IFPRI
EGYPT
Strategy Support Program

EGYPT SSP WORKING PAPER 04 | APRIL 2017

Linking the Economics of Water, Energy, and Food: A Nexus Modeling Approach

Perrihan Al-Riffai, Clemens Breisinger, Alam Hossain Mondal, Claudia Ringler, Manfred Wiebelt, and Tingju Zhu

The International Food Policy Research Institute's (IFPRI) Egypt Strategy Support Program (Egypt SSP) is a policy research, capacity strengthening, and communication program that has as its main objectives the reduction of poverty and the improvement of food and nutrition security in Egypt. Launched in March 2016, the program works closely with national and international partners using funding primarily from the International Fund for Agricultural Development and United States Agency for International Development (USAID). IFPRI's mission is to provide research-based policy solutions that sustainably reduce poverty and end hunger and malnutrition. In line with IFPRI's mandate and mission, Egypt SSP aims to support development policy and project design and to strengthen the capacity of Egyptian institutions in the areas of impact evaluation and monitoring.

The paper received financial support from the Federal Ministry for Economic Cooperation and Development, Germany, under the CGIAR Research Program on Water, Land and Ecosystems, support which is gratefully acknowledged. The authors would also like to thank Sherman Robinson and James Thurlow for their valuable feedback and comments, as well as all the conference and seminar participants who interacted with the authors and provided comments on this paper.

ACRONYMS

CGE	Computable general equilibrium
CO_2	Carbon Dioxide
DCGE	Dynamic Computable General Equilibrium
DSSAT	Decision Support System for Agrotechnology Transfer
GW	Gigawatts
MARKAL	MARket ALlocation model
MARKAL-EFOM	MARket ALlocation – Energy Flow Optimization Model
NOx	Nitrogen oxides
PJ	petajoule
SAM	Social Accounting Matrix
SOx	Sulfur oxides
TFP	Total Factor Productivity
USD	U.S. Dollar

Table of Contents

List of Tables

List of Figures

1. INTRODUCTION

By 2050, global food security will face significant challenges from climate change, global population pressures (expected to reach the nine billion mark), and increased urbanization (FAO 2009). The recently adopted Sustainable Development Goals demand progress on key dimensions of human development and environmental sustainability. However, as a result of growing natural resource scarcity, making progress in one area, such as food security, will likely adversely affect progress towards desired outcomes in other areas, such as water security or environmental sustainability. As a result, business as usual approaches are no longer an option. Instead, advances in food security need to be addressed within a nexus perspective incorporating key interlinkages with related sectors, including water and energy.

In order to maintain our current patterns of food consumption globally, it is estimated that production between 2010 and 2050 needs to increase by approximately 60 percent, annual cereal production has to increase by 50 percent, and annual meat production has to more than double (FAO 2009; IFPRI 2016). At the same time, around 800 million people globally go to bed hungry and more than 100 million children under the age of five years are stunted.

Policy makers will need to design local policies that take into account not only local actors and challenges, but their global equivalents as well (De Pinto et al. 2016). Investment in agricultural research and development needs to be stabilized and increased; linkages with key connected sectors must be better understood and managed; and the natural resource base on which both humans and nature depend conserved, all the while meeting human development needs across the water, energy and food sectors. This is challenging as agricultural land is being degraded through increasing salinity, desertification, climate change, and pressures from an increasing urban population (Hoff 2011; Nkonya et al. 2016).

The food security challenges place an added burden on the available water sources over and above the higher demand brought about by population increases. On average, 70 percent of all fresh water (surface and groundwater) is used by the agriculture sector, with the rest used for drinking, industrial use, and the surrounding ecosystem. (FAO 2014; HLPE 2015). By 2050, projections show that global per capita renewable water resources will fall by 25 percent. These pressures vary greatly across different regions of the world. In general, per capita water resources will fall more in developing countries than in developed countries. In the Middle East and North Africa, further declines, estimated from 778 m3 to 506 m3 per capita per year, are expected to severely constrain livelihoods and economic development (FAO 2014; HLPE 2015).

Energy security is similarly essential to most development outcomes. Energy is used along the entire food supply chain, which uses close to one third of all energy consumed worldwide, ranging from fertilizer production (using slightly over 1 percent of global energy use), groundwater pumping, to food preparation (HLPE 2015; Bogdanski 2012). Energy production has to increase 50 percent over current levels by the year 2035 in order to achieve energy security (HLPE 2015; FAO 2014). However, achieving this increase without prioritizing a reduction in greenhouse emissions would only exacerbate climate change-related challenges globally. Research shows that increasing the global reliance on alternative fuels rather than fossil fuels will go a long way towards achieving the objective of increased energy supplies without adverse climate change impacts (Ringler et al. 2016; IEA 2012). The use of some renewable energy technologies is increasing, including hydropower, biomass conversion, onshore wind, and solar photovoltaic. However, technological advances in other renewables, such as offshore wind and concentrated solar power, is still lagging behind (IEA 2012).

The 2030 agenda for the Sustainable Development Goals bridges a policy and sectoral gap that the Millennium Development Goals failed to address. When the earlier goals identified and worked towards achieving sectoral goals and targets, they failed to highlight and emphasize the links across these sectors (UN ECOSOC 2016). The Sustainable Development Goals and the 2030 agenda identify these policy gaps and acknowledge that some of the thematic areas under the latter goals are interrelated. For instance, there is the gender-education-health nexus, the water-energy-food nexus, and the climate-land-energy-water nexus, among others (UN ECOSOC 2016). The water-energy-food nexus is of considerable significance for economic and human development prospects in the East Nile Basin countries. This is what we focus on in this paper.

Climate change alone puts pressure on food security, energy, and water resources around the world, particularly in resource constrained regions and those expected to be adversely impacted by climate change (Nelson et al. 2010; IPCC 2014). One such region is the continent of Africa, and specifically the Nile Basin (Al-Riffai et al. 2012; Verner and Breisinger 2013). Populations in the East Nile Basin countries of Ethiopia, Sudan and Egypt are expected to continue to increase due to continued high fertility, which will increase demand for food, water, and energy and challenge their food, water, and energy security.

Reduced water availability, whether as a result of climate change or as a result of man-made interventions, such as dams, is expected to directly impact the agriculture sector, the energy sector, as well as the rest of the economy in the Eastern Nile Basin countries. Throughout the water value chain, energy features as a prominent input in all its segments. Whether it is used for extraction, for powering desalination plants, or as a product of hydro energy generation, water and energy are closely linked (Al-Zubari n.d.; Hoff 2011; HLPE 2015). Water quality can also be directly impacted by the generation of energy as a result of oil spills or the contamination of water sources (HLPE 2015). The food-water connection is also strong, as is the energy-food interdependency. The relationship between energy and food operates both ways – energy is used for the production of food, but also food can be used in the production of energy, such as through the use of food crop outputs for ethanol production.

We use an innovative methodology to model the socio-economic linkages between water, energy, and food in the East Nile Basin. Based upon a theoretical nexus framework, the methodology is expanded into a quantifiable modeling suite that underlies the analysis of each of three country case studies. The advantages are that, despite resource shortages being a challenge, the modeling suite aids in devising policies and strategies that formulate these sectoral interdependencies and provide the evidence-based research results necessary for their design in a way that exploits synergies existing across sectors, countries, and regions (Al-Zubari n.d.). This paper lays out the methodology and gives an example of an application and scenarios by focusing on three countries in the East Nile Basin. This methodology paper will be followed by three individual country case studies that highlight the water, energy, and food nexus for each.

A Nexus Perspective

The policy questions we will cover with this methodology focus on the socio-economic impacts of water, energy, and food challenges on the agriculture sector and the rest of the economy in the Eastern Nile Basin countries of Ethiopia, Sudan and Egypt. Specific foci will be on the impact of water availability on crop efficiency scenarios and on exploring the investment in conventional and alternative energy sources required to satisfy growing demand for energy.

Attention will be given to water-energy-food nexus modeling and its implications for achieving national development goals and objectives in these countries. At the macroeconomic level, some of the policy questions we will ask are: What will be the resultant changes in Gross Domestic Product and trade patterns? What kind of structural change will eventually take place at the sectoral level? What will be the changes in energy and water demand and land use? What will be the evolving patterns in food production and macro food security? How will the countries in the region change their use of energy and water in the face of these interdependent challenges, and more importantly, what will be the welfare effects of future changes in the water-energy-food nexus?

There has been an increasing focus on employing the nexus approach in policy design (Figure 1), and studies have explored the water-energy-food nexus for this purpose. However, not many studies explore this tripartite nexus in considerable detail[1] and none do so for the Eastern Nile Basin countries. It is estimated that if we are to maintain our current patterns of production and consumption globally, the agricultural sector has to produce 70 percent more than its current production by the year 2050, and energy production has to increase 50 percent more than its current levels by the year 2035 (Hoff; 2011).

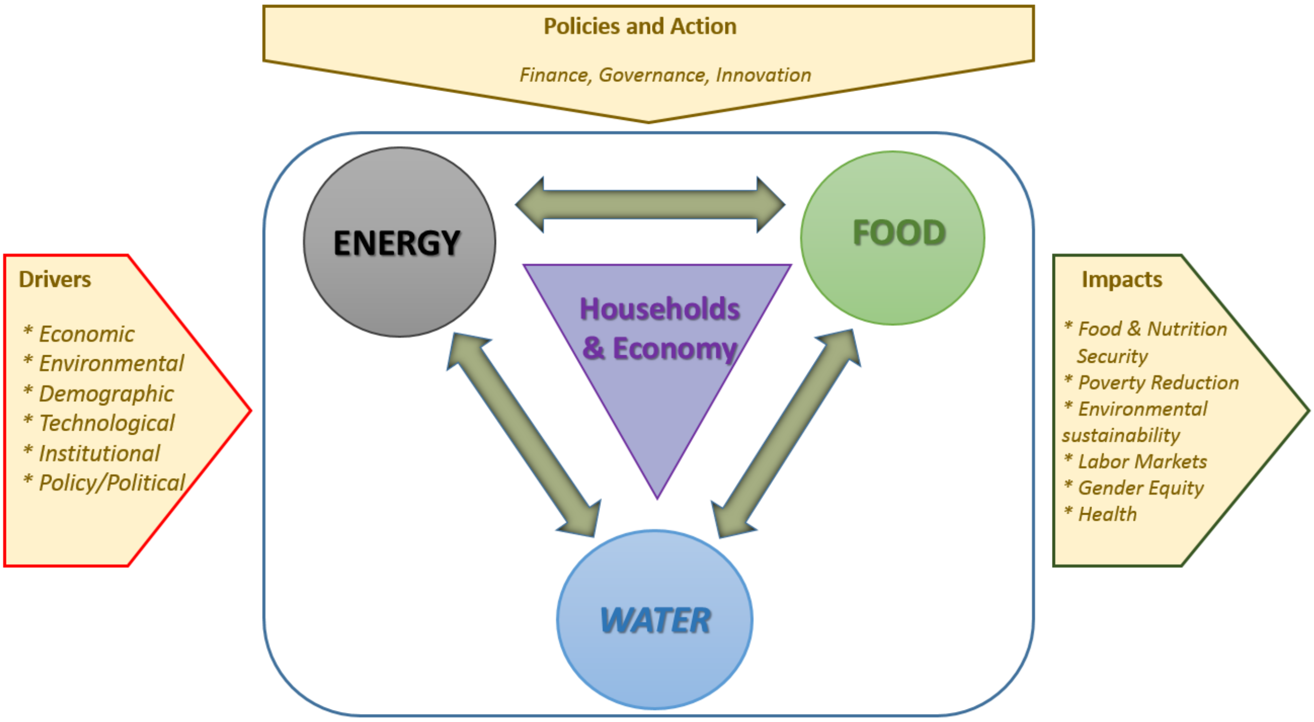
There are close interlinkages and interdependencies between energy, water and land, and food and nutrition (Figure 1). These three axes impact the welfare of households, communities, and economies at large. As a result of socio-economic, institutional, technological and environmental drivers, governments will devise policies and actions to influence the tripartite links in this nexus in the hopes of positively impacting socio-economic challenges, including those around food and nutrition security, poverty, environmental sustainability, labor markets, gender empowerment and equity, and health (Hoff 2011; von Braun 2015). A prominent and more immediate concern is that increasing water scarcity implies diminishing ability for societies to achieve food self-sufficiency, resulting in rising food insecurity in affected countries, and an even greater need to explore alternatives and synergies that may have not existed before.

Using the water-energy-food nexus in Figure 1 as a background, we present a suite of tools that will allow us to model this tripartite link and show its socio-economic impacts on the economies of the East Nile Basin countries in order to draw policy recommendations. Our modeling framework is composed of three components; biophysical, energy, and socio-economic.

---

[1] One of the few examples is Conway et al. (2015) who explore climate change and its impact on the water-energy-food nexus in southern Africa.

Figure 1—The Water, Energy, and Food Nexus Perspective



Source: Authors' adaptation of Hoff (2011) and von Braun (2015)

The paper is structured as follows: Section one outlines the rationale behind our framework, focusing on the nexus perspective. Section two gives a brief review of how water and energy were modeled in the economic literature, while section three explains the nexus model, highlighting its three modules; the biophysical module, the energy module, and the socio-economic model. Section four describes how the three models are linked and how they "talk" to each other when modeling various policy scenarios. Finally, section five concludes and proposes ways forward.

2. MODELING WATER AND ENERGY IN THE LITERATURE

Economists, water specialists, and energy analysts have been modeling the water and energy sub-sectors. Economists emphasize the connection between resource scarcity in the sub-sector of focus and the rest of the economy, modeling these interlinkages in stylized general equilibrium models. These models use general equilibrium theory and the neoclassical theory of economic growth as their economic underpinnings (Bergman 1988). Water and energy practitioners, in contrast, provide highly detailed and specific water and energy partial equilibrium models that emphasize the technological intricacies of these resources within the sub-sector(s) of focus. However, despite their technological richness, partial equilibrium models do not have the capacity to asses and analyze the impact of policy changes on the rest of the economy. Moreover, despite their capacity to address that shortcoming, general equilibrium models – more specifically, computable general equilibrium (CGE) models – are unable to fully capture the technological intricacies of partial equilibrium models. In short, "stylizing" water in CGE models is inadequate for water and energy modelers and "stylizing" economics in water and energy models is inadequate for economists (Robinson and Gueneau 2013).

Water and economic models

There are few resources that capture the essence of economic theory like water. With temperatures around the world expected to rise by over 4 degrees Celsius post-2050 and drier climates expected to prevail, in the context of continuing population growth, water is truly an embodiment of limited resources and unlimited wants (Nelson et al. 2010). In 1992, following an international conference on water and the environment, convening experts officially recognized and declared that the scarcity and inefficient use of water is a serious threat to humanity and sustainable development (UN n.d.). At the close of the conference, the Dublin Statement on Water and Sustainable Development was adopted. The Statement contained four guiding principles to shape policy around the use of water, urging the use of economic valuation techniques in the allocation of this vital resource. From needing water in general to sustain life to specifically using it to generate energy, water as a resource has been well researched and studied in the economic literature, in both partial and general equilibrium frameworks.

Partial equilibrium models of water are of significant value when analyzing small changes in the availability of water, water quality concerns, and water pricing. Generally the changes modeled are considered small enough not to significantly impact prices in the rest of the economy (Fadali et al. 2012). However, as previously mentioned, partial equilibrium models neither take into consideration direct impacts on the rest of the economy nor do they account for direct and indirect impacts on welfare.

Water has been modeled in general equilibrium frameworks in various ways depending on the policy question. Earlier water-focused CGE models assessed the socioeconomic impacts of shortages in the water supply on the agricultural sector, the production sectors, or on the household sector. Early general equilibrium models, such as Seung et al. (1997), Berck et al. (1990, 1998), Seung et al. (1998), Seung et al. (1999), and Seung et al. (2000) focused on water for agricultural use. Berck et al. (1990), for example, focused on the San Joaquin Valley in California, studying the impact of a falling water supply on both the agriculture sector and the wider economy of the Valley. Later, water used for non-agricultural purposes was modeled by Goodman (2000), Watson and Davies (2011), and Wittwer (2009), among others. The agriculture sector has been the predominant sector of focus in CGE modeling of water issues. The prime reason is that the sector is by far the largest user of water as a resource for food production (Fadali et al. 2012). From establishing a market and hence a price for water (Dixon 1990; Horridge et al. 1993; Gomez et al. 2004; Diao et al. 2008; Hassan et al. 2008) to modeling surface and ground water sources (Diao et al. 2008; Calzadilla et al. 2010) to modeling seasonality in the agriculture sector (Strezpek et al. 2008; Robinson et al. 2008), water has received its fair share of representation in general equilibrium models.

While water has been incorporated into economic models through general equilibrium models and economics has been incorporated into water models through partial equilibrium models, neither approach alone is enough to satisfy the details needed for robust policy analysis (Robinson and Gueneau; 2013). As a result, interlinked, hybrid platforms have been emerging. The results are specialized models that do not compromise on the details of each discipline, complementing each other to present an integrated methodology that optimizes on the different features of each component. Yu et al.(2010) use such interlinked hybrid models to study the impact of climate change on food security in Bangladesh in order to devise adaptation strategies for the agricultural sector. They use the hydrological model that the government of Bangladesh employs for their annual flood forecasts with an economy wide CGE model for Bangladesh. Robinson and Gueneau (2013) use a combined CGE model and a regional water system model (river basin simulation model) for Pakistan to analyze the economic impacts of changes in water supply as a result of water shocks in the Indus river basin on the rest of the economy. Osman et al.(2015) assess the impact of improving the quality of water and soil on the Egyptian agricultural sector and on the rest of the economy. They link water satellite accounts to their model to highlight the relationship between physical water systems and the rest of the economy. Hybrid modeling techniques are increasingly being recognized as platforms for more comprehensive analysis for generating policy information.

Energy and economic models

Following the energy crisis in the early 1970s, interest in energy supply and energy policy was on the rise. Energy systems that focused on the energy sector were mainly of the partial equilibrium type, i.e., they used exogenously determined demand for energy to endogenously determine the cost minimizing levels of resource extraction, conversion, and distribution (Bergman 1988).

The resultant partial equilibrium models were very detailed and helped provide input for energy planning needs. Among the first was the energy model developed by Nordhaus (1974) that was used to analyze how markets allocate scarce resources over time, focusing on the efficient allocation of energy resources (Bergman; 1988: Nordhaus 1974). Later, the MARKAL model was developed by researchers at the International Energy Agency (Bergman 1988). These models are referred to as partial equilibrium or bottom-up models. But, despite the richness of their technological and sectoral details and their ability to inform the energy planning process, these models cannot provide information on the impact of energy supply changes or domestic energy policies on relative prices and the allocation of resources in the economy (Bergman 1988; Böhringer and Rutherford 2005). Although they model the energy sector with considerable detail, they tend to ignore linkages between the sector and the rest of the economy, and so provide an incomplete picture of the impact of energy policies on the rest of the economy.

At the other end of the spectrum, CGE models have become a much used tool to analyze energy policy and its impact on the rest of the economy. As a direct consequence of the rich sectoral and agent interlinkages founded on macro and micro economic theory, economists use these CGE models to analyze the socioeconomic impacts of energy taxation[2] (Solaymani and Kari 2014) and energy market regulation (Vandyck and Regemorter 2014). Energy-focused CGE models also have been used to study the sensitivity, or lack thereof, of the economy to oil price changes (Sanchez 2011; Aydin and Acar 2011; Balke, Brown and Yucel 2008). These models rely on a macro and micro economic framework that represents the whole economy (sectors, factors of production,

---

[2] Energy taxation policies focus on both fiscal and environmental considerations.

and taxation and subsidy systems), as well as economic actors (producers, households, government, and the rest of the world). However, they cannot provide a detailed technical representation of the energy system (Böhringer and Rutherford 2005). The energy sector, although explicitly identified in these models, is represented by production functions that portray transformation processes using constant elasticities of substitution. This approach fails to capture the technological intricacies of the energy sector (Böhringer and Rutherford 2005). Furthermore, the empirical estimations of these elasticities are unavailable for all countries as they rely on assumptions of the growth in technology, the time horizon involved, and the level of aggregation employed.

The two types of models mentioned above (partial equilibrium or bottom-up and CGE or top-down, respectively) mainly differ with respect to the level of detail modeled for the energy sector and the interlinkages modeled of the different sectors and agents in the economy. Various modeling efforts have successfully linked these two types of models in order to capture the strength of each. Arndt et al. (2015) linked the South Africa TIMES[3] model to the South Africa General Equilibrium Model to explore the socioeconomic impact of introducing a carbon tax and liberalizing import restrictions in South Africa in order to make use of regional hydropower available from other southern African countries. Other single country linked models for exploring policy issues in the energy sector include Fortes et al. (2013) for Portugal, Riekkola et al. (2013) for Sweden, to name a few. Linking top-down and bottom-up models for energy policy analysis also has involved regional and global models that have incorporated policy scenarios of energy efficiency (Martinsen 2011) and energy policies in general.

3. THE NEXUS MODELING FRAMEWORK

To employ a nexus approach to water, energy, and food security, this analysis will use methods that work across sectors. We use a methodology suite of three models that work together to capture the biophysical, energy, and economic impacts of the various resource stresses facing the Eastern Nile Basin. By linking a biophysical and energy component to a rich general equilibrium (economic) component, we explore water, energy, and food policies and their impacts on the economies of Ethiopia, Sudan, and Egypt to provide a rich integrative canopy of interactions that can capture the tradeoffs involved and highlight externalities and synergies that could exist among these countries.

The three component models in our modeling framework are a biophysical, an energy-focused, and an economic model (Figure 2). The biophysical component model provides an insight on water, land, and food production by combining a hydrological model, a river basin management model, and a crop model. The energy component model uses the MARKAL/TIMES (TIMES is a successor of MARKAL model) energy model to give us a detailed analysis that captures the role of energy in the nexus. Finally the socio-economic component model connects the energy and biophysical components, allowing us to analyze the impacts of changes in water and energy supply on the economy as a whole and on poverty and income distribution in particular, all the while exploring policy scenarios for action and for potential synergies that may present themselves. For the socio-economic component of our nexus modeling, we use a country-specific dynamic recursive computable general equilibrium model (DCGE). The DCGE completes the nexus framework and allows us to design water and energy sector and broader economic policy from a nexus perspective.

Biophysical Model

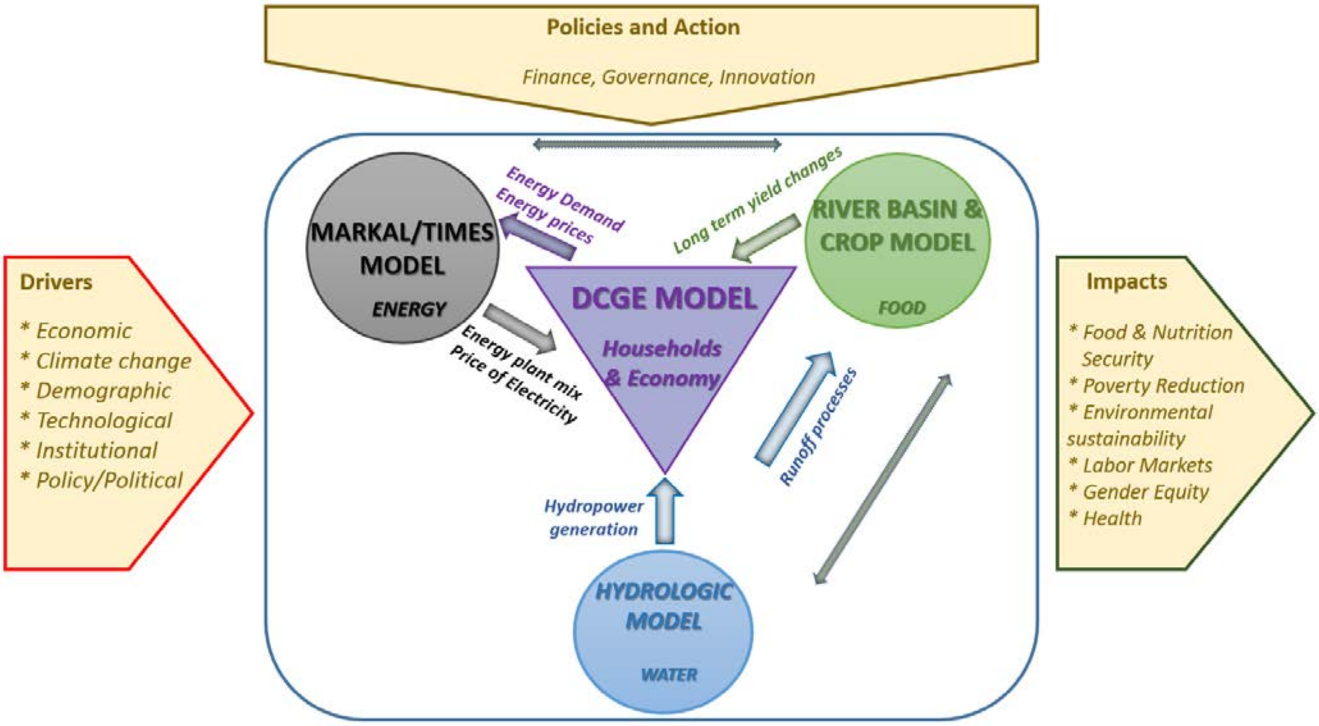
Water Management Optimization for the Nile Valley in Egypt

We choose six climate change scenarios (see Appendix) to profile the climate change possibilities in the Eastern Nile Basin. These scenarios were common runs between those present in the Nile Basin Initiative's database and those present in the database for the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT).

---

[3] The Integrated MARKAL-EFOM System

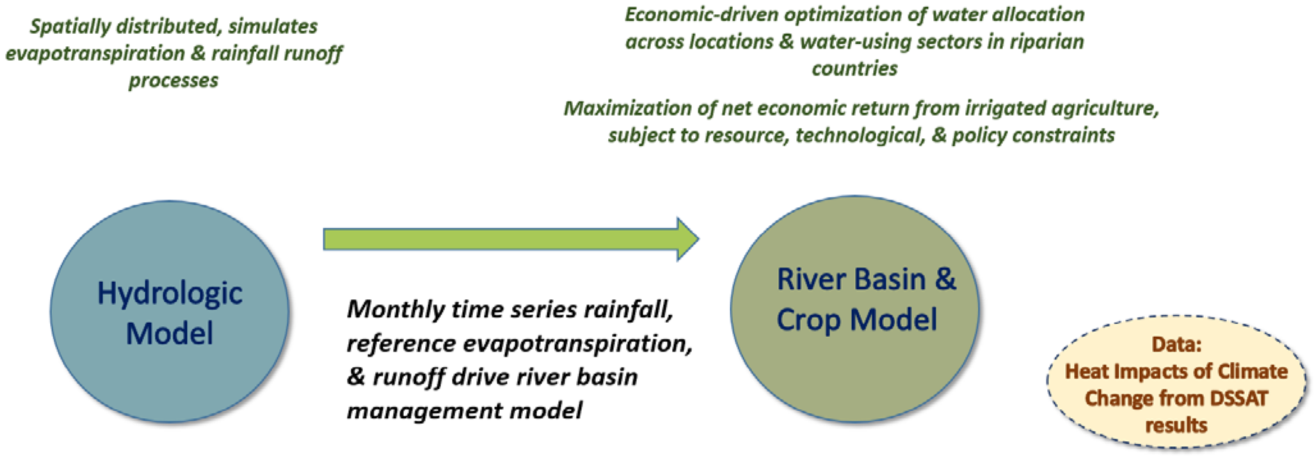
Figure 2—The Nexus modeling suite



Source: Author's adaptation of Hoff (2011) and von Braun (2015)

The hydrologic system in our modeling suite is a river basin management model composed of a river basin model and a DSSAT (Decision Support System for Agrotechnology Transfer) data optimization crop model. The hydrologic system is used to give us the climate change impacts on crop yields and hydropower generation in the economy. This biophysical system carries through all of our scenarios. Within this biophysical system, the river basin model simulates climate change impacts on precipitation and the crop model simulates climate change impacts on temperature. The river basin model uses a spatially distributed hydrologic model which simulates evapotranspiration and rainfall runoff processes that feed into a river basin and crop model. The river basin and crop models maximize net economic return from irrigated agriculture subject to resource, technological, management, and policy constraints. Previously generated data on the heat impacts of climate change from the DSSAT model are used to simulate the temperature impacts of climate change. The end results are crop yield changes over the entire period of study from 2010 to 2050 under a baseline scenario of no climate change as well as under the six climate change scenarios.

Figure 3—The hydro-economic system



Source: Authors' own representation

The Water Management Optimization Model (Figure 3) for the Nile Valley is a regional hydro-economic optimization model that maximizes the economic benefits from crop and hydropower production through optimal regulation and allocation of water flows over time, space, and crop activities. In this model, each irrigated area is regarded as a representative farm. The implicit stochastic optimization model is formulated as: [4]

$$Max\ Z = \sum_{nc} \sum_{c} \sum_{y} \left(pc_{nc} \cdot Y_{c,y}^{nc} - cp_{c}^{nc}\right) \cdot A_{c,y}^{nc} + \sum_{nn} \sum_{t} NIB_{t}^{nn} + \sum_{np} pp_{np} \sum_{t} HEG_{t}^{np} - \sum_{n} \sum_{t} (cs_{n} \cdot WS_{t}^{n} + cg_{n} \cdot WG_{t}^{n}) \quad (1)$$

The objective *Z* represents net economic benefit accrued over the entire period defined by the length of the hydrological record being used in the model, with socioeconomic and water infrastructure condition fixed at the planning year level. The multi-year period of hydrology being used is exclusively for analyzing the performance and risks of the river basin management system in the context of the stochastic nature of weather and river flows.

The node indices *nc*, *nn*, *np* and *n* represent the agricultural water demand, non-irrigation water demand, hydropower plant, and general water demand nodes, respectively. The index *c* refers to crop type, *y* year, and *t* time interval (usually month), respectively. Producer price of crop commodity *c* is denoted as *pc.* The crop yield $Y_{nc,c,y}$ is estimated using the empirical crop water production function provided by FAO (Rao et al. 1988). For countries where irrigated area is not expected to drastically expand, calibration of the model is critical so that it can reproduce base year observations of crop yield and area, hydropower production, and flows to sinks.

The production input cost (except water) is assumed to be proportional to crop area, and the total cost per unit area is denoted as *cp*, which is determined using a Leontief technology matrix estimated using available data. Crop area is denoted as *A*; benefit of water use in non-irrigation sector is denoted as *NIB*; and *HEG* is hydropower production, with unit electricity price of *pp*. The cost of surface water use *WS* and groundwater use *WG* at each demand site are respectively *cs* and *cg*, with surface water cost usually represented by a water charge and groundwater cost represented by cost of pumping.

Hydropower production is a function of flow through the turbine QP and hydraulic head above the turbine *H*, namely

$$HEG_{np,t} = \eta_{np} \cdot \rho \cdot g \cdot QP_{t}^{np} \cdot H_{t}^{np} \quad (2)$$

where parameter η is turbine efficiency, ρ water density, and g is gravitational acceleration.

The main constraints for this optimization model include:

Water balance equation at each node. The following water balance equation states that storage change at a node during time period *t* equals total incoming flow minus total outgoing flow during the period.

$$S_{t}^{n} - S_{t-1}^{n} = \sum_{nu \in (nu,n)} Q_{t}^{nu,n} - \sum_{nd \in (n,nd)} Q_{t}^{n,nd} \quad (3)$$

where S_{t}^{n} is storage of node *n* in time period *t*, and $Q_{t}^{nu,n}$ represents flow from node *nu* to node *n*. This water balance equation applies to node types that include surface reservoir, groundwater aquifer, river reach, artificial conveyance facilities, such as canals and pipelines, and junction nodes. For river reach or conveyance facility, their storage capacity is negligible and therefore the left hand side of the equation becomes zero, forcing total incoming flow to be equivalent to total outgoing flow in any time period. Incoming flow node type *nu* includes river reach, local stream, reservoir, groundwater aquifer, and irrigation return flow. Reuse of wastewater is also considered a local inflow node. Outgoing flow node types include reservoir, river reach, groundwater aquifer, reservoir evaporation as a sink, river basin outlet as a sink, and demand site.

For a reservoir node with hydropower plant, total release to the downstream equals to the sum of flow running through the turbines QP plus reservoir spill QS.

$$\sum_{nd} Q_{t}^{np,nd} = QP_{t}^{np} + QS_{t}^{np} \quad (4)$$

Water delivery and allocation at demand node. At demand node *n*, total water delivery from surface water *WS* equals $\sum_{nu \in SW(nu,n)} Q_{t}^{nu,n}$. For coastal areas that have desalination plants, an “other” source, *WO*, is considered. Therefore, total water supply for a demand site node is

$$Q_{t}^{n} = \sum_{nu \in (nu,n)} Q_{t}^{nu,n} + WO_{t}^{n} \quad (5)$$

Meanwhile, at the demand node, water delivered to the end user equals total delivery multiplied by efficiency. For irrigation, total irrigation water delivery is allocated to crops, as follows

---

[4] Notation convention is that all decision variables are written in uppercase, while all parameters are written in lowercase.

$$Q_t^n \cdot e_n = \sum_c IRD_t^n \cdot A_{c,y}^n \tag{6}$$

where e_n is irrigation efficiency in node *n*, IRD_t^n irrigation water requirement in time period *t* in depth unit, and $A_{c,y}^n$ irrigated area of crop *c* in year *y*. IRD_t^n can be determined either using maximum evapotranspiration for crop *c* and effective rainfall or through a soil water balance equation in the root zone. The year value *y* can be determined using the time period value *t*.

Return flow from demand node. The coefficients of return flow are differentiated by the source of water supply. Return flow usually ends in the next river reach or junction node.

$$Q_{n,y,m}^R = r_n^s \cdot WS_{n,y,m} + r_n^o \cdot WO_t^n \tag{7}$$

Besides water balance through the river basin network, a set of constraint equations are applied to set the upper and lower bounds for decision variables, including, but not limited to, reservoir storage capacity and dead storage, hydropower generation capacity and sometimes firm power, conveyance capacity, river flow regime for aquatic ecosystem protection or minimum instream flow requirement, and range of planted areas of certain crops.

Energy Model

For our modeling suite we use the MARKAL (MARKet Allocation)/TIMES (The Integrated MARKAL-EFOM (Energy Flow Optimization Model) System, a successor of MARKAL). The MARKAL/TIMES model assumes perfectly competitive markets for energy carriers (energy source or energy form). It is also a technology rich and demand driven model that has been adopted in energy and environmental studies in over 70 countries, has been used over 35 years, and is one of the most widely used energy models to design energy policies (IEA-ETSAP 2015; Loulou et al. 2004; Loulou et al. 2005).

MARKAL is an energy planning tool that was developed in 1974 just after the oil crisis by a consortium of members of the International Energy Agency. It is a large-scale model used for long-term analysis of energy systems for a city, province, country, or region. A linear programming model, it identifies the technological configuration of an energy system, subject to user-specified constraints, that minimizes the total discounted energy-system costs (Fishbone et al. 1983).

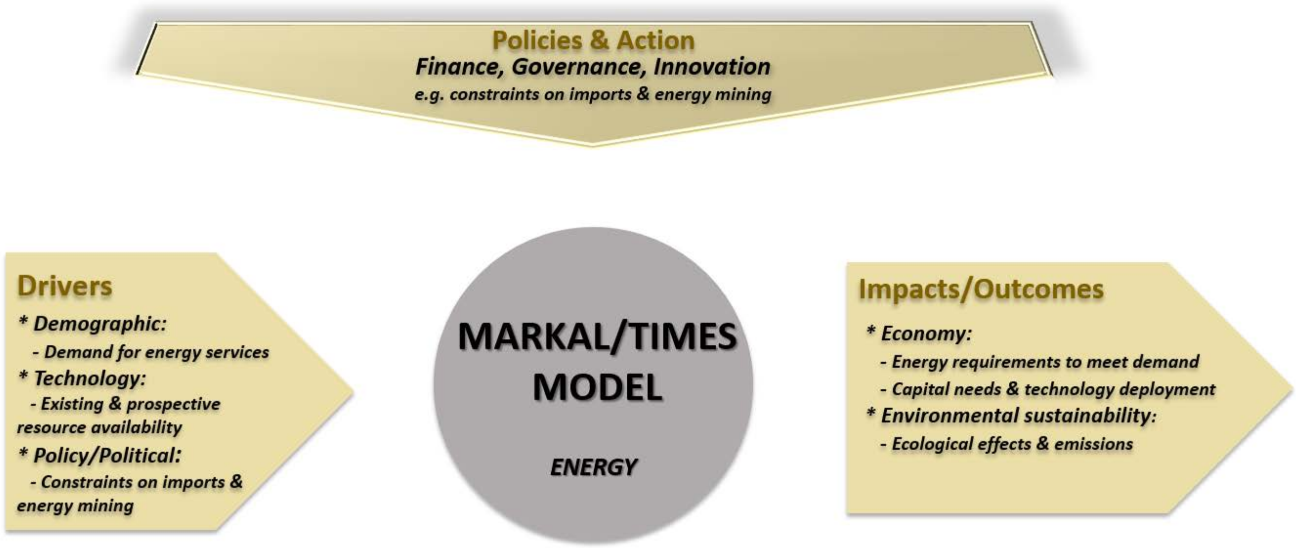
The driving force of the model is socioeconomic development (Mondal et al. 2014) where the environment is an important constraint on development. The energy demand is driven by the availability of technology and the primary energy resources that can be exploited. These factors will then determine energy consumption in the various economic sectors, capital needs and technology deployment, and the effects on the environment through pollutant releases to various ecological systems.

The TIMES model combines advanced versions of the MARKAL model. Its generator was developed as part of the International Energy Agency-Energy Technology Systems Analysis Program, an international community which uses long term energy scenarios to conduct in-depth energy and environmental analyses (Loulou et al. 2004). The TIMES model is the successor of the MARKAL model. The executive committee of the Energy Technology Systems Analysis Program decided to promote the TIMES model for new users from 2008 onwards. Nonetheless, the MARKAL code is still in use.

Similar to MARKAL, TIMES is a linear programming bottom-up energy model. The model computes an economic equilibrium for energy markets from supply to end use energy services. TIMES computes both the energy flow and energy prices in such a way that the suppliers of energy produce exactly the amount of energy the economy needs. The MARKAL/TIMES is a demand driven model. However, TIMES acknowledges that demands are elastic to their prices (Vaillancourt et al. 2008). A typical MARKAL/TIMES model for the evaluation of energy systems is presented in Figure 4.

The model mainly consists of the description of a large set of energy technologies, linked together by energy flows, jointly forming a reference energy system. The reference energy system is the structural backbone of this model for any particular energy system. Its great advantage is that it gives a graphic idea of the nature of the system. Another important characteristic of MARKAL/TIMES is that it is driven by a set of demands for energy services. The feasible solutions are obtained only if all specified end-use demands for energy for all periods are satisfied. The user exogenously supplies these demands in the model. Once the reference energy system has been specified, the model generates a set of equations that hold the system together. In addition, the model possesses a clearly defined objective, which is usually chosen to be the long-term discounted costs of the energy system. The objective is optimized by running the model, which means that configuration of the reference energy system is dynamically adjusted by the model in such a way that all model equations are satisfied, and the long-term discounted system costs are minimized. In this process, the model computes a partial equilibrium of the energy system for each period, i.e., a set of quantities and prices of all energy forms, such that supply equals demand in each period. A variety of constraints can be supplied to the model for making the solution more realistic.

Figure 4—A typical structure of the MARKAL/TIMES model



Source: Authors' representation

Model constraints

The basic constraints of the model take into account the following (Condevaux-Lanloy and Fragniere 2000; Loulou et al. 2005):

- The satisfaction of projected energy demands, which are exogenous in the MARKAL/TIMES model in the methodology used in the paper, coming from the DCGE model;
- The limits on emissions of various pollutants imposed on the system for environmental reasons;
- The energy balance for each energy carrier at different levels of the energy system;
- The capacity transfer between successive periods and capacity expansion due to investment;
- The bound on production as a result of installed capacities or limited fuel supply; and
- Various other technological constraints needed to represent the complex production systems involved.

The constraints (equations or inequalities) and objective function (criterion to be minimized or maximized) include decision variables and parameters, where decision variables are endogenous and, thus, are determined by the model, or are exogenous and, thus, are determined by the modeler.

Some of these decision variables include:

- *INV (r, k, t)*: the investment in new capacity addition for technology *k*, at period *t*, in the region *r*. Typical units are PJ/year for energy technologies and GW for electricity (1 GW=31.536 PJ/year).
- *CAP (r, k, t)*: the capacity of technology *k*, at period *t,* in region *r*;
- *ACT (r, k, t, s)*: the activity of technology *k*, at period *t,* in region *r,* during time slice *s*;
- *MINING (r, c, t, l)*: the amount of commodity *c* (PJ per year) extracted in region *r* at price level *l*, in the period of *t:* the coefficient in the objective function is the unit cost of extracting the commodity required to provide by the modeler.
- *IMP (r, c, t, l)*: the amount of commodity *c* (PJ per year) at price level *l*, exogenously imported by region *r* in the period of *t*. For example, in a single region model, these variables would have to treat the imports of oil to this single region as exogenous; the coefficient of the import variable in the objective function is the unit price of importing the commodity and is provided by the user
- *EXP (r, c, t, l)*: the amount of commodity *c* (PJ per year) at price level *l*, exogenously exported by region *r* in the period of *t*. For example, in a single region model these variables would have to treat the exports of oil from this single region as exogenous; the coefficient of the export variable in the objective function is the unit price of importing the commodity and is provided by the user.
- *ENV (r, t, p)*: the emission of pollutant p, at period *t* in region *r*.
- *D (r, t, d)*: the demand for end use *d*, at period *t* in region *r*.
- *TRADE (r, t, c, s, imp)* and *TRADE (r, t, c, s, exp):* quantity of a commodity *c (*PJ/year*),* exp/imp by region *r* to/from all other regions at period *t* for the time slice *s* (electricity).

The model constraints are summarized below in the simplified form given in the MARKAL and TIMES documentation (Loulou et al. 2004)(Loulou et al. 2005)[5].

Energy flow conservation. For the flow of each energy form, the consumption must not exceed availability according to equation (8), where *k* is energy technology, c the quantity of a commodity, $out_{k,\,f}$ the amount of commodity c produced by one unit activity in technology *k*, and $inp_{k,\,f}$ = amount of commodity c required to operate one unit of activity of technology *k*.

$$\sum_{k} out_{k,t,c} \cdot ACT(k,t,c) + \sum_{s} IMP(t,c,l) - \sum_{k} inp_{k,f} \cdot ACT(k,t,c) - \sum_{d} EXP(t,c,l) \geq 0 \qquad (8)$$

Energy demand satisfaction. The demand for each energy service *d* must be met at each period where $dem_{d,\,t}$ is the demand for end-use of energy at period *t* for all simulations of all the technologies *k*, which produce energy for demand d. This is gross demand that includes losses of transmission, distribution and utilization, incorporated through different parameters in the model.

$$\sum_{k} CAP(k,t) \geq dem_{d,t} \qquad (9)$$

Capacity transfer. In case of each technology *k*, total capacity at any period is determined by the capacity installed previously that is still operative, the initial capacity, and investment in new capacity.

$$CAP(k,t) - \sum_{p} INV(k,p) \leq resid_{k,t} \qquad (10)$$

where $resid_{k,t}$ is the residual capacity of technology *k* at period *t*. The summation extends over all previous periods *p* such that *t-p* does not exceed the life time of the technology *k*.

Capacity utilization. For each technology *k*, activity must not exceed the installed capacity at any time period *t* where $util_k$ is the annual utilization factor of technology *k*.

$$ACT(k,t) - util_k \cdot CAP(k,t) \leq 0 \qquad (11)$$

Electricity generation technologies may have a single annual utilization factor or seasonal utilization factors, the sum of which should be less than unity.

Source capacity. The use of any energy carrier or form of energy f through technology *k* must not exceed the annual availability of this capacity at any time period *t*. $srcap_{f,\,t,\,i}$ is the annual availability of energy form *f* from source *i* at period *t*.

$$\sum_{k} inp_{k,f} \cdot ACT(k,t) \leq \sum_{i} srcap_{f,t,i} \qquad (12)$$

Growth constraint. Limited extraction facilities for fuel or sometimes regional priorities and constraints will influence the capacity of each technology, therefore growth cannot exceed a certain percentage rate in each period.

$$CAP(k,t+1) - (1+growth_k) \cdot CAP(k,t) \leq 0 \qquad (13)$$

where $growth_k$ = maximum allowable growth factor for each technology at period *t*.

Emission constraints. Emission constraints set the upper limit on emissions of certain pollutants by the energy system as a whole. These limits can be imposed separately for each time period or cumulatively over the whole planning horizon. For these constraints to be active within the model, emission coefficients must have been defined for all polluting technologies. Instead of an emission limit, the user may also specify an emission tax $Etax(t,p)$. If so, then the quantity $ENV(t,p).Etax(t,p)$ is added to the annual cost expression, adversely impacting the emissions at a constant rate. The total emissions and emissions limit can be expressed as:

$$ENV(t,p) = \sum_{k} \left[EMINV(t,p,k) \cdot INV(t,k) + EMCAP(t,p) \cdot CAP(t,k) + EMACT(t,p,k) \cdot \sum_{s} ACT(t,k,s) \right] \qquad (14)$$

and

---

[5] For a single region, in the notations used in the following equations, the names of decision variables appear in upper-case italics and the known parameters in lower-case italics.

$$ENV(t,p) \leq ENV\_LIMT(t,p) \qquad (15)$$

where $EMINV, EMCAP, EMACT$ are emission coefficients for pollutant *p* linked respectively to the construction, capacity, and activity of a technology. $ENV\_LIMT(t,p)$ is the upper limit set by the user on the total emission of pollutant *p,* at time period *t*.

Objective function

The objective function is the sum of all regional objectives, where all are discounted to the same selected base year. Each region (country) may have different discount rates and the model will calculate each separately. The sum of the total discounted cost is the model's objective function as shown in equation (16).

$$OBJ(z) = \sum_{r \in REG} \left[REG\_OBJ(z,r) \right] \qquad (16)$$

where $OBJ(z)$ is the total system cost discounted to the beginning of the year z, and r is the region.

Each regional (REG) objective $OBJ(z)$ is decomposed into the sum of nine components.

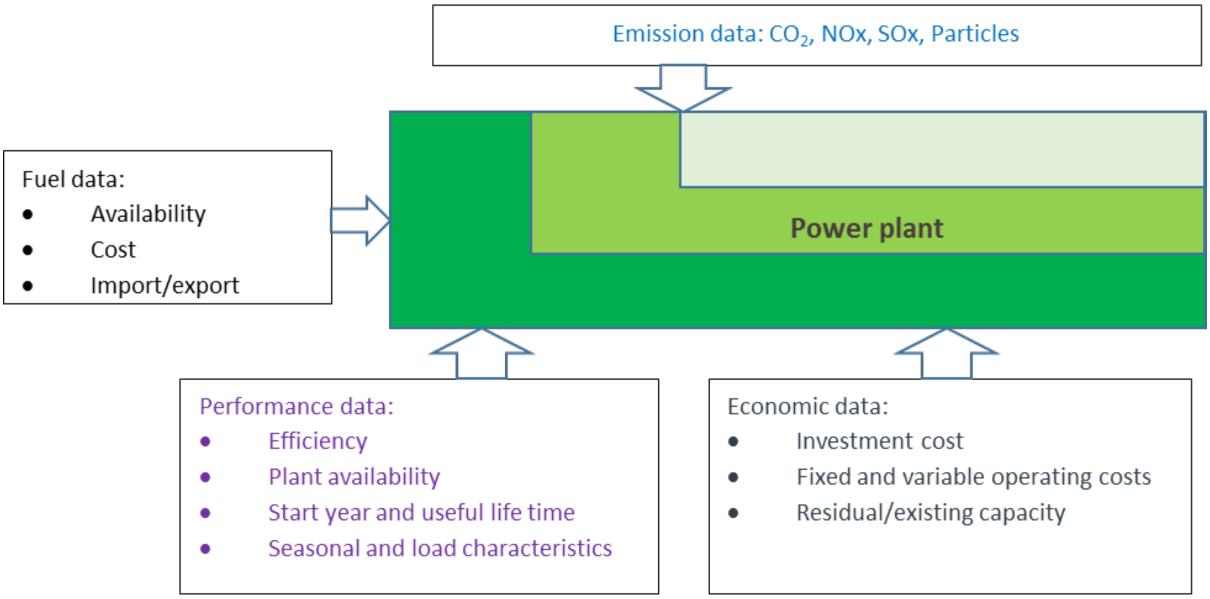
$$REG\_OBJ(z,r) = \sum_{r \in (-\infty,+\infty)} DISC(y,z) \times \begin{bmatrix} INVCOST(y) + INVTAXSUB(y) + INVDECOM(y) \\ + FIXCOST(y) + FIXTAXSUB(y) + VARCOST(y) + \\ ELASTCOST(y) - LATEREVENUES(y) - SALVAGE(z) \end{bmatrix} \qquad (17)$$

where $DISC(y,z)$ is the value discounted to the beginning of year z using a general discount factor (the regional index r is omitted from the nine components for simplicity of notation). The first and second terms are linked to investment costs. The third term is related to decommissioning capital costs. The fourth and fifth terms are linked to fixed annual costs. The sixth term is linked to all variable costs, while the seventh is demand loss costs, and the eighth term is the revenue that accounts for commodity recycling which occurs after the end of the analytical time horizon. The ninth term is the salvage value of all capital costs of technologies whose life extends beyond the end of the analytical time horizon.

The MARKAL/TIMES input parameters

Input specifications, such as technology performance data, emission data, economic data, etc., are required by the TIMES model. (See an example in Figure 5). The model builds a representation of the energy system for the given region by specifying energy flows in and out of each technological component in the system.

Figure 5—Example of MARKAL/TIMES model input component block



Source: Adapted from (Gargiulo 2015; Mondal 2010)

The model requires extensive data input, which can be classified into data groups such as data for the technology group, the energy carriers group, the end-use demand group, the emissions group, as well as other or additional stylized constraints imposed on the model.

Each group of data input requires a set of defined information. The user also has to choose proper units for costs, energy flows, final energy demands, activity levels, and capacities of conversion technologies (Nobel 2007; Loulou et al. 2005; Amorim et al. 2014).

Model outputs

A typical MARKAL/TIMES solution consists of the following results (Mathur 2001; Nobel 2007; Loulou et al. 2005; Gargiulo 2015; Vaillancourt et al. 2008.):

- A set of investments in technologies selected by the model at each time period. This set refers to the level of new investments expressed in terms of plant capacity (GW) of each technology in each period.
- A set of operating levels of all technologies at each period; the model suggests the optimum utilization level of each technology. It is expressed in terms of percentage utilization of installed power generation capacity.
- Electricity outputs in PJ by technology by year.
- The quantities of each fuel produced, imported, or exported at each period. Based on the information on plant capacity and utilization factors, the model gives the total quantity of each fuel required or consumed in the energy system in each period.
- The emission of pollutants at each period. If sufficient information about different emissions is provided in terms of coefficients for each technology, this emission result set provides values of total emissions due to the utilization of different technologies.
- The overall total discounted system cost. It is the minimum value of operation of the reference energy system under the defined energy demand levels for each time period of the analysis period. It is the value of the objective function of the model.

Energy demand and fuel prices assessed by the DCGE model directly can be used as inputs to the MARKAL/TIMES model. All fuel price or cost data is user defined. The outputs from the TIMES model, such as technology capacity (GW), electricity unit generation cost (USD/kilowatt-hour) by technology, energy supply mix, marginal technology investment cost, marginal electricity price, levelized cost of electricity generation, and others can be used as inputs in the DCGE model. Hydropower generation capacity (GW) assessed by the hydro model can use as constraints in the MARKAL/TIMES model to select other options to meet energy demand.

Economic Model

For the socio-economic component of our nexus modeling, we use a country-specific dynamic recursive computable equilibrium (DCGE) model for each of the countries. This DCGE model works to complete the nexus framework and help us design policy from a nexus perspective. The model connects the energy and biophysical components and allows us to analyze the impacts on the economy as a whole and on poverty and income distribution in particular, all the while exploring policy nexus interventions to mitigate and adapt to the impacts of climate change.

The DCGE model, developed at the International Food Policy Research Institute, is a multi-sectoral dynamic computable general equilibrium model of a single country.[6] It has been designed primarily for the analysis of agricultural strategies, income distributions, and household welfare in an open economy facing import and export competition on world commodity markets. The model is based on microeconomic theory. The economy is modelled as a competitive economy with flexible prices and market clearing conditions. Agents represented in the model are consumers who maximize utility, producers who maximize profits, and the government. The economy is connected to the rest of the world via trade and capital flows.

The DCGE is recursively-dynamic, meaning that the evolution of the economy over time is described by a sequence of single-period static equilibria (within period component) connected through capital accumulation, changes in the supply of labor and agricultural land, and sector specific technical progress (the between period component). The economic structure of DCGE is fully specified and covers production, investment, and final consumption by consumers and the government. Policy instruments in the DCGE are taxes, subsidies, or quantity constraints in factor markets, product markets, and in international trade. The model results show relative changes to a reference scenario that also needs to be defined.

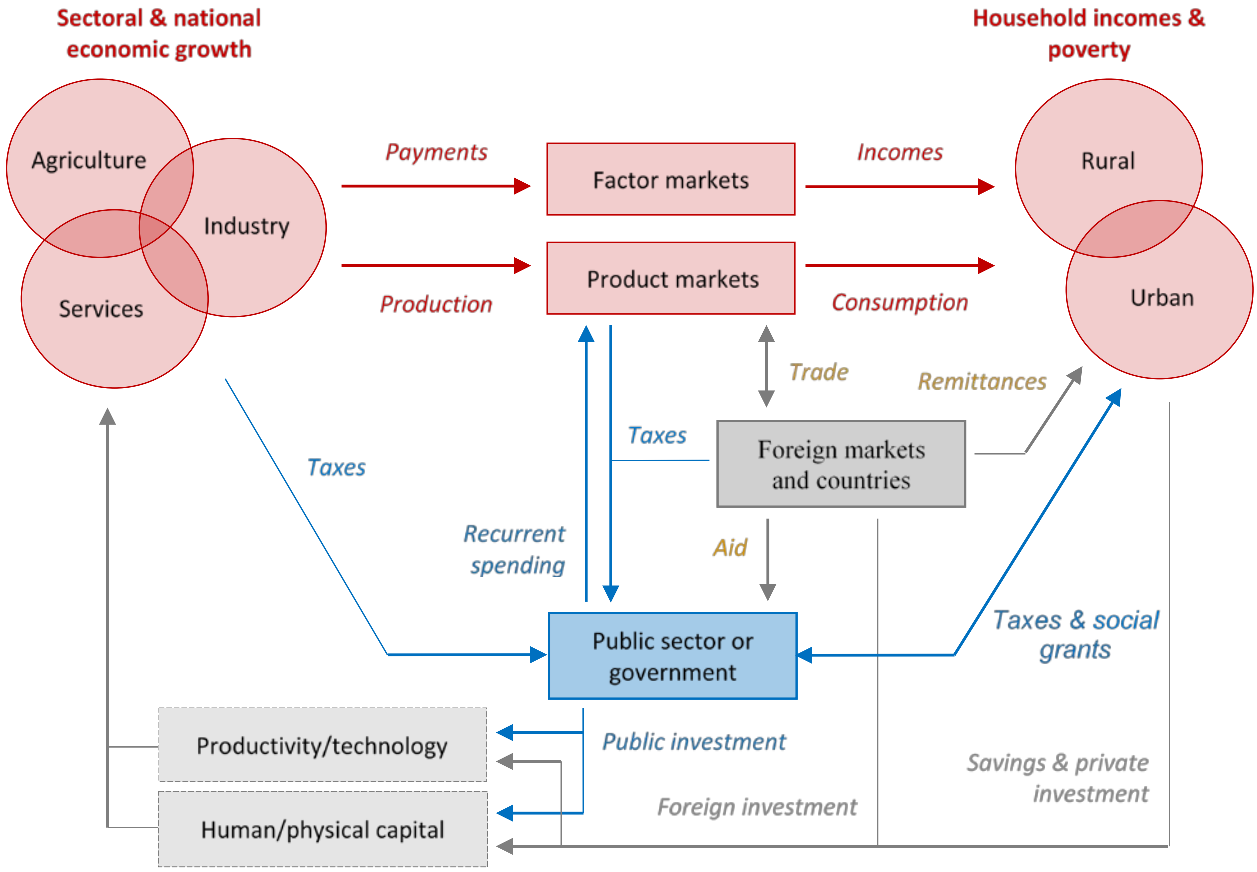
Figure 6 describes the circular flow of income and spending between economic agents in the DCGE. Producers in the agriculture, industry, and services sectors purchase land, labor, and capital inputs from factors markets, and intermediate inputs from

---

[6] See Diao and Thurlow (2012) for a detailed description and full mathematical presentation of the DCGE model.

product markets, using these inputs to produce goods and services. These domestically produced goods are supplemented by imports and then sold on product markets to households, the government, investors, and foreigners. Households and enterprises, own the factors of production, receive factor earnings or value added from producers, transfers from the government, and remittances from abroad and spend their total income on the consumption of goods and services, savings, and tax payments. The public sector or the government receives revenues from taxation and foreign aid and spends these revenues on recurrent spending, including remuneration of public employees, transfer payments, and public spending on productivity and factor-enhancing investment. Finally, the rest of the world receives foreign exchange for the provision of goods and services (in the form of domestic imports) and pays foreign exchange for its demand of domestically produced goods and services (exports). In addition, the rest of the world also pays out transfers to the domestic economy, through workers' remittances and as transfers to the government.

Figure 6—Circular flow of income in a CGE model



Source: Diao and Thurlow (2012).

We adapt the standard CGE model in several ways to make it more suited for modeling the water-energy-food nexus in the East Nile Basin. Although renewable electricity capacity and generation has substantially increased in the last years, its share in the energy mix is still modest or nonexistent in most East Nile Basin countries. To model possible energy transition plans, we split the electricity sector in the individual country case studies to include (where relevant) solar, wind, and conventional technologies[7]. For countries currently producing electricity from renewable sources, we use the statistical information from the International Energy Agency. For countries without renewable power production, we assume that a small amount of solar and wind electricity is generated by a standard power plant running at minimum capacity.[8]

The production technology of solar and wind power plants is defined according to the cost structures provided by Dii's industry survey (2012) and is assumed to be identical for all countries. There is not enough information to model grid operation

---

[7] Conventional technologies include hydropower, gas, combined cycle, and diesel production technologies.

[8] This assumption does not distort the energy mix because a small production is added for solar and wind technologies in the case studies countries. Doing so also allows us to model future development of solar and wind power production in countries where production is currently nonexistent.

independently; therefore we use the same assumption as the original electricity sector in DCGE. That is, each electricity sector accounts for electricity generation, collection and distribution. In addition to the different electricity generation sectors, the DCGE models four energy sectors where relevant, coal, oil, gas, and petroleum products, which helps us to represent the complete interaction of different energy sources on the domestic energy market.

In the *business-as-usual policy scenario*, renewable electricity production in DCGE is mainly driven by fossil fuel prices and competitiveness. High fossil fuel prices make expensive the production of electricity from conventional sources incentivizing the production of electricity from renewable sources. Competitiveness, on the other hand, is determined by the levelized cost of electricity and the learning curve. High levelized cost of electricity and poor reduction costs are directly linked to production subsidies in the model, which makes its production unattractive.

The electricity produced by each type of power plant is sold to domestic markets and part of it could also be exported. The distribution to intermediate demand and final demand of renewable electricity is assumed to be similar to the distribution of conventional electricity. Therefore, we use a high elasticity of substitution between solar, wind, and conventional electricity, which characterizes a very homogeneous good.

The dynamics underlying the CGE model are composed of two components, the within and between period components. The former (equations 18-35) maximizes consumer and producer utility and profits, respectively, subject to consumers' budget constraint and the prevailing factor prices for the producers. Prices clear the product and factor markets. For the latter (the between period component, equations 36-38), certain exogenous variables such as population growth, labor and land supply growth, and total factor productivity, are set period to period, and the rate of capital accumulation is determined endogenously in the model based on the investment level in the previous period.

Consumers. Consumers[9] in a CGE model maximize their utility subject to their budget constraint (equations (18) and (19)). C_{hi} is the consumption level for each household for each good, γ_{hi} is a subsistence level of consumption, and β_{hi} are the marginal budget shares.

$$\underset{i}{Max}\, U_h = \prod_i (C_{hi} - \gamma_{hi})^{\beta_{hi}}] \tag{18}$$

subject to

$$\textstyle\sum_i (P_i \cdot C_{hi}) = (1 - s_h - ty_h) Y_h \tag{19}$$

Expenditures must always equal disposable income less savings for the consumer, where s_h is the savings rate, ty_h is the direct (income) tax rate, Y_h is income earned[10] and $P_i \cdot C_{hi}$ is their spending on consumption.

Using a Stone-Geary utility function, the consumer's optimization problem yields a linear expenditure system of consumer demand equations that determines their demand for each of the goods and services on the market.

$$C_{hi} = \beta_{hi}[(1 - s_h - ty_h)Y_h - \textstyle\sum_{i'}(P_{i'} \cdot \gamma_{hi'})]P_i^{-1} + \gamma_{hi} \; where \; i' \approx i \tag{20}$$

Producers. Producers employ factors of production (labor, land and capital) to produce goods and services. Depending on the economy under analysis, the disaggregation of the production sector varies. However, for the purposes of this research, the agriculture, energy, and water sectors are disaggregated as much as possible for policy purposes. Each producer faces a constant elasticity of substitution production function (equation (21)) where in order to produce good/service X_i, $V_{if}^{-\rho_i}$ of factors of production are employed. Λ_i is sectoral total factor productivity, α_{if} is the share parameter of each factor employed, and the factor substitution elasticity is σ_i where $\sigma_i = 1/(1 + \rho_i)$.

$$X_i = \Lambda_i \left(\textstyle\sum_f \alpha_{if} \cdot V_{if}^{-\rho_i}\right)^{-1/\rho_i} \tag{21}$$

The first order conditions from profit maximization yields the factor demand equations

---

[9] The number of households represented in the model varies from economy to economy.

[10] Households earn income from factor returns, transfers from the government, and workers' remittances.

$$V_{if} = \Lambda_i^{-\frac{\rho_i}{1+\rho_i}} \cdot X_i \left(\alpha_{if} \cdot \frac{PV_i}{W_f}\right)^{1/(1+\rho_i)} \tag{22}$$

Factor demand is directly proportional though non-linearly, to the relative price of value added price (of the good) to the price of the factor, $(\frac{PV_i}{W_f})$.

The government. The government does not follow any behavioral functions in the model. The government uses the net revenue[11] it collects from taxes (income taxes, sales taxes, customs duties) and foreign grants, $(R + rw)$, to spend on recurrent expenditure (goods and services, $\sum_i(P_i \cdot G_i)$). The residual, if positive, becomes a fiscal surplus and, if negative, a fiscal deficit (FB).

$$R + rw = \sum_i(P_i \cdot G_i) + FB \tag{23}$$

International trade. In the DCGE, trade with the rest of the world (when it exists) relies on the fact that there is product differentiation or imperfect substitutability between domestically produced goods and similar products on the international market.

Producers can produce for the domestic market or for exports. The decision to do so relies on a constant elasticity of transformation function where $D_i^{\varphi_i}$ is domestic production going to the domestic market and $E_i^{\varphi_i}$ is domestic production being exported.

$$X_i = \Gamma_i\left[\tau_i \cdot D_i^{\varphi_i} + (1+\tau_i)E_i^{\varphi_i}\right]^{1/\varphi_i} \tag{24}$$

Using the same rationale, the supply of goods and services available to domestic users can either come from domestically produced goods and services or their imported equivalents. Using an Armington function that assumes imperfect substitutability between domestically produced and imported products,

$$Q_i = \Omega_i\left[\mu_i \cdot D_i^{-\theta_i} + (1+\mu_i)M_i^{-\theta_i}\right]^{-1/\theta_i} \tag{25}$$

trade decisions depend on the relative prices[12]. In the case of exports, if the price of the good produced is higher globally than domestically, then the producer will decide to export the good instead of selling it to the domestic market.

$$\frac{D_i}{E_i} = \left(\frac{\tau_i}{1-\tau_i} \cdot \frac{PD_i}{PE_i}\right)^{1/(\varphi_i-1)} \tag{26}$$

where

$$PE_i = (1 - te_i)pwe_i \tag{27}$$

Similarly, if the price of the imported good is higher compared to the price of its domestic equivalent, then the consumer will decide to consume the domestically produced good instead. The consumer can thus satisfy his/her taste for variety.

$$\frac{D_i}{M_i} = \left(\frac{\mu_i}{1-\mu_i} \cdot \frac{PM_i}{PD_i}\right)^{1/(1+\theta_i)} \tag{28}$$

$$PM_i = (1 + tm_i)pwm_i \tag{29}$$

The model represents a small open economy that exports and imports goods and services from the rest of the world. However, the assumption is that the countries are small enough that their export and import decisions do not affect the world prices of goods and services. Therefore, the export price of a good (in foreign currency) pwe_i and the import price of a good (in foreign currency) pwm_i are exogenous. te_i and tm_i are export taxes and import tariff rates, respectively.

Savings and Investment. The ex-post savings-investment identity of National Accounts holds in a CGE model ex-ante. Savings in the system can come from private (household) savings $(\sum_h s_h Y_{ht})$, the fiscal surplus (or deficit) FB_t, and official grants and loans from abroad $(ER_t FS)$.

$$I_t = \sum_h s_h Y_{ht} + FB_t + ER_t FS \tag{30}$$

Investment demand is also not determined through a behavioral equation. The value of investment spending $(P_i \cdot N_i)$ must equal all the investible funds in the system $(I \cdot \varepsilon_i)$.

---

[11] Transfers to institutions (households and enterprises) and subsidies paid out to some activities and commodities are netted out in this relationship.

[12] Equations (26) and (28) are derived from the first order conditions of the CET and Armington function, respectively.

$$I \cdot \varepsilon_i = P_i \cdot N_i \qquad (31)$$

$$N_i \epsilon \, Q_i$$

Current account. The balance-of-payments current account balance may be defined as the difference between national savings and investment ($S - I$). If the difference is positive, then those surplus savings are invested abroad (net foreign assets) and, if negative, then the gap is financed by foreign capital inflows.

$$CA = S - I = \Delta NFA \qquad (32)$$

Alternatively, the current account balance may also be defined as the trade balance ($TE - TM$) plus net foreign transfers or workers' remittances ($\sum_h hw_h$), and foreign aid/grants accruing to the government (rw).

$$CA = TE - TM - NFI \qquad (33)$$

$$TE = \sum_i (pwe_i \cdot E_i) \text{ and } TM = \sum_i (pwm_i \cdot M_i) \qquad (34)$$

$$NFI = \sum_h hw_h + rw \qquad (35)$$

The above equations model the within period component of the DCGE model. As for the between period growth component, that is modeled through the assumed growth in factor supplies (equation 36) -all except capital accumulation, total factor productivity (equation 37), and the change in government recurrent spending (equation 38).

$$VS_{ft+1} = VS_{ft}\left(1 + gv_{ft}\right) \text{ where } f \neq k \qquad (36)$$

Factor supply in the following period, VS_{ft+1}, is assumed to grow at a rate of gv_{ft}, per year. The production shift parameter, Λ_{it}, grows at the rate of gp_{it}, which represents total factor productivity.

$$\Lambda_{it+1} = \Lambda_{it}(1 + gp_{it}) \qquad (37)$$

Finally, government recurrent spending is assumed to grow at an annual rate of gg_{it}, per annum.

$$G_{it+1} = G_{it}(1 + gg_{it}) \qquad (38)$$

All three components of the nexus modeling framework, the biophysical, the energy, and the economic components, interact and "talk" to each other. As previously mentioned, output from the energy and biophysical components is entered as input into the CGE model, and output from the CGE model feeds into the energy model in order to allow us to assess the macroeconomic and distributional impacts of the policy questions posed. The links between the different components of the framework come into play when the system is used to assess different policy scenarios.

4. SCENARIOS AND NEXUS MODELING LINKS: EXAMPLE OF THE NILE BASIN COUNTRIES

Our quantitative framework explores the impact of climate change on the water, energy, and food sectors and assesses nexus policy interventions in those three sectors and the impact this has on the economies of three of the East Nile Basin countries; Egypt, Ethiopia, and Sudan. By employing a nexus approach, the economies of the three countries can move one step closer to sustainable development systems by amplifying and optimizing on the net benefits of intersectoral integration (Hoff 2011).

The food, energy and water nexus highlights not just the multiplier effects involved in an efficient and coherent tripartite nexus intervention, it also highlights the vulnerabilities of these three systems and their combined and compounded fragilities as a result of strong sectoral interlinkages and the consequent impact on economic growth and development. Adding climate change to the challenges makes a policy maker's job even more difficult when devising nexus policy interventions. In order to keep up with population increases under climate change impacts, more and more food, water and energy are needed despite their increasingly constrained supply. As a result of climate change, crop yields will change, resultant water stress upstream will negatively impact the hydropower generation of downstream countries, and rising sea levels and soil compaction in the delta will adversely impact the agriculture sector in affected downstream countries.

Climate change will directly impact the economies of the three countries through the three sectors that we choose to highlight and emphasize in this paper. Climate change will place stress on water supply, namely Nile waters. It will also affect the food sector through two main pathways; crop yield changes as a result of changing precipitation and temperatures, and loss in agricultural land in the Nile delta as a result of rising sea levels and delta compaction. Finally, for this study, climate change will also impact the energy sector by potentially adversely impacting hydropower generation capabilities. Adapting to climate change inevitabilities will require a series of nexus interventions on the part of policy makers[13].

We employ Nielson et al.'s (2015) definition for the water, energy, food nexus, in which they state that the "…food-energy-water security nexus encompasses synergies and tradeoffs between food, energy, and water security that are impacted by endogenous and exogenous drivers and cannot be captured if these sectors are analyzed in isolation." When proposing nexus intervention policies, Nielson et al. make a distinction between the direct and indirect effects of policies on these three sectors. Direct effects occur when the policy intervention affects at least one of these three sectors directly, while an indirect effect is when polices and occurrences affect these sectors through a complementary system. These channels of impact are important because for an intervention or a policy "…to be considered a nexus intervention, the intervention must impact food, energy, and water security, of which at least one impact must be direct." We use this definition when devising and setting out the policy scenarios.

Scenarios

We undertake six policy scenarios, the first three provide the scenario where there is no adaptation to climate change, while the next three are aimed at mitigating the adverse effects of climate change through climate change adaptation policies. The first three scenarios are compared against a baseline where climate change does not take place, while the last three are compared against a world of climate change without adaptation (Table 1). In both sets of scenarios, climate change impacts are assessed in the three sectors of water, energy, and food.

Table 1—Nexus policy interventions

Scenario	Policy Intervention	Water Security	Energy Security	Food Security
CC-Fa – climate change adaptation by focusing on the **food sector**, especially after crop yields change and, if relevant, sea levels rise	Increasing or decreasing cropped area of land in order to counter yield changes	*Direct*: Water use for agricultural production will change while also increasing for industry and private consumption	*Direct*: More energy is used by consumers and farmers.	*Direct*: Net production of food is unknown. On the one hand, any change in crop yields will change agricultural output. However, adding or taking away from the cropped area will impact agricultural output. *Indirect*: Potentially employment in the agriculture sector will change, thus impacting incomes and access to food.
CC-Ea – climate change adaptation scenario that focuses on the **energy sector**	Change in energy mix by relying more on renewables in electricity generation, keeping subsidies intact	*Direct*: Greater use of water in the process of electricity generation	*Direct*: More energy available for use by consumers through a more efficient energy mix and less reliance on fossil fuels	*Direct*: More electricity is available for consumption, but not clear if output price of electricity will fall because some of the renewable sectors will depend on subsidies to operate efficiently. Consequently, price of electricity for intermediate demand is indeterminate at this point. *Indirect*: Potentially higher employment in electricity generating sectors contributing to higher incomes and greater food access
CC-Wa – climate change adaptation by focusing on the **water sector** – more efficient water allocation	Relying on alternative sources of water and improving water use efficiency, e.g., more desalination and investing in more efficient irrigation systems	*Direct*: More efficient use of water systems	*Direct*: More energy will be needed to operate these irrigation systems	*Direct*: Productivity expected to increase in the agriculture sector *Indirect*: Increased employment as a result of employing these more efficient irrigation networks

Source: Nielsen et al.(2015) and authors' representation

In the presence of climate change but with no adaptation measures being taken, our analyses demonstrate the following:

Food production systems are challenged (CC-Fna): Climate change leads to temperature changes and greater water stress facing the agriculture sector. As a result, crop yields are affected, impacting agriculture production. Furthermore, in coastal countries, the rise in global sea levels may affect coastal countries, specifically Egypt's delta which would ultimately reduce the land available for growing the crops currently grown in and around there.

---

[13] It is more difficult to put in place country level mitigation practices to slow down sea level rise than to build into policy adaptation measures to the phenomenon. Though reduction in greenhouse gas emissions is an important adaptation measure, one single country cannot sufficiently reduce greenhouse gas emissions to affect sea level rise.

Water sources are challenged (CC-Wna): Water use efficiency may become compromised as a result of climate change. So, depending on the outcomes of the different GCMs predicting water stress, the country's business as usual use of water may become unsustainable.

Energy production is adversely impacted (CC-Ena): Climate change may impact hydropower generation capacity. Combined with increasing demand for energy in the three countries, depending on each country's net energy production, this may lead to stresses on the energy sector that would be reflected throughout the economy.

Once these three main impacts of climate change are modeled, we propose adaptation measures to help alleviate some of the adverse reactions to climate change. The three adaptation measures we focus on are (also see Table 1):

Food sector interventions (CC-Fa): Increasing the availability of food, whether through more domestic production or more imports, can counter some of the reductions in food supply as a result of reduced crop yields. Increasing production of food is possible by increasing productivity, land expansion or changes in the crop mix (more fruits and vegetables, less cereals), or even increasing exports in order to finance higher food imports.

Water sector interventions (CC-Wa): Increasing water use efficiency and investing in and using alternative sources of water. The former can be achieved through investing in improved irrigation schemes and improving wastewater reuse, while the latter includes investing more in desalination technology, water harvesting, or even using groundwater resources, non-renewable though they may be.

Energy sector interventions (CC-Ea): Electricity production will be affected by climate change. It will become necessary to rely on alternative sources of energy to support each economy's growth and development. All three East Nile Basin countries are committed to changing the energy mix towards more climate-resilient technologies in order to counter any negative effects and also to the countries meet their renewable energy strategy. Furthermore, this scenario assumes that over time these countries will benefit from a global learning curve that leads to a reduction in the cost of producing these non-conventional energy technologies.

Climate change and water supply shortages are both expected to impact crop yields in the agricultural sector. The results from the hydro-economic model produce the supply of water available for each country and long term crop yields. The relationship between water and the rest of the economy is not only through agriculture, but water is also used for industrial and for household consumption purposes. Water used for agricultural and industrial purposes appears in the demand for intermediate goods. The model uses a Leontief technology to model the relationship between gross output and the use of intermediate goods.

Crop yield changes produced by the biophysical models are in turn used in the CGE model to reflect changes in the total factor productivity (TFP) of the agricultural subsectors over time. The model uses a nested constant elasticity of substitution production technology that allows us to use the shift parameter to model these yield changes. TFP growth in turn determines the growth as well as the growth in the entire system. In the case of a negative shock, for example, if crop yields fall due to adverse climate change impacts or reduced supply of water, TFP growth will be negative. This negative shock is translated into reduced sectoral production, reductions in the use of factors of production, and through the model's linkages, impacts on factor income, household income, exports and imports.

It is through these links that we are able to bring together the modeling to highlight the socio-economic impacts of climate change in each country. If the country of interest experiences both the adverse impacts of water shortages (whether through climate change or through man-made means) and long term yield reductions as a result of high average temperatures, then we expect a negative impact on the agricultural sector in general and on the directly impacted agriculture subsectors specifically. By taking the analysis one step further, we are able to explore the direct and the indirect linkages among the sectors and agents and also explore poverty and income distribution consequences.

Nexus modeling links

In this section we highlight the links among the three model components by listing which equations from each serve as channels for these links.

Biophysical and energy model links. One possible channel of communication between the river basin model and the energy sector is through the electricity derived from hydropower production. The river basin model can provide the system with hydropower production changes as a result of climate change. However, the energy sector model determines the allowable electricity produced by hydropower, both of which are used as input into the CGE model.

Hydro-economic model and socioeconomic model links. We conduct two sets of scenarios; the first compares the impacts of climate change on the water, energy, and food sectors in a world of no climate change, and the second set models the different nexus policy interventions the governments can consider in order to adapt to a future of climate change. That second set of scenarios is compared to climate change without adaptation measures.

Climate change is expected to impact the three nexus sectors through changing crop yields, changes in hydropower generation, and the land available for crop agriculture. Policy makers can adapt to a changing climate by targeting these three sectors directly. In the food sector, there are a couple of potential options to take: increase agricultural production or productivity, increase agricultural imports, or both. In the water sector, governments can rely on alternative water sources, such as desalination, more groundwater extraction, water harvesting, and the like; improve the efficiency of water use in the economy; or a mixture of both. In the energy sector, in the event that climate change is expected to bring about adverse impacts on energy generation or usage, changing the energy mix by relying more on renewables is a viable option, especially since all three case study countries emphasize that trend in their development strategies.

The section below highlights the equations used in the modeling framework and how they interact in order to clarify these two different sets of scenarios.

Impacts on the food sector

Climate change affects the food sector system through two pathways; changing crop yields in the agriculture sector and changing land available for crop agriculture.

Modeling crop yield changes

In the hydro-economic model. The modeling suite obtains the long term changes in crop yields from the hydro-economic model. A crop water production function in heuristic multiplicative form is applied, as shown in equation (39). It is based on the heuristic assumption that the Boolean principle is applicable and the yield expected at the end of any growth stage is determined with respect to the maximum yield expected at the beginning of that stage. The function is applicable over a wide range of stress conditions (Rao, Sarma, and Chander 1988).

$$\frac{Y^c}{Y_m{}^c} = \prod_i \left[1 - K_{c,i} \left(1 - \frac{AET_{c,i}}{PET_{c,i}} \right) \right] \tag{39}$$

where Y is actual crop yield reported by the analyzer, Y_m maximum yield under no water stress, $K_{c,i}$ yield factor for growing stage i, and $AET_{c,i}$ is actual crop evapotranspiration in growing stage i.

In the DCGE model. Precipitation and temperature changes over the time horizon are expected to change long term crop yields for crop agriculture. Those crop yield changes are considered as total factor productivity changes to the crop sectors. The model uses a nested constant elasticity of substitution production technology. These changes are captured through changes in the shift parameter Λ_{it} of each agriculture subsector's production function:

$$X_i \ = \Lambda_i \left(\sum_f a_{i\,f} V_{if}{}^{-\rho i}\right)^{-1/\rho i} \tag{40}$$

where $a_{i\,f}$ is the share parameter of the factor used in the production of good i and V_{if} is the quantity demanded of each factor, and the technological change/shift in each period Λ_{it+1} as in equation (37) is captured by gp_{it}, which represents total factor productivity or the change in the production function's shift parameter

Modeling agricultural land shocks in the DCGE model

Equation (41) is the equilibrium condition in the factor markets, where the sum of factor demand ($\sum_{ir} V_{irft}$) is equal to the supply of that factor in each time period. If climate change or policy leads to a decrease/increase in the land area available for crop production, then land supply is affected in the model.

$$\sum_{ir} V_{irft} \ = VS_{ft} \tag{41}$$

We assume that factor supply grows at an exogenously set rate of gv_{ft} (equation 36). In the event of a negative/positive shock land supply in future periods (VS_{ft+1}) changes accordingly.

Impacts on the water sector

Unlike other attempts to model water in an economic model, this framework makes use of a hydro-economic optimization model to model the intricacies and details of the water sector and ultimately derive the long term crop yields as highlighted in equation

(36). In the DCGE model, water is a standalone sector that distributes water to the economy and, thus, any exogenous shocks that would affect either the supply of water or its demand and use in the economy.

Modeling water stress/changes in the DCGE model

The governments may decide to address water stress by adopting more efficient water management practices, such as improving water irrigation networks or improving the water supply and distribution network as a whole. These changes can be modeled in the DCGE model as positive TFP shocks in the water sector in the economy through gp_{it} (equation 37), thus changing productivity in that sector. Alternatively, more efficient water management practices affect the demand for water used in agriculture, industry, and for private consumption. For the first two cases, we can affect the demand for water as an intermediate good (equation (42))[14] by assuming lower input output coefficients, $io_{i\prime i}$ in the future.

$$PP_i = PV_i + \sum_{i'} P_{i'}\, io_{i'i} \tag{42}$$

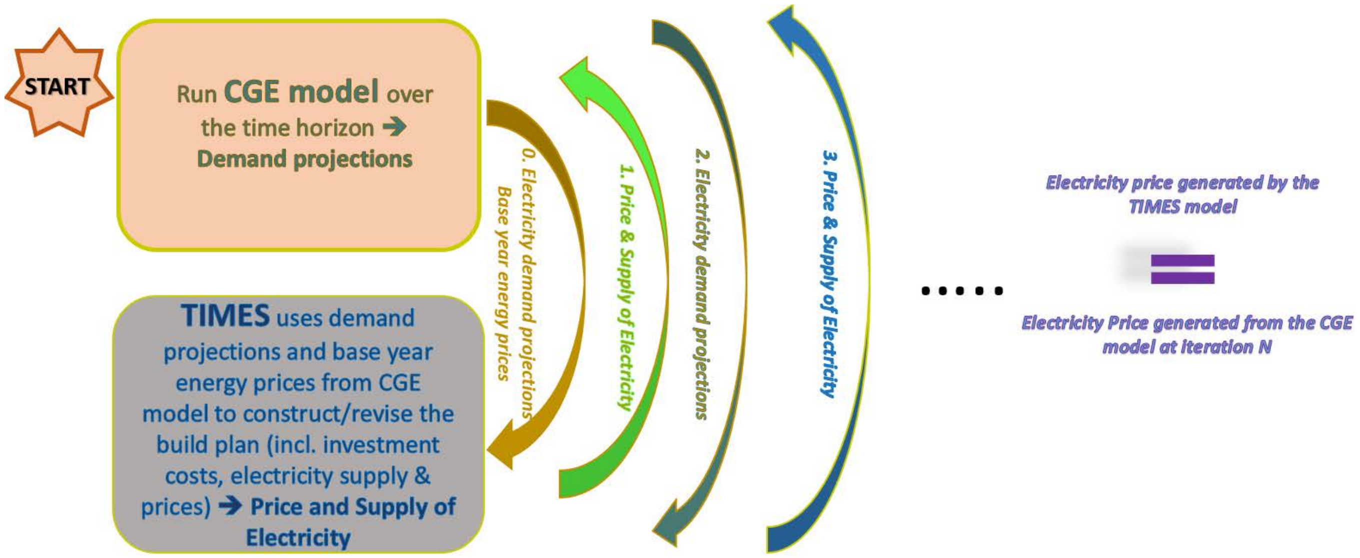
As for the impact on household consumption of water, the above changes will lead to a changing market price for water for the households and through their demand (equation 42), P_i, the market price for water will change, thus influencing C_{hi}, household consumption (equation 20).

Impacts on the energy sector

Water stress as a result of climate change is expected to affect available water used for hydropower and underlines the necessity for the East Nile Basin countries to change their energy mix more in favor of renewable energy rather than their traditional energy sources. However, for countries that plan to increase their production of hydropower as a part of their development plans, the negative impact of climate change on their hydropower generation will not matter, and the net effects are more likely to be increased hydropower production. Regardless of the net outcome (positive or negative), climate change is expected to cause an exogenous shock in the energy sector.

In order to capture the intricacies of energy production, the TIMES energy sector model is used as part of the framework for this sectoral focus where the TIMES and DCGE are involved in a back and forth data dialogue (Figure 7) until the committed build plan is generated for the entire time period of interest.

Figure 7—Data dialogue between the TIMES model and the DCGE model



Source: Author’s representation

The indicators linking the two models are the electricity demand projections, and the average price of electricity derived from the MARKAL/TIMES model. The DCGE model starts by providing the TIMES model with the economy’s projected electricity demand for each country over the time period of analysis. The MARKAL/TIMES model then uses this as an input to generate the investment costs and the generated electricity over the time horizon. The DCGE then takes the calculated average price and runs the model and generates a new set of electricity demand projections that are in turn passed on to the TIMES model for another

---

[14] The model uses a Leontief technology to model the relationship between gross output and the use of intermediate goods. PP_i is the producer price of the goods produced domestically, PV_i is the value added price, and P_i is the market price in equation (41).

rerun. This back and forth continues until the average electricity price generated by the TIMES model converges to the supply price of electricity generated by the DCGE model.

Electricity demand and prices from the DCGE model to the TIMES model. The MARKAL/TIMES model uses the projected electricity demand generated by the DCGE model in its first run. For each time period *t*, region *r*, and demand *d*, the total activity of end-use technologies servicing that demand must be at least equal to the specific demand (equation (9)). For instance, electricity - demand expressed in PJ per year - may be satisfied by a combination of several types of power plants (coal, oil, gas, solar, etc.).

The DCGE model provides the MARKAL/TIMES model with the base year prices for all energy products (domestically produced, exported, or imported) to use in its first run. The energy model uses those as an input in its energy flow conservation (equation (8)).

Electricity prices in the DCGE model. In order to use the electricity prices from the TIMES model in the CGE model, the price of electricity commodity is determined exogenously, allowing the commodity sales tax (tc_i) to clear the market for electricity (equation (43)).

$$(1 - tc_i)P_i \cdot Q_i = PD_i \cdot D_i + PM_i \cdot M_i \tag{43}$$

where *i* is electricity commodity, P_i is the market price, Q_i the quantity of electricity supplied in the market, PD_i and D_i, are the price and quantity, respectively, of domestically produced electricity, PM_i is the domestic price of imports, and M_i is the supply of imported goods available in the market.

Alternatively, instead of fixing the commodity price of electricity, the producer price (PP_{it}) may be determined exogenously allowing the activity tax on the electricity sectors (ta_i) (equation 44) to become flexible in order to clear the market for the different electricity processes produced.

$$(1 - ta_i)\ PP_{it}QA_{it} = PV_{it}QV_{it} + \textstyle\sum_{i'}\ P_{i't}io_{i'i}\,QINT_{it} \tag{44}$$

where *i* = solar, wind, hydroelectric, gas, or diesel, QA_{it} is domestic production, $PV_{it}QV_{it}$ is value added, and $\sum_{i'} P_{i't}io_{i'i}\,QINT_{it}$ is the value of intermediate demand

Modeling climate smart energy in the CGE model.

All three countries plan to diversify their energy supply mix in favor of more renewable energy, so as part of their climate change adaptation policies, countries will invest more in non-traditional electricity production. There are two pathways to doing that; either through increased investment in the renewable energy sectors or, through more efficient management and using newer technologies, significantly improving productivity in the renewable energy sector.

Increasing investment in the renewable energy sectors. The decision to increase investment using domestic funding requires that the opportunity cost of these investment choices be accounted for in the framework. Depending on the individual country's policy direction, part of the investment is directed towards the target electricity generation technologies, the rest will then be allocated towards the rest of the sectors in the economy. Equation (45) models this relationship. The sectoral allocation of capital (SK_{ikt}), will depend upon the sectoral profit share (SP_{ikt}), the new investment mobility parameter (ω), and a ratio of the difference between the return to capital at the sectoral level (SR_{ikt}) less the average economy-wide capital rental rate (AR_t).

$$SK_{ikt} = SP_{ikt} + \omega SP_{ikt}\left(\frac{SR_{ikt} - AR_t}{AR_t}\right) \tag{45}$$

Increasing the productivity in the renewable energy sectors. By using newer technologies for producing renewable energy, the production process becomes more efficient with time, implying that TFP in these sectors will over time become higher than that in the traditional electricity sectors. As a result, gp_{it} ((equation 37)) for all the renewable electricity sectors increases.

Data used in the DCGE model

The DCGE model's main data source is a social accounting matrix (SAM). A SAM is a representation of an economy showing the flow of income from production activities in the form of factor payments to the households and the consequent flow back to product markets through household spending on goods and services. It is a square matrix where the column sum must equal the sum of the corresponding row. Each cell in the SAM can either represent the payments from a column account to a row account, or, an income received by a row account from a column account (Breisinger et al. 2009). The rows indicate income received, whereas the columns indicate payments made. As a result, the SAM represents an analytical tool that highlights the interactions throughout the economy in the form of circular flows. Subject to data availability, the SAM accounts in each category may be disaggregated appropriately to address the policy questions addressed in the CGE models.

For the DCGE models used in the water-energy-food nexus model framework, the country SAMs will have to show detail in the sectors of focus – the agriculture sector, the water sector, and the energy sector. For the agriculture sector, each country's strategic crop mix will be highlighted, subject to data availability. As for the water sector, it will be important to disaggregate that sector to at least water for irrigation sector and another for all other uses of water when possible. The energy sector will also require some detailed disaggregation. Again, depending on the specific country's energy plans and current uses of energy types, the detail in that sector will vary. For instance, Egypt is looking to exploit alternative energy sources in its energy plan. As a result, the disaggregation of its energy sector in the SAM will include conventional electricity, electricity derived from natural gas, electricity derived from solar energy, that derived from wind power, as well as electricity derived from diesel. Ethiopia, on the other hand, has an energy sector that primarily focuses on conventional energy and energy from biomass. The latter will have to be disaggregated from its forestry sector, which in some cases is part of the agriculture sector.

5. CONCLUSION AND WAY FORWARD

By employing a nexus approach and making use of decades-worth of significant investments in advanced quantitative models, one can add to the literature and provide robust evidence based research as solutions to the challenge of the impact of climate change and population growth on the nexus of water, energy, and food.

Despite the significant modeling strides taken in partial and general equilibrium models, each genre on its own cannot provide the level of detail and interconnectedness needed to tackle the challenges we now face in the water-energy-food nexus. It is proving more and more imperative to see the big picture and approach development challenges by taking into consideration all their different drivers and accounting for all their expected impacts. The level of sectoral detail associated with partial equilibrium models alone may provide us with the intricacies needed to understand how the sector works. However, they are unable to tell us how these changes interact with the rest of the economy. By marrying the rich detail in partial equilibrium models to the rich economic interlinkages of a CGE model, we can achieve the best of both worlds to inform policy in the Eastern Nile Basin countries. There are other considerations to contemplate in order to bring forth the right mix of research tools to dialogue on how to provide policy solutions to address the interlinked challenges to water, energy, and food resources arising from climate change and continuing population growth.

The Nile basin covers about one tenth of Africa's total land mass and is home to about 300 million people, many of whom live in poverty and are malnourished. The Nile plays an important role for these countries' economies by providing water for irrigation, industrial use, electricity generation, and household consumption. Access to improved water and electricity is limited in most Nile countries resulting in severe implications on health and other social indicators, especially among women.

Of all the countries neighboring the Nile, Egypt is most dependent on Nile river water, as the river makes up 74 percent of all the water available. Egypt has been the main user of Nile water throughout history and continues to be dependent on water from upstream countries. However, water from the Nile and its tributaries also plays an important role in the development of all upstream countries. The river's importance is likely to further increase in the future to support urgently needed acceleration of economic growth, food security, and poverty reduction.

Access to data, research results, and models is a necessary yet insufficient condition for evidence-based policy making. Oftentimes, the lack of coordination and the exchange of information and tools among different agencies concerned deters development, even in the presence of tools discussed here (EgSSP 2016). Furthermore, in the absence of an overarching development framework to guide and integrate that research, even the most comprehensive and shared research tools are insufficient to promote development.

There are significant and outstanding policy questions that require application of the research tools described here to address growing natural resource scarcity and the challenges facing the water-energy-food nexus in the East Nile Basin countries (EgSSP 2016). One such question is what is the impact of climate change on the water, energy, and food futures in the region? Specifically, what nexus policy interventions can help in mitigating or reducing the impacts of climate change on these sectors and on the economy as a whole? Furthermore, what policies are required to address the growing reduction in the quality of available natural resources, for instance, water pollution and soil degradation. In the presence of water scarcity, how can non-renewable fossil ground water be governed to optimally support development in the long term? Also, given the increase in population and economic growth, how can the demand for natural resources be optimized to support both industrial and private needs, as well as sustainably support rural development and contribute to food security?

Following this analysis of methods, we will develop specific modeling suites for each of the three countries of the East Nile Basin on which we will focus – Egypt, Ethiopia, and Sudan. For each of these countries, the core six policy scenarios mentioned above will be applied. However, within these scenarios, stylized country policies may also be added where relevant.

APPENDIX. SELECTED CLIMATE CHANGE SCENARIOS USED IN THE NEXUS ANALYSIS

Scenario name	Global climate model	Representative Concentration Pathway (RCP)
HadGEM2_RCP8p5	HadGEM2-ES	RCP 8.5
NorESM1_RCP8p5	NorESM1-M	RCP 8.5
NorESM1_RCP4p5	NorESM1-M	RCP 4.5
GFDL_RCP4p5	GFDL-ESM2M	RCP 4.5
MIROC_RCP8p5	MIROC-ESM-CHEM	RCP 8.5
MIROC_RCP4p5	MIROC-ESM-CHEM	RCP 4.5

REFERENCES

Al-Riffai P., C. Breisinger, D. Verner, T. Zhu. 2012. ”Droughts in Syria: An Assessment of Impacts and Options for Improving the Resilience of the Poor.” *Quarterly Journal of International Agriculture* 51(1): 21-49.

Al-Zubari, W. n.d. “Water, Energy, and Food Nexus in the Arab Region.” Accessed October 10, 2015. http://agora.med-spring.eu/sites/default/files/uploads/nexus_in_the_arab_region_afed_energy_report.pdf

Amorim, F., A. Pina, H. Gerbelová, P. Pereira da Silva, J. Vasconcelos, and V. Martins. 2014. “Electricity Decarbonisation Pathways for 2050 in Portugal: A TIMES (The Integrated MARKAL-EFOM System) Based Approach in Closed Versus Open Systems Modelling.” *Energy* 69: 104–112.

Arndt, C., R. Davies, S. Gabriel, K. Makrelov, B. Merven, F. Hartley, and J. Thurlow. 2015. “A Sequential Approach to Integrated Energy Modeling in South Africa.” *Applied Energy* 161(1): 591-599.

Aydın, L. and M. Acar. 2011. “Economic Impact of Oil Price Shocks on the Turkish Economy in the Coming Decades: A Dynamic CGE Analysis.” *Energy Policy* 39(3): 1722–1731.

Balke, N.S, S. P. A. Brown, and M. K. Yücel. 2008. *An International Perspective on Oil Price Shocks and U.S. Economic Activity*. Globalization and Monetary Policy Institute Working Paper 20. Dallas: Federal Reserve Bank of Dallas.

Berck, P., S. Robinson, and G. Goldman. 1990. *The Use of Computable General Equilibrium Models to Assess Water Policies*. Working Paper No. 545. California: University of California Berkeley. Accessed on October 1, 2015. http://escholarship.org/uc/item/082465zv

Bergman, L. 1988. “Energy Policy Modeling: A Survey of General Equilibrium Approaches.” *Journal of Policy Modeling* 10(3):377–399.

Bogdanski, A. 2012. “Integrated Food-Energy Systems for Climate-Smart Agriculture.” *Agriculture and Food Security* 1(9).

Böhringer, C. and T. Rutherford. 2005. *Integrating Bottom-Up into Top-Down: A Mixed Complementarity Approach*. ZEW Discussion Papers 05-28. Mannheim: Center for European Economic Research. http://econstor.eu/bitstream/10419/24137/1/dp0528.pdf

Breisinger, C., M. Thomas, and J. Thurlow. 2009. *Social Accounting Matrices and Multiplier Analysis: An Introduction with Exercises*. Food Security in Practice Technical Guide Series. Washington, DC: International Food Policy Research Institute.

Calzadilla, A., K. Rehdanz, and R. Tol. 2010. “The Economic Impact of More Sustainable Water Use in Agriculture: A Computable General Equilibrium Analysis.” *Journal of Hydrology* 384(3):292-305.

Condevaux-Lanloy, C., and E. Fragniere. 2000. “An approach to deal with uncertainty in energy and environmental planning: the MARKAL case.” *Environmental Modeling and Assessment* 5: 145–155.

Conway, D., E. Archer van Garderen, D. Deryng, S. Dorling, T. Krueger, W. Landman, B. Lankford, K. Lebek, T. Osborn, C. Ringler, J. Thurlow, T. Zhu and C. Dalin. 2015. “Climate and Southern Africa’s Water-Energy-Food Nexus.” *Nature Climate Change* 5: 837-846.

De Pinto, Alessandro; Wiebe, Keith D.; and Rosegrant, Mark W. 2016. *Climate Change and Agricultural Policy Options: A Global-to-Local Approach*. IFPRI Policy Brief. Washington, D.C.: International Food Policy Research Institute (IFPRI).

Diao, X. and J. Thurlow. “A Recursive Dynamic Computable General Equilibrium Model.” In *Strategies and Priorities for African Agriculture: Economywide Perspectives from Country Studies* edited by X. Diao, J. Thurlow, S. Benin, and S. Fan, 17:50. Washington D.C., US: International Food Policy Research Institute.

Diao, X., A. Dinar, T. Roe, and Y. Tsur. 2008. “A General Equilibrium Analysis of Conjunctive Ground and Surface Water Use with an Application to Morocco.” *Agricultural Economics* 38(2008): 117–135.

Dii (Desertec Industrial Initiative). 2012. “Desert Power 2050: Perspectives on a Sustainable Power System for EUMENA.” Unpublished. Munich: Dii.

Dixon, P. 1990. "A General Equilibrium Approach to Public Utility Pricing: Determining Prices for a Water Authority." *Journal of Policy Modeling* 12(4): 745-67.

EgSSP (Egypt Strategy Support Program). 2016. “Modeling the Water-Energy-Food (WEF) Nexus in the Arab World – The Case of Egypt.” http://egyptssp.ifpri.info/2016/04/24/modeling-the-water-food-energy-wef-nexus-in-the-arab-world-the-case-of-egypt/

Fadali, E., K. Rollins, and S. Stoddard. 2012. “Determining Water Values with Computable General Equilibrium Models”. A Report submitted for presentation at “The Importance of Water to the U.S. Economy” technical workshop, September 19. Washington, D.C.: National Academy of Public Administration.

FAO (Food and Agriculture Organization of the United Nations). 2014. “The Water-Energy-Food Nexus: A New Approach in Support of Food Security and Sustainable Agriculture.” Rome. http://www.fao.org/nr/water/docs/FAO_nexus_concept.pdf

---------. 2009. “How to Feed the World in 2050.” Rome, FAO. http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf

Fishbone, L.G., G. Giesen, G. Goldstein, H.A. Hymmen, K.J. Stocks, H. Vos, D. Wilde, R. Zoelcher, C. Balzer, and H.B. Abilock. 1983. “User’s Guide for MARKAL (BNL/KFA Version 2. 0): A Multi-Period, Linear-Programming Model for Energy Systems Analysis.” Long Island, USA: Brookhaven National Laboratory; Jülich, Germany: Kernforschungsanlage.

Fortes, P., S. Simoes, J. Seixas, and F. Ferreira. 2013. "Top-down and Bottom-up Modelling to Support Low-Carbon Scenarios: Climate Policy Implications. *Climate Policy* 13(3):285-304.

Gargiulo, M. 2015. "Elements of Energy Technology Systems Analysis and Introduction to the TIMES Model Generator." *IEA-ETSAP VEDA-TIMES Training*. https://iea-etsap.org/newsfiles/Training-program-D3.pdf.

Gómez, C.M., D. Tirado & J. Rey-Maquieira, 2004. "Water Exchanges Versus Water Works: Insights from a Computable General Equilibrium Model for the Balearic Islands." *Water Resources Research* 40(10): W105021-W1050211.

Goodman, D.J. 2000. "More Reservoirs or Transfers? A Computable General Equilibrium Analysis of Projected Water Shortages in the Arkansas River Basin." *Journal of Agricultural and Resource Economics* 25(2): 698-713.

Hassan, R., J. Thurlow, T. Roe, X. Diao, S. Chumi, and Y. Tsur. 2008. *Macro-Micro Feedback Links of Water Management in South Africa: CGE Analyses of Selected Policy Regimes*. Policy Research Working Paper. Washington, DC: The World Bank. http://www.econrsa.org/wkshops/cge/session8-hassan-thurlow-2008-%20water-policies-south-africa.pdf

High Level Panel of Experts (HLPE). 2015. *Water for Food Security and Nutrition*. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome: FAO.

Hoff, H. 2011. "Understanding the Nexus." *Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus*. Stockholm: Stockholm Environment Institute. http://www.water-energy-food.org/en/whats_the_nexus/background.html

Horridge, M., P.B. Dixon, and M.T. Rimmer. 1993. "Water Pricing and Investment in Melbourne: General Equilibrium Analysis with Uncertain Streamflow," *Preliminary Working Paper IP-63*. Clayton: Centre of Policy Studies, Monash University.

IEA (International Energy Agency). 2012. *Energy Technology Perspectives 2012: Pathways to a Clean Energy System*. Paris: IEA.

IEA-ETSAP (Energy Technology Systems Analysis Program). 2015. The Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency (IEA) home page. Accessed 26 April 2017. http://www.iea-etsap.org/web/index.asp

IFPRI (International Food Policy Research Institute). 2016. *2016 Global Food Policy Report*. Washington, D.C.: IFPRI.

IPCC (Intergovernmental Panel on Climate Change). 2014. "Summary for Policymakers." In *Climate Change 2014: Mitigation of Climate Change*. edited by O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx. Cambridge, United Kingdom and New York: Cambridge University Press.

Loulou, R., G. Goldstein, and K. Noble. 2004. *Documentation for the MARKAL Family of Models*. Paris: IEA - Energy Technology Systems Analysis Programme (ETSAP).

Loulou, R., U. Remne, A. Kanudia, A. Lehtila, and G. Goldstein. 2005. *Documentation for the TIMES Model: Part III*. Paris: IEA Energy Technology Systems Analysis Programme (ETSAP).

Martinsen, T. 2011. "Introducing Technology Learning for Energy Technologies in a National CGE Model Through Soft Links to Global and National Energy Models." *Energy Policy* 39(6): 3327–3336.

Mathur, J. 2001. "Development of a Modified Dynamic Energy and Greenhouse Gas Reduction Planning Approach through the Case of Indian Power Sector." PhD dissertation, Duisberg, Germany: Universität Duisburg-Essen.

Mondal, M.A.H. 2010. "Implications of Renewable Energy Technologies in the Bangladesh Power Sector: Long-Term Planning Strategies." PhD dissertation, Bonn: University of Bonn.

Mondal, M.A.H., S. Kennedy, T. Mezher. 2014. "Long-Term Optimization of United Arab Emirates Energy Future: Policy Implications." *Applied Energy* 114: 466–474.

Nelson, G., M. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, R. Robertson, S. Tokgoz, T. Zhu, T. Sulser, C. Ringler, S. Msangi, and L. You. 2010. *Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options*. IFPRI. Washington D.C.

Nielsen, T., F. Schunemann, E. McNulty, M. Zeller, E. Nkonya, E. Kato, S. Meyer, W. Anderson, T. Zhu, A. Queface, and L. Mapemba. 2015. *The Food-Energy-Water Security Nexus: Definitions, Policies, and Methods in an Application to Malawi and Mozambique*. IFPRI Discussion Paper 1480. Washington, D.C.: International Food Policy Research Institute (IFPRI).

Nkonya, E., A. Mirzabaev and J. von Braun (eds.). 2016. *Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development*. Cham, Switzerland: Springer International Publishing.

Nobel, K. 2007. *ANSWER v6 MARKAL User Manual: ANSWER MARKAL, an Energy Policy Optimization Tool.* Australia: Noble-Soft Systems Pty Ltd.

Nordhaus, W. 1974. "The Allocation of Energy Resources." *Brookings Papers on Economic Activity* 3: 529-576.

Osman, R., E. Ferrari, and S. McDonald. 2015. "Water Quality Assessment SAM/CGE and Satellite Accounts Integrated Framework." *89th Annual Conference of the Agricultural Economics Society* Warwick, England: University of Warwick. http://ageconsearch.tind.io//bitstream/204291/2/Rehab_Osman_Water_Quality-AES.pdf

Rao, N.H., P.B.S. Sarma, and S. Chander. 1988. "A Simple Dated Water-Production Function for Use in Irrigated Agriculture." *Agricultural Water Management* 13(1): 25–32.

Riekkola, A.K., C. Berg, E. Ahlgren, and P. Soderholm. 2013. *Challenges in Soft-Linking: The Case of EMEC and TIMES-Sweden*. Working Paper 133. London: National Institute of Economic Research.

Ringler, C.; D. Willenbockel, N. Perez, M.W. Rosegrant, T. Zhu, N. and Matthews. 2016. "Global Linkages Among Energy, Food and Water: An Economic Assessment." *Journal of Environmental Studies and Sciences* 6(1): 161 -171.

Robinson, S. and A. Gueneau. 2013. *CGE-W: An Integrated Modeling Framework for Analyzing Water-Economy Links Applied to Pakistan*. GTAP, Shanghai, June 2013. https://www.gtap.agecon.purdue.edu/resources/download/6371.pdf

Sanchez, M. V. 2011. "Welfare Effects of Rising Oil Prices in Oil-Importing Developing Countries." *The Developing Economies* 49(3): 321-46.

Seung, C.K. 1999. "Application of a Computable General Equilibrium Model to Evaluate Surface Water Reallocation Policies." *Review of Regional Studies* 29(2): 139-55.

Seung, C.K., T.R. Harris, T.R. MacDiarmid & W.D. Shaw. 1998. "Economic Impacts of Water Reallocation: A CGE Analysis for the Walker River Basin of Nevada and California." *Journal of Regional Analysis and Policy* 28(2): 13-34.

Seung, C., J. Englin, and T. Harris. 1997. "Application of Computable General Equilibrium Model to Derive Impacts of Surface Water Allocation Policy." *Western Journal of Agricultural Economics* 22(2).

Seung, C. K., T. R. Harris, J. E. Englin, and N. R. Netusil. 2000. "Impacts of Water Reallocation: A Combined Computable General Equilibrium and Recreation Demand Model Approach." *Annals of Regional Science* 34(4): 473-487.

Solaymani, S. and F. Kari. 2014. "Impacts of Energy Subsidy Reform on the Malaysian Economy and Transportation Sector." *Energy Policy*. 70 (7):115-125.

Robinson, S., K. Strzepek, M. El-Said, and H. Lofgren, 2008. "The High Dam at Aswan". In *Indirect Economic Impacts of Dams: Case Studies from India, Egypt, and Brazil* edited by R. Bhatia, R. Cestti, M. Scatasta, & R. P. S. Malik. New Delhi: Academic Foundation.

Strzepek, K. M., G.W. Yohe, R.S.J. Tol, and M.W. Rosegrant. 2008. "The Value of the High Aswan Dam to the Egyptian Economy." *Ecological Economics 66*(1): 117–126.

UN ECOSOC. 2016. "Breaking the Silos: Cross-Sectoral Partnerships for Advancing the Sustainable Development Goals (SDGs)." 2016 Partnership Forum. Accessed online on February 14, 2017. https://www.un.org/ecosoc/sites/www.un.org.ecosoc/files/files/en/2016doc/partnership-forum-issue-note1.pdf

United Nations (UN) Documents. "The Dublin Statement on Water and Sustainable Development." Adopted January 31, 1992 at the International Conference on Water and the Environment, Dublin, Ireland. Accessed September 28, 2015. http://www.un-documents.net/h2o-dub.htm.

Vaillancourt, K., M. Labriet, R. Loulou, J. Waaub. 2008. "The Role of Nuclear Energy In Long Term Climate Scenarios: An Analysis With the World-Times Model." *Energy Policy* 36(7): 2297–2307.

Vandyck, T. and D. Van Regemorter. 2014. "Distributional and Regional Economic Impact of Energy Taxes in Belgium." *Energy Policy* 72:190–203.

Verner, D. and C. Breisinger, eds. 2013. *Economics of Climate Change in the Arab World: Case Studies from the Syrian Arab Republic, Tunisia, and the Republic of Yemen*. Washington DC: World Bank.

von Braun, J. 2015. "The Nexus Modeling: Bridging Scales, Sectors and Disciplines." Presented at The *Water-Energy-Food Nexus Technical Workshop*. Addis Ababa.

Watson, P. and S. Davies. 2011. "Modeling the Effects of Population Growth on Water Resources: A CGE Analysis of the South Platte River Basin in Colorado." *Annals of Regional Science* 46:331-348.

Wittwer, G. 2009. "The Economic Impacts of a New Dam in South-East Queensland." *Australian Economic Review*, 42(1): 12-23

Yu, W., M. Alam, A. Hassan, A. Khan, A. Ruane, C. Rosenzweig, D. Major, and J. Thurlow. 2010. *Climate Change Risks and Food Security in Bangladesh*. Washington, DC: Earthscan, The World Bank Group.

ABOUT THE AUTHORS

Perrihan Al-Riffai is a Senior Research Analyst with IFPRI's Development Strategy and Governance Division and a core team member of IFPRI's Egypt SSP, based in Washington, DC. **Clemens Breisinger** is a Senior Research Fellow with IFPRI's Development Strategy and Governance Division and Head of IFPRI's Egypt SSP, based in Cairo. **Alam Hossain Mondal** is a Research Fellow with IFPRI's Environment, Production, and Technology Division, based in Washington, DC. **Claudia Ringler** is Deputy Division Director in IFPRI's Environment, Production, and Technology Division, based in Canada. **Manfred Wiebelt** is a Professor in the Poverty Reduction, Equity, and Development Division of the Kiel Institute for the World Economy. **Tingju Zhu** is a Research Fellow with IFPRI's Environment, Production, and Technology Division, based in Washington, DC.

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
A world free of hunger and malnutrition
2033 K Street, NW | Washington, DC 20006-1002 USA
T: +1.202.862.5600 | F: +1.202.467.4439
Email: ifpri@cgiar.org | www.ifpri.org

IFPRI – EGYPT STRATEGY SUPPORT PROGRAM
World Trade Center, 1191 Corniche El Nile, Cairo, Egypt
Office: +2(0)22577612
Mobile: +2(0)1066910782
http://egyptssp.ifpri.info/

This publication has been prepared as an output of the Egypt Strategy Support Program of IFPRI. It has not been peer reviewed. The research presented here was conducted as part of the CGIAR Research Program on Policies, Institutions, and Markets (PIM), which is led by IFPRI. The contents of this publication and any opinions stated herein are the responsibility of the authors and do not necessarily reflect the views of IFPRI and its partners.