land-use change and climate impacting greenhouse gas (GHG) trajectories. In this study, an open-source integrated modelling framework is used to map the ripple effects of a policy change related to reducing biomass consumption. We find that, despite the reduction in deforestation of woodlands and forests, the GHG emissions in the power sector are expected to increase in between 2040–2050, owing to higher fossil fuel usage. This policy change is also likely to increase the cost of electricity generation, which in turn affects the agricultural land types. There is an unforeseen shift from irrigated to rainfed type land due to higher electricity costs. With this integrated model setup for Uganda, we highlight the need for integrated policy planning that takes into consideration the interlinkages between the resource systems and cross propagation effects.

Introduction

The land, energy and water systems provide vital resources which are fundamental to human existence. In the recent past, there has been considerable interest in not only exploring these systems in detail but also analyzing the interdependencies between them and their climatic links—in short, the nexus between Climate, Land, Energy and Water (CLEW) systems [1–4]. Despite the excitement in the academic community about the CLEW nexus, their uptake in actual policy formulation has been limited. Ministries still formulate policies in isolation. For example, the Indian state of Punjab has a food production policy to provide irrigation electricity subsidies for farmers. This has resulted in over-abstraction and depletion of the water table. Moreover, this over-pumping has resulted in higher electricity demand, putting a strain on the local grid that is predominantly coal-powered. Thus, resulting in more greenhouse gas (GHG) emissions when, in parallel, there are other policies enacted to achieve the opposite [5]. There are other examples of such faulty planning which have resulted in unintended consequences in other linked systems [6, 7]. In this article, a case study of Uganda is presented, where a carefully interlinked model setup is used to demonstrate the need for sectoral policies to be considerate of inter-system...
linkages. Uganda is chosen owing to the following reasons. (a) Hydropower contributes to more than 80% of Uganda’s electricity generation needs and is expected to be the mainstay for the foreseeable future; hence, vulnerable to climatic changes [8]. (b) Biomass (primarily firewood) provides about 80% of the total final energy consumption; hence highly unsustainable [9]. (c) Less than 1% of the cultivated area is under irrigation. Hence, a potential need to irrigate to meet future crop demand [10, 11]. (d) Uganda’s forest cover as a share of the total land area has reduced from 24% in 1990 to 9% in 2015. Additionally, there are concerns about the resilience of infrastructure in the systems mentioned above to an uncertain future climate [12, 13]. These aspects, collectively, make Uganda an ideal case study to observe the ripple or cross-propagative effects of isolated policy decisions.

Since the Bonn-2011 conference on the nexus [14], there has been a significant number of modelling frameworks and tools that highlight the systemic interlinkages. The integrated assessment modelling community, through the use of their models (Integrated Assessment Models-IAMs), develop many of these inter-sectoral modelling exercises. Notable mentions include models like IMAGE [15], GCAM [16] and MESSAGE [17] (to name a few) that have been used to develop the Shared socio-economic pathways (SSPs) [18]. Many of these modelling frameworks mentioned above include a detailed representation of the individual resource systems. Despite good technical detail, many times, they require domain expertise in utilizing them. Also, some of them are not open or freely available, and even in those that are open source, there is a steep learning curve.

In addition to the IAMs, the frameworks/models developed by (a) Mukuve et al [19, 20], (b) Payne et al [21], (c) Vinca et al [22] and (d) Alfstad et al [23] take a detailed approach to representing the individual systems and their climatic links. Amongst them, (a) is a closed setup that looks at a particular point in future and uses Sankey diagrams to map the linkages. Models (b), (c) and (d) are generic, developed using open source languages. Therefore, free to use. Frameworks (b) and (c) link multiple open modelling tools or involve obtaining data from sources, which warrant for domain-specific expertise. The integrated CLEW’s framework (d) and its recent enhancements [24] are chosen for this case study owing to their simple generic structure, smooth learning curve and well-established data processing and freely available visualization scripts. This modelling setup aims to create a platform where the impact of a policy decision on interlinked resource systems can be analyzed in a simplified manner.

With the United Nations (UN) dedicating individual Sustainable development goals (SDGs) to the provision of food (SDG2), water (SDG6) and energy (SDG7) for all, model setups such as the one described in this manuscript could explore the synergies and trade-offs and inter-sectoral policy spillovers while achieving the goals. This study, using the integrated CLEW’s model, explores the case of Uganda gradually shifting away from its use of biomass. Two simple scenarios are designed to reflect the biomass strategy in Uganda [25], and the potential pressure points that they will create on other interlinked systems. Some insights derived from this study, specific to deforestation, are intuitive. Whereas, the change in agricultural types and greenhouse gas (GHG) emissions outlook from the power sector demonstrate the need for such a multi-sectoral analysis to support robust policy formulation.

Material and methods

This section summarises the modelling methodology and the flow of information in this case study. Figure 1 presents a simplified schematic of the CLEW’s integrated modelling framework used in this study. The supplementary information (SI) material is available online at stacks.iop.org/ERC/2/085003/mmedia provides a schematic of the resource systems and their connections. All the resource systems are modelled using a modified version of OSeMOSYS-The open-source energy modelling system [26], which accommodates for changes in land-cover and land-use [24]. The model consists of demands for public water supply, energy (all fuels based on the latest available energy balance) and crop production. It is a linear optimization model, which identifies an optimal strategy for resource supply, transformation and use to meet the annual energy, water and agricultural crop demands until 2050. In the model, the energy system demand-supply balance happens on a national scale, whereas the balance for the land and the water systems are managed on a regional level. The following subsections describe the resource-system specific modelling assumptions and scenario descriptions. The link between the climate and the individual systems has been implemented implicitly. Some links, which are not (yet) part of the model setup are also highlighted.

Energy system

The 2016 energy balance from the United Nations statistics (UNSTATS) [9] and the International Energy Agency (IEA) is used as a base to develop the energy demand projections for Uganda. For the projections, the
GDP [27], population [28] and urbanization [29] projections corresponding to a middle-of-the-road scenario from the Shared socioeconomic pathways (SSP-2) [30] are used. The energy systems module consists of a yearly demand for biomass, electricity and other hydrocarbons classified into residential, industrial, commercial, transport and agricultural sectors.

A reference energy system (RES) for Uganda is presented in the supplementary material. In the RES, all fuel flows are represented as lines, and the boxes represent the entities that use and produce these fuels. Supply and demand for firewood, charcoal and vegetable residues are grouped under one category called biomass. In 2016, Uganda’s share of biomass in the final energy consumption was 80% [8]. Almost all of this biomass comes from Uganda’s forests and woodlands [25]. Uganda, at present, depends on imports for its hydrocarbon demand. However, it has proven reserves of crude oil and natural gas in the Lake Albert region [31]. Necessary provisions are made available in the model for local natural gas and refined crude oil consumption. A conservative assumption has been made for the start year (2030) for the use of domestically recoverable fossil fuels. Fuel costs have been calculated assuming the transport of fuel by road from the nearest port in Mombasa, Kenya to Kampala.

For the domestic fuels, when available, a 20% reduction from the import prices is assumed after discussions with local stakeholders, as no real projections exist. For the electricity supply system, the latest available information from the Uganda Bureau of Statistics (UBOS) [8] and recent communications with the electricity regulatory authority (ERA) of Uganda are used. The energy module represents all the existing and planned power plants individually and groups the uncommitted future power plants by fuel type. Distributed electricity generation technologies like rooftop solar-PV and diesel gen-set options are also made available in the model. The techno-economic parameters for electricity generation are obtained from the 2017 edition of the World energy outlook (WEO) [32] and the ERA.

Despite no electricity and limited fossil fuel consumption in the agricultural sector (in 2016), it is expected to grow. Hence, the model has provisions for endogenous demand for fuels in the agricultural sector. These demands come into picture if the model finds it optimal to invest in technologies that use them, like irrigation, tractor usage etc. Thus, in addition to the exogenously defined demand in the energy system module, electricity is also consumed by processes in other interconnected resource systems (land and water). Hydropower plants produce ~86% of the total electricity generated in the country (2016). Thus, it is significant to represent the overall annual maximum generation potential. In this analysis, an average site-specific capacity factor has been assumed for all existing hydropower plant from recent publications [33, 34].

**Land system**

This section describes the land cover and agricultural use model structure. Land availability is limited by the total land area in the country (~241 000 sq.km.). The land cover and land use types are obtained from the Global Agro-Ecological zoning (GAEZ) database [35]. GAEZ splits the land area for Uganda into cells of 0.09deg X 0.09deg (about 84 sq.km. each at the equator). The land cover is split between water bodies, barren land, built-up land, forests, grasslands and woodlands, cultivated and other lands. Figure 2 presents the split in land cover for Uganda in 2012. The GAEZ database is relatively old (2012/13 edition) in comparison to the recent outputs.
from the Inter-sectoral Impact Model Inter-comparison Project (ISIMIP) or the Agricultural Model Inter-comparison and Improvement Project (AgMIP). However, the GAEZ dataset is used owing to its consideration of different input management levels regarding the use of fertilizers, energy use, etc.

In this analysis, Uganda is divided into seven regions, a split motivated by the different water management zones. The cultivated land area per crop is obtained from Aquastat [36] for 2016. Crops are ranked based on the area under cultivation, total production and their monetary value. Nine crops were identified using the above criteria. Larger the area of a particular crop under cultivation, the more influence it will have on the water balance. Hence, the area under cultivation is prioritized. Crops like coffee are not cultivated over a large area but constitute a significant share of the GDP through exports, hence the inclusion of crop monetary value as another criterion.

Due to the non-availability of spatially explicit datasets on cultivated area per crop, the latest official agricultural production figures (district-specific) are used to arrive approximately at a share of cultivated crop per region. This aspect is also used to calibrate the entire model for the crop produced in the base year. The GAEZ classifies crop production systems based on a combination of input levels (low, intermediate and high based on energy use, mechanization and use of fertilizer etc) and water use (rain-fed and irrigated). Since there is no combination of low input and irrigation, there are five types in total. For each of these categories, there is an agro-climatically attainable crop yield provided by GAEZ. This value is, amongst other aspects, dependant on average historical (1960–1990) climatic conditions, agricultural and soil type in each cell.

A commonly used clustering technique called agglomerative hierarchical clustering is used to group cells together based on their agro-climatically attainable crop yields. The clustering is implemented for each of the seven regions. To validate the consistency of the analysis, an elbow method (graph) is used. The selection of the number of clusters is based on a threshold point (elbow point) in the graph, after which the marginal advantage of having more clusters is small. In this model setup for Uganda, the number of regional clusters ranges from four to ten. A higher number of clusters indicate a wider variety in the region’s crop yields, which is a function of the local climate, soil type and the access to mechanization and fertilizers, to name a few. The yield statistics for selected crops across the country, along with the chosen number of clusters per region can be obtained from the supplementary material (SI).

There is a two-step calibration process implemented in the model for the base year. To start with, crop intensity levels (area under cultivation per crop per region) are modified to arrive at a crop yield value reported by the FAO for the base year (2016). Depending on the gap between modelled and FAO reported crop yields for the base year, a scaling factor is introduced to compensate for the difference.

**Water system**

The water balance, apart from the demand and supply-side components, is integrated inside the land system. The demand for public water is calculated using the latest available statistics for rural and urban water use in the country [10]. Spatially explicit population maps (with a rural and urban split) [37] and projections [38] are used for this demand projection. The consolidated projections are made available in the supplementary material. There are different sources of water supply in the model: precipitation, existing surface water, groundwater. Water balance factors for each land class and crop type are calculated using information from the GAEZ database. Assumptions are made for region-specific shares of groundwater recharge. Each of the land clusters has water inputs (precipitation or exogenous water supply for irrigation) and outputs (surface runoff, groundwater recharge and evapotranspiration), thereby representing the water balance. The region-specific maximum (sustainable) groundwater abstraction limit from the latest national water resource assessment report

![Figure 2. Uganda Land cover (2012).](image)
is implemented. The latest available maps for water table depth (WTD) are used to estimate the pumping energy demand. We use the average historical climate between the period 1960–1990 to derive the region-specific precipitation and evapotranspiration factors.

Scenario description
In order to simulate a policy change and capture its propagative impact across systems, two scenarios are explored: a baseline and a sustainable development scenario (sus-dev) with a reduction in biomass consumption. In the baseline scenario, the land, energy and water systems have their business as usual setup leading up to 2050. Biomass is expected to contribute to a significant share of the total final energy consumption in the country. In the sus-dev scenario, a change in biomass consumption is introduced. It is assumed that starting from 2020, the share of biomass in the total final energy consumption will reduce from its current levels (approximately 80%) to 50% in 2050. This scenario is modelled after the strategies discussed in the Ugandan Biomass Energy Strategies (BEST) report. It is also assumed that people will shift to using electricity. In reality, the transition is expected to include a mix of fuels (LPG, kerosene, electricity, etc) and the use of efficient devices (improved cooking stoves and burners, etc). Since the objective of this analysis was to capture the cross propagation effects of a policy change, we have tried to avoid the uncertainties related to the energy transition. The sus-dev scenario explores the effects of a policy change, not only on the energy system but also across the interlinked water and land systems. In Uganda, the change to cleaner forms of energy is expected to reduce the cutting of forests and woodlands to source firewood. Thus, an estimation is also made for the forests that can be prevented from being cut.

A relationship is established between the reduction of biomass consumption and the increase in electricity consumption. The firewood/electricity consumption in household cooking from a study by Nerini et al is used to establish this relationship. Firewood yield of ~48.4 Mt/1000 sq. km and energy content of 15 MJ/kg are used to relate the decrease in biomass usage to the amount of area deforested. The value for firewood yield is obtained by calculating the difference in deforested forest and woodland area and relating it with the amount of biomass consumed in the same period. The data for this calculation is obtained from the national land physical asset account for Uganda. Also interesting to observe is the impact that deforestation will have on climate impacting GHG (CO2) trajectories. Emission factors of 1.9 kg of CO2/kg of fuelwood and a sequestration rate of 7.9 t of CO2/ha/year of forests and woodland are used in this study.

Results and discussion
In this section, the shift from biomass to electricity consumption and its impact on deforestation, long-term electricity supply infrastructure, crop production, water consumption, land-use change and climate impacting GHG trajectories are explored. In the baseline scenario, hydropower plants dominate the electricity supply infrastructure. The share of solar PV and biomass-based electricity generation is expected to contribute about 30% of the total electricity demand towards the end of the modelling period.

Cumulatively, about 35 k sq. km of forest and woodland are expected to be cut in the baseline to satisfy the biomass consumption. In the baseline, as the demand for crops increase, there is a shift from rainfed to irrigated land. In 2050, the share of irrigated land to the total cultivated land is expected to increase above 90%.

The sus-dev scenario, in comparison to the baseline, is expected to result in cumulative conservation of ~7250 sq. km of forest and woodland area—which is ~3% of the total land area in the country (figure 3). However, the proposed reduction in biomass use and increased electricity consumption has impacts on other interconnected systems. Cumulatively, the increase in electricity demand, as a result of the shift and the expected increase in population, GDP per capita and urbanization, leads to higher generation costs. With hydropower plants expected to reach their maximum generation potential, new investments in supply infrastructure (renewables, natural gas and diesel) result in higher costs (figure 4). During the initial years, the cost of electricity generation in the sus-dev scenario is expected to be lower than the baseline. This drop in the cost of generation (2020–2030) is due to higher generation from the hydropower plants in the sus-dev scenario compared to the baseline—with no new added capacity. In the baseline, until 2030, the system has overcapacity and the plants (predominantly hydro) function at part load. Thus, in the sus-dev scenario, the plants are expected to increase their utilization rates and thereby bring down the cost of electricity generation. However, this situation reverses in the last two decades (2030–2050), where new capacity additions and fossil fuel usage lead to higher generation costs. It is essential to highlight that, at present, Uganda has one of the highest electricity prices in SSA. Moreover, a further increase in electricity pricing could pose roadblocks to an expanding industrial sector in the country.

Furthermore, the switch to lower biomass consumption could result in sequestration of ~50 Mt of CO2 in forests and woodlands (cumulatively), more than in the baseline scenario (figure 5). However, cumulatively, this
change is expected to release \sim 33 \text{ Mt of } CO_2 \text{ from the power sector more than in the baseline scenario. The power sector emissions are expected only in the last decade of the modelling period (2040–2050).}

Despite the cumulative net emission reductions, this is only a part of the emissions spectrum. This model, in its current setup, does not account for all other emissions—namely from the land use change, industrial and agricultural sectors. However, it has the capability to include the emission from the above-mentioned sectors.

In the agricultural sector, the shift in biomass consumption leads to a decrease in the amount of area under irrigation. Figure 6 highlights the difference in the rain fed and irrigated land area between the sus-dev and the baseline scenarios. This shift is due to the higher cost of electricity generation in the sus-dev scenario compared to the baseline. Higher electricity costs lead to lower agricultural electricity consumption in the sus-dev scenario, which simultaneously leads to lower water consumption and thus a shift from irrigated to rain fed agriculture.
By 2050, \(\sim 10 \) k sq. km of land, which was irrigated in the baseline scenario, is replaced by 15 k sq. km of rainfed land in the sus-dev scenario.

The major staple crops in the country propel the transformation to rain-fed agriculture, namely plantain bananas, maize and cassava. Also interesting to note that the amount of irrigated land under coffee cultivation remains practically unaffected by this policy change. Despite the relatively low production (in comparison to maize and bananas), coffee brings a significant amount of revenue from exports.

Figure 7 highlights the differences in yearly agricultural electricity consumption in the two scenarios, along with the respective decadal water consumption statistics. It is expected that cumulatively, there will be a 15% reduction in water consumption, between the two scenarios, in the agricultural sector. In 2050, the reduction in water consumption is expected to the tune of 1.2 BCM, which is 3% of the total internal renewable water resource (IRWR) in the country (39 BCM). The implications of the change in land cover and agricultural type will need a deeper dive to understand the total costs to society. In reality, in addition to the energy costs, other non-technical, political and communal aspects that play a significant role in decision-making. The most important takeaway from this analysis is that a policy change in one resource system has ripple effects on other interlinked systems, which may not be coherent with the overall objectives of the introduced policy. Shifting from firewood usage may lead to increased electricity costs leading to changes in agricultural practices. Therefore, it is imperative to understand and consider such cross-sectoral links during policy formulation.

Despite a comprehensive approach taken to identify the linkages discussed above, the model comes with its limitations. This model setup, though inherently accounting for exports and imports in demand for crops, does not take into consideration the import and export market (though having the capability to do so) as considered by Burin et al [21]. The model also does not consider the possibility to export/import electricity. A local surplus in electricity (as is the case today) could propel exports to neighbouring countries. This aspect has not been considered to reduce the uncertainty in the model concerning price dynamics, despite having the necessary...
functionalities to represent electricity interconnectors. Nevertheless, to estimate the impact of electricity trade, a new scenario run is made where the model can export electricity to neighbouring countries (DRC, Kenya, Tanzania and Rwanda). For this scenario, we assumed that the cost of electricity exports (Uganda has overcapacity and is expected to be a net exporter in the region) would be the same as the current export price to Kenya (roughly 0.13 USD/kWh) [44]. We kept this price constant throughout the modelling period, as no precise projections are available for how this price arrangement will change. The total capacity of inter-country transmission lines is gathered from Pappis et al (2019) [45] and only the historical, under construction and planned links are considered. This change is implemented on top of the sus-dev scenario. Since there is an opportunity to export electricity and generate revenue, the model decides to invest in more generation capacity in the country and exports electricity. The total system cost in the scenario with trade decreases by 1% in comparison to the sus-dev scenario. From the emissions perspective, the emissions increase by 1.2% in comparison to the sus-dev scenario. This is because the model decides to export some HFO based generation in the initial years (to gain export revenue). The supplementary information (SI) document has some figures from this new scenario run. It is interesting to observe that most of the exported electricity is coming from renewable-based sources (solar, biomass and hydro). It was also interesting to observe that the agriculture and water consumption side are not affected by the introduction of trade.

Additionally, a new scenario detailing the improvements in power plant efficiencies is also developed. Power plant efficiency improvements result in lowering the emissions but not by a significant share as natural gas is the most used fossil fuel (along with some HFO and Diesel) in electricity generation and the efficiency improvements according to the source estimates [45] are only expected to increase by 6% over the modelling period. As expected, this scenario also did not create any significant changes in the other sectors (namely water use and agriculture). That being said, a type of efficiency improvement that can help bring about significant changes should be on the demand side, where the efficiency of buildings and devices can be improved. Therefore decreasing the total demand.

The two additional scenarios mentioned above are to highlight that uncertainty in input parameters is crucial to any analysis involving multiple sectors and numerous internal links. Their impact on the results (in such a model setup), however, is subjective to price dynamics. The changes introduced above did not create a significant ripple in the system. However, a sensitivity analysis of the costs used in these scenarios could help us inform at which point, there could be wider cross-system impacts.

This model, despite accounting for water inflows and outflows does not (yet) link up dynamically with a hydrological balance setup, such as the one implemented by Vinca et al [22]. This aspect, again, is left out temporarily to keep a simplified water balance in the model, without involving a complex hydrological model link up. However, such a hydrological component is expected to be integrated into future iterations to represent water availability consistently.

Despite the substantial level of spatial detail in the land resource system, the energy system is not spatially disaggregated. All the new power plants per fuel type (e.g. all-new diesel power plants) are grouped under one technology. It could be the case that investments in transmission and distribution may be underrepresented, which is a downside of this aggregated approach. These aspects can be improved by incorporating new parameters in the code that have a spatial attribute for the energy system as presented by Trotter et al [46] in their recent work. However, the computational advantage of having such spatial detail will have to be evaluated. This study considers the transport sector energy consumption and the corresponding GHG emissions. However, it does not explore any optimization of the transport sector, considering a switch in technology or fuel type. Despite the transport sector contributing a significant share of the total emissions in the country, its optimization lies outside the scope of the current study. In addition to the limitations mentioned above, it is assumed that the relationships between the resource systems are linear. It is not necessarily true for all cases. In future iterations, it remains to be explored if this non-linearity can be taken into consideration without adding any additional computational complexity.

**Conclusions**

With Uganda pledging to increase its forest cover to 21% of the total land area by 2030 [47], there is significant work ahead to reduce its dependence on forest biomass. This study, taking the example of a policy shift in firewood consumption in Uganda, explores the interconnectedness between the energy, water and land resource systems. It also highlights the need for non-siloed policy formulation by showing that a policy mechanism in one sector can have unintended consequences on other interlinked sectors.

Uganda, in addition to the transition in fuel usage (from biomass) and new policy mechanisms (investments and subsidies), will also need a change in its societal thinking. Many urban dwellings, despite having access to electricity, still use charcoal for cooking and heating purposes. The situation is not very different in the industrial
and commercial sectors. Therefore, in the longer term, institutional efforts and a gradual change in people’s mind-sets are warranted to implement this transition to cleaner fuels effectively.

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