AMERICAN UNIVERSITY OF BEIRUT

WATER-ENERGY-FOOD-CARBON NEXUS: AN OPTIMIZATION APPROACH

by
ZEINAB HUSSEIN CHAMAS

A thesis
submitted in partial fulfillment of the requirements
for the degree of Master of Engineering
to the Department of Civil and Environmental Engineering
of the Faculty of Engineering and Architecture
at the American University of Beirut

Beirut, Lebanon
December 2018

AMERICAN UNIVERSITY OF BEIRUT

WATER-ENERGY-FOOD-CARBON NEXUS: AN OPTIMIZATION APPROACH

by
ZEINAB HUSSEIN CHAMAS

Approved by:

for Dr Majdi Najm

Abou Najm, Majdi, Assistant Professor — Advisor
Department of Civil and Environmental Engineering

Yassine, Ali, Professor — Member of Committee
Department of Industrial Engineering and Management

Al Hindi, Mahmoud, Associate Professor — Member of Committee
Department of Chemical Engineering

Hamzeh, Farook, Assistant Professor — Member of Committee
Department of Civil and Environmental Engineering

Date of thesis defense: December 6, 2018

AMERICAN UNIVERSITY OF BEIRUT

THESIS, DISSERTATION, PROJECT RELEASE FORM

Student Name:	Chamas	Zeinab	Hussein
	Last	**First**	**Middle**

☒ Master's Thesis ○ Master's Project ○ Doctoral Dissertation

☐ I authorize the American University of Beirut to: (a) reproduce hard or electronic copies of my thesis, dissertation, or project; (b) include such copies in the archives and digital repositories of the University; and (c) make freely available such copies to third parties for research or educational purposes.

☒ I authorize the American University of Beirut, to: (a) reproduce hard or electronic copies of it; (b) include such copies in the archives and digital repositories of the University; and (c) make freely available such copies to third parties for research or educational purposes after:

One ---- year from the date of submission of my thesis, dissertation, or project.
Two ---- years from the date of submission of my thesis, dissertation, or project.
Three -✓- years from the date of submission of my thesis, dissertation, or project.

Zeinab Chamas January 30, 2019
Signature Date

ACKNOWLEDGEMENTS

First and foremost, I thank God Almighty for providing me this opportunity and the capability to proceed successfully.

I would like to deeply thank my supportive advisor Dr. Majdi Abou Najm who steered me in the right direction and provided me the needed help and guidance. I extend my sincere gratitude to my committee members: Prof. Ali Yassine for his valuable help in the model validation, Prof. Mahmoud Al Hindi for his invaluable contribution and Prof. Farook Hamzeh for his constructive input and comments.

I also acknowledge funding support of the University Research Board of the American University of Beirut.

My deepest gratitude goes to my family for supporting me and believing in me all the way and to my stress reliever, my fiancé, who never failed to inspire and motivate me. I wouldn’t be here if not for you.

Finally, I dedicate this dissertation to my late father and my beloved brother who never questioned my success and raised me to become who I am today.

AN ABSTRACT OF THE THESIS OF

Zeinab H. Chamas for Master of Engineering
Major: Environmental and Water Resources Engineering

Title: Water-Energy-Food-Carbon Nexus: An Optimization Approach

Pressures from rapidly growing populations and increased urbanization intensified the demands for water, energy and food. This increase in demands has caused overwhelming stress on natural resources; threatening global water, energy and food securities which are intrinsically intertwined. As growing demand and shrinking supplies have reached a critical point, the nexus concept between water, energy and food (WEF) evolved to assess the intertwining between those sectors in an effort to boost efficiencies of all nexus pillars. While the literature is rich with multiple frameworks and modelling schemes evaluating one or two of the WEF sectors, it lacks models that attempt to incorporate the three sectors simultaneously. As such, there is a need to develop a comprehensive mathematical model to optimize the full nexus. We address this challenge through the development of an optimization model that incorporates energy to an existing water-food optimization model by utilizing the resource footprint concept. This incorporation recognized the wide range of energy sources and the significant differences in their carbon footprint, leading to its incorporation as a significant component in the nexus. The model is distinguished from other tools in that it is based on the footprint concept, which assigns water, energy and carbon footprints for each optimum unit of resource produced or naturally generated. The model serves as an effective decision-making tool that enables policy makers to assess multiple WEF sources and recommend the optimum resource allocation under various policy, technology, and resource constraints. Serving as a comprehensive nexus tool, the model also allows to test different frameworks, targets and concepts such as the planetary boundary concept which constrains anthropogenic carbon generation to a recommended limit. Finally, the model was successfully validated using a hypothetical case study to test its efficiency under several resource availability scenarios and different policy targets.

CONTENTS

Chapter

Appendix

ILLUSTRATIONS

Figure Page

TABLES

CHAPTER I

INTRODUCTION

Pressures from rapidly growing populations and increased urbanization intensified the demands for water, energy and food (Bizikova et al., 2013). This increase in demands has caused overwhelming stress on natural resources, threatening global water, energy and food securities (Zhang et al., 2018) which are intrinsically intertwined (Liu et al., 2018) . For example, meeting water demands often requires energy inputs to match water quality guidelines, and generates emissions that are highly dependent on treatment processes and technology used (Bauer et al., 2014). In turn, treatment options vary with the location and quality of available water sources as well as desired water quality outputs, which are governed by water-use policies and regulations (Abdulbaki et al., 2017). Furthermore, water extraction and distribution require significant energy inputs (Brouwer et al., 2018). Food adds yet another layer of complexity requiring significant amounts of water (WWAP, 2012) and energy in nearly all food supply and production stages (El-Gafy, 2017). In fact, almost 30% of global energy is consumed in food production (FAO, 2011a) while some energy sources like biofuels require food (FAO, 2011a). To close the loop, and just as energy is needed to supply water, water plays an influential role in meeting energy and food demands. Approximately 70% of fresh water is withdrawn for agricultural purposes (WWAP, 2012) and 15% of water withdrawals were used for energy production in 2010 (WWAP, 2014).

As growing demands and shrinking supplies between water, energy and food (WEF) have reached a critical point, the nexus concept evolved to assess the interlinkages between those sectors to boost efficiencies of all nexus pillars. Since it was firstly presented at the 2011 Bonn Conference (Hoff, 2011), the WEF Nexus had been assessed from different perspectives. Several initiatives framed the nexus by focusing on policy implementations to reduce tradeoffs and increase synergies between the different nexus pillars (Endo et al., 2017; FAO, 2014b; Karabulut et al., 2018). (Daher & Mohtar, 2015) defined a framework based on the linkages between water, energy and food sectors. The authors developed a dynamic nexus modeling tool, offering policy makers a platform to assess resource demands based on food focused scenarios tested in Qatar (Daher & Mohtar, 2015). (Mortada et al., 2018) also developed a food focused model optimizing the composite water-agriculture, to ensure food security is being met within a constrained framework (Mortada et al., 2018). The model solves for an optimum agricultural policy that provides for an optimal food basket that satisfies the constraints from nutritional guidelines, food preferences, water resources, crop-water requirements, crop yields, climatic conditions, land resources and soil texture. The Climate, Land-Use, Energy, Water (CLEW) framework adds to the list of Nexus tools. Although it is not an independent model, it builds on existing planning tools providing a comprehensive illustration of the synergies within its sectors (Kaddoura & El Khatib, 2017). The baseline scenario, resembling the business as usual scenario, the carbon tax scenario and the 2 and 4-degree Celsius scenarios were developed to analyze those synergies (UN, 2017). Tailored to model a specific nexus area, the Water Evaluation and Planning system (WEAP) is a robust approach used in water planning (SEI, 2018), yet it cannot be solely used to address the full nexus for it lacks the integration of energy (Kaddoura & El Khatib, 2017).

This review of the literature around nexus modeling highlights a few gaps. In fact, most models abstract the nexus as a static resource-allocation problem whereas it is highly dynamic system in space and time. Climate change, pollution, population growth, and socioeconomic prosperity are among the most significant drivers of this dynamic system leading to increasing demands and decreasing supplies. Although climate change is not a primary nexus driver, it is highly interlinked with the three nexus pillars (Allouche et al., 2015) which are known to be climate sensitive sectors (Rasul & Sharma, 2016). Estimates indicate a decrease in groundwater recharge and crop yields by 70% and 30% respectively by 2050 in specific geographical regions (Baba et al., 2011; Rasul & Sharma, 2016). Fossil based energy production, and forestry and agriculture account for 57% and 24% of greenhouse gases emissions respectively (Edenhofer et al., 2011; Paustian et al., 2006). Therefore, generating a feedback loop between the nexus and climate change. Climatic changes, including temperature rise and precipitation alteration, induce changes in water availability and predictability (IPCC, 2007) leading to changes in agricultural productivity (Calzadilla et al., 2014). This in turn constrains food diversity and availability (Fanzo et al., 2018). As such, a dynamic nexus model must incorporate climate change by tracing and accounting for the emissions of greenhouse gases, mainly carbon dioxide, that result from adopted water, energy and food policies.

Another fundamental gap is the lack of consensus around defining water, energy and food securities and the scale dependencies associated with existing concepts. While some define resource security in terms of availability, accessibility and reliability (IRENA, 2015), others further expand this definition by adding scale dimensionality to it. Studies such as (Parthemore, 2010) examine resource security status from a national perspective and link natural resources availability to national security and stability. Other researchers consider it as a collaborative issue that must be tackled on a broader level. While an exact definition of resource security is still debatable, researchers agree that achieving security in one sector depends on other sectors security status (IRENA, 2015). For instance, water scarcity threatens both energy and food security, as it limits water availability for hydropower production and for irrigation. This dependency exacerbates the challenge of developing a model that commensurate with the already complex system. Although we acknowledge the added layers of complexity, we attempt to decipher these strained links and dubious concepts by the mean of optimization.

As the WEF nexus is an emerging concept, much effort is still being carried out to fully understand the inter-linkages between its sectors in a simplified way. While the literature is rich with multiple frameworks and modelling schemes evaluating the WEF sectors, it lacks models that attempt to optimize the use and allocation of the three sectors simultaneously while accounting for climate change and emissions. As such, there is a need to develop a comprehensive mathematical model to optimize the full nexus. We address this challenge through incorporating energy and carbon to an existing water-food optimization model developed by (Mortada et al., 2018). This incorporation recognized the wide range of energy sources and the differences in their carbon footprint, leading to its incorporation as a significant component in the nexus. As constraint, we recognize that climate change is one of the transgressed planetary boundaries (Rockström et al., 2009) and incorporate the planetary boundary concept to ensure that optimum WEF policies are within safe operating limits for humanity (Rockström et al., 2009). The model is distinguished from other tools in that it is based on the footprint concept, which assigns water, energy and carbon footprints for each optimum unit of resource produced or naturally generated. The model serves as an effective decision-making tool that enables policy makers to assess multiple WEF sources and recommend the optimum resource allocation under various policy, technology, and resource constraints. Serving as a comprehensive nexus tool, the model also allows to test different frameworks, targets and concepts such as the planetary boundary concept which constrains anthropogenic carbon generation to a recommended limit.

CHAPTER II

METHODOLOGY

A. Energy Security Definition

Ever since humans discovered the usefulness of fire as an energy source, energy became of significant importance for human survival and development (Zou et al., 2016). This increased the interest of nations to have a secure energy sector. Many attempted to defining energy security, yet there’s no consensus on what it exactly should be as it is highly context dependent (Ang et al., 2015). In the literature, researchers focus primarily on linking energy security to aspects related to the security of supply (Winzer, 2012). IEA defines energy security in terms of two components: energy availability and affordability (IEA, 2018), while other researchers argue for a more extended definition covering sustainable development (Laponche & Tillerson, 2001).

A thorough definition of energy security concepts is listed in table 1. In this paper, energy security will be defined in terms of energy availability because it is a common feature of all reviewed definitions and it tops all the concepts listed in table 1 (Barton, 2011). This definition is broadened to account for environmental concerns, to highlight the causality between energy security and climate change.

B. Model Components

The model optimizes the resource allocation at a regional scale. The region can contain multiple districts (d) with each having different climatic (r) and soil (s) conditions. For optimum nexus efficiency, the model differentiates between different resources at the crop (m, n), food (i, j), livestock (m', n'), land, water (u, v, w), and energy (e, f, g) levels.

Table 1.Energy security concepts

Aspect[a]	Concept	Definition
Physical	Availability[a] Accessibility[b]	Determined by the diversification of energy sources and supplies and the ability to provide uninterrupted supply
Economical	Affordability[a]	Determined by energy prices
Environmental	Acceptability[c] Sustainability[c]	Determined by the ability to satisfy current population demand without impeding the ability of future generation to meet their needs.

a (Ang et al., 2015)
b (Intharak et al., 2007)
c (Winzer, 2012)

1. Agriculture

Agriculture is a complex system. It is essential to define its components and boundaries to manage its water (u, v, w) and energy (e, f, g) inputs. Crops (m, n), livestock (m', n'), food (i, j) and land (TAL) form the agricultural components. Crop (m, n)/livestock (m', n') production starts and ends at the farm and is usually followed by the transport of products to the processing plant/slaughter house where the crop (m, n)/livestock (m', n') to food (i, j) conversion occurs, and is usually accompanied by losses. Food products are then packed and distributed to retailers and wholesalers to be purchased by consumers (figure 1).

Definitions, classifications and data of crop (m, n) and food (i, j) related components, including nutritional guidelines, groups and lists, were detailed in (Mortada et al., 2018). Moreover, Mortada et al. highlighted the various land resources (TAL) and their physical, biological and chemical components. They also accounted implicitly for the livestock sector for the need to calculate fodder crops demand and animal product food consumption. In our model, this sector will be further detailed for its significant contribution to the carbon cycle. Livestock (m’, n’) will be categorized based on the commonly consumed animal protein (FAO, 2014a), into five major groups which are: Cattle, Buffalo, Sheep, Goats, Pigs and Poultry. Each category is broken down to sub-categories determined by the production system employed. The Food and Agricultural Organization (FAO) defined in one of its reports livestock production systems, which differ mainly by animal diet, for their effect on livestock feed structure, yields and other animal related aspects (FAO, 2011b). Grazing and mixed are the prime production systems defined by FAO. In a grazing system, also known as solely livestock system, feed mainly comes from pastures, rangelands and forages, whereas in a mixed system more than 10% of feed come from crop by products (FAO, 1995). It is worth mentioning that, production systems and livestock categories along with climate influence feed composition (Mekonnen & Hoekstra, 2010) which is generally identified based on livestock nutritional needs rather on actual quantified feed (Smith, 1944). Several studies have identified livestock nutritional needs, but none have suggested a standardized animal diet while accounting for the animal’s nutritional intake. However, in their paper, (Mekonnen & Hoekstra, 2010) collected data from multiple sources and presented a country specific standardized animal diet which can be used in cases where data is not available.

Following crop cultivation and livestock breeding, is food processing. Processed food products are either vegetal based or animal based. Depending on the origin of the product, single or composite conversion occurs. While for vegetal foods, raw inputs, crops, are directly converted into consumable items, animal products follow a double phased conversion process. Crops are firstly transformed to feed for raising livestock which are then converted to food products.

This model aims at quantifying land (CL_{mndrsq}), energy (e, f, g) and water (u, v, w) consumed during the production (at the farm level) and processing stages (processing plant/slaughter house). Inputs of water (u, v) and energy (e, f, g) at the consumption level, for heating and cooking, are considered part of the per capita daily energy and water domestic demands.

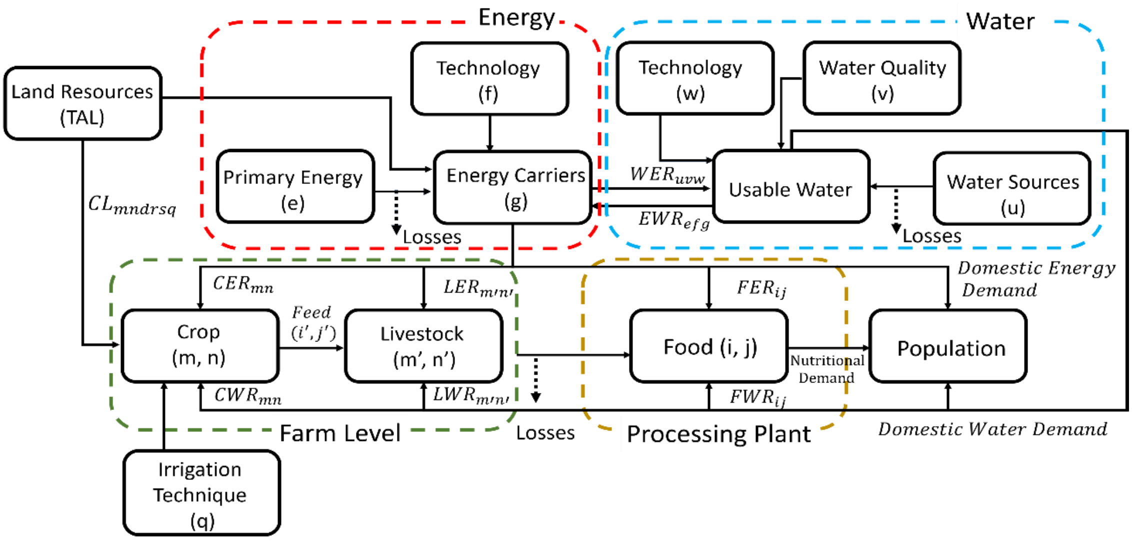


Figure 1. Simple model flowchart

2. Water

Water has an irreplaceable role in human survival and sustainable development (UN, 2018). To highlight its importance, the UNDP established the 6th sustainable development goal covering the entire water cycle (United Nations Educational, 2018). Although we acknowledge its significance, anthropogenic disturbances, including urbanization and climate change, continue to add pressures on the already stressed water resources (Matthews, 2016). These threats exacerbate the challenge of having a secure water sector and must be addressed by adopting effective water management strategies. The UN stresses the fact that there are enough water resources, but not proper management, to meet increasing water demands (WWAP, 2015). Therefore, managing water quality is key to enforcing a water security oriented approach. For instance, (IRENA, 2015) defines water security in terms of water quality, which is determined by water use guidelines (Abdulbaki et al., 2017), to emphasize the importance of water safety in a secure water sector. Besides abiding by water quality regulations, exploiting the full potential of different water sources is a useful water management practice. Tracking water origin allows improved utilization of green water (soil moisture) and leads to a decrease in blue water (surface and groundwater) demand (Mortada et al., 2018). Moreover, treating wastewater is crucial since the discharge of untreated wastewater into water bodies further aggravates water insecurity status.

a. Water Footprint

The water footprint concept (WF), introduced by (Hoekstra, 2003), combines direct and indirect freshwater use along supply chains. It is a multidimensional indicator, reflecting water consumption (green and blue water) and the degree of pollution, known as grey water, caused during the production of a commodity (Hoekstra et al., 2011). (Hoekstra et al., 2011) suggested two ways to calculate the WF of a product: the chain-summation approach and the stepwise accumulative approach. The latter is the generic approach as it quantifies the WF of a product by summing the WFs of all the input products to that of the last processing step. As grey water quantification is excluded from our analysis, water consumed will be referred to as virtual water or water requirements instead of water footprint.

b. Agriculture Water Requirements

Agriculture is the largest water consuming sector (Al-Ansari, 2015). Crops (m, n), livestock (m’, n’) and their derived food products (i, j) consume huge water amounts. Quantifying those amounts is crucial to building a robust WEF model.

As observed in figure 1, water consumption starts at the primary production level (farm level), where substantial water amounts are consumed to satisfy crop water requirements (CWR_{mn}) and livestock water requirements ($LWR_{m'n'}$). (Mekonnen & Hoekstra, 2011) presented a comprehensive study where they quantified the water footprint of crops and derived crop products using a grid-based dynamic water balance model. Blue, green and grey water footprints were estimated using the framework developed by (Hoekstra et al., 2011) and parameters needed for the calculation of green and blue water footprint in crop production were obtained from CROPWAT model. Blue and green crop water requirements global averages, quantified for several crop items, are summarized in appendix A.

Likewise, (Chapagain & Hoekstra, 2003) quantified livestock water requirements ($LWR_{m'n'}$) by summing direct water originating from drinking and servicing and indirect water from animal feeding. Although livestock drinking, and service water represent a relatively shrinking share of the overall water needed for livestock raising, it is still part of the analysis. (Mekonnen & Hoekstra, 2010) quantified drinking and service water requirements for animals raised in various farming systems and the results are summarized in appendix B.

Following crop cultivation and livestock breeding, water is then needed to meet food water requirements (FWR_{ij}) mostly consumed during the conversion of primary agricultural products to consumable food products. Although it is significantly lower than that consumed during primary production (Kirby et al., 2003), food processing is still among the largest water consuming industries (Compton et al., 2018). Few water-focused studies of the food processing phase exist. On the contrary, studies reporting water consumed as a bulk quantity for a food item, are relatively more common. Among those studies, is that conducted by (Mekonnen & Hoekstra, 2011) who quantified the blue, green and grey water footprint for derived crop products and the results are presented in appendix B.

c. Energy Water Requirements (EWRefg)

Processes used in converting renewable and nonrenewable energy sources (e) into available energy carriers (g) require various amounts of water (Gerbens-Leenes et al., 2008a) for fuel mining, energy facility construction and maintenance, and power plants cooling (Gleick, 1994). As seen in figure 1, the consumptive use of water varies with varying energy sources (e) and technologies (f). For example, crude oil consumes considerable amount of water compared to uranium (Gerbens-Leenes et al., 2008b) and renewable energy sources such as photovoltaic and wind turbines have minimal water consumption rates compared to hydroelectric plants (Gleick, 1994). Although some renewables require less water compared to conventional sources, others such as biomass and hydropower are water intensive alternatives. Hence, shifting towards renewable energy might exacerbate the pressure on water resources (Gerbens-Leenes et al., 2008a).

3. Energy

For an inclusive understanding of the energy sector, we begin by outlining the primary energy sources (e), the available technologies (f) used for harnessing energy and the different forms of energy carriers (g). Primary energy sources (e) are naturally found energy sources that have not been transformed or converted into man made energy form (Khaligh & Onar, 2018). They are grouped into two broad categories according to their renewal time after consumption. Fossil fuel such as coal, oil and natural gas, known as conventional energy sources, are nonrenewable sources whereas wind, water, solar radiation, biomass and geothermal energy are renewable. The use of non-renewable energy sources is constrained as much by the availability of fossil stocks as by the environmental impacts of these fuels. From here emerges the need to use a more sustainable energy source in terms of availability and emissions. Moreover, to extract fossil fuels and to harness energy from renewable sources, different technologies (f) are being used. Table 2 summarizes those technologies (f) with their respective end products known as energy carriers (g) which are electricity, heat and fuels, including solid, liquid and gaseous fuels (IPCC, 2007). Just like water, energy is needed in almost every activity of the WEF sector. A thorough quantification of energy requirements for agriculture and water sectors will be discussed in this section.

a. Agriculture Energy Requirements

In 1995, agriculture accounted for 3% of global energy consumption (Woods et al., 2010). An accurate quantification of energy consumed in the agri-food industry is challenging because it is highly affected by the type of product, the cultivated area, the farming practices and many other factors (Monforti et al., 2015). For example, organic farming systems are more energy efficient when compared to conventional systems (Woods et al., 2010). Moreover, certain activities require specific form of energy carriers (g). For instance, energy associated with crop production originates mainly from solar and fossil energy. The former is a naturally occurring transformation where plants convert solar energy into stored chemical energy and is not accounted for when quantifying crop energy consumption. Due to the over reliance on fossil energy, researchers focused on the use of conventional energy while disregarding the use of renewable energy when assessing energy used in crop production. In his handbook, Pimentel presented a detailed breakdown of all the energy required in an agricultural farm from direct energy inputs for farm operations to indirect inputs used in the production of machinery, fertilizers, pesticides and the construction of farm buildings (Pimentel, 1980). He also included the energy needed for propagation, liming, irrigation and raw material transportation.

By quantifying crop energy requirements (CER_{mn}), we have quantified a big chunk of livestock energy requirement ($LER_{m'n'}$), since energy consumed by livestock is mainly for feed production. However, many attempts to breakdown livestock energy requirements were reported. For example, (Woods et al., 2010) expressed the energy from feed, manure and litter, housing and direct energy use as percentages and concluded that around 70% of energy originate from feed.

Finally, to convert raw agricultural and animal products to consumable food products, large amounts of energy are required (FER_{ij}) (Compton et al., 2018). Canning, freezing, processing, and packaging are all processes occurring beyond the farmgate and known as post-harvest operations (Parikh & Syed, 1988). Due to their substantial energy share, these operations must be included in the analysis as they account for around 15% of the total energy used in developed countries (Parikh & Syed, 1988).

Table 2. Energy classification

Primary Energy Source	Technology	Energy End Product
Coal	Processing Combustion	Electricity Heat
Oil	Refining Process (Distillation)	Fuel [like Diesel] Electricity Heat
Natural gas	Processing	Fuel Electricity Heat
Water	Hydropower Wave	Electricity Electricity
Uranium	Fusion	Electricity
Solar	CSP Systems	Heat Electricity
	PV Systems	Electricity
Wind	Onshore wind turbine Offshore wind turbine	Electricity Electricity
Hydrogen	Electrochemical Cells	Battery
Geothermal	Wells	Electricity Heat
Biomass	Processing	Biofuels Electricity Heat

b. Water Energy Requirements (WERuvw)

Energy required for water production (WER_{uvw}) varies depending on the water supply source (u), its quality, the technology employed (w), and the quality of water output dictated by the end user (v) (Abdulbaki et al., 2017). For instance, if surface water is to be used, a combination of coagulation, flocculation and ultrafiltration will render it suitable for irrigation. Performing disinfection, as an additional step, will make it drinkable while approximately adding $2.6x10^{-4}$ KWh to the previously expended energy for every 1 m^3 of disinfected water (Plappally & Lienhard V, 2012). Moreover, using RO for seawater desalination requires 4-6 KWh per m^3 of desalinated water whereas MSF consumes roughly 19.5-27 KWh/m^3 (Al-Karaghouli & L. Kazmerski, 2013). A detailed review of energy consumption in the production, treatment, distribution, end use and disposal of water is presented by (Plappally & Lienhard V, 2012).

4. Carbon

a. Carbon cycle

Carbon is exchanged between five pools: oceanic, geological, atmospheric, pedologic and biotic (Lal, undated). The major interactions occur between the oceanic, atmospheric and terrestrial (pedologic and biotic) reservoirs (Al-Ansari, 2015). Prior to the industrial revolution, the carbon cycle formed a self-regulatory system. More than one third of atmospheric CO2 is absorbed by plants for photosynthesis (Prentice et al., 2001). Half of it is returned to the atmosphere by autotrophic respiration and the other half, known as the net primary production (NPP), is fixed by plants and used for plant growth. Eventually, almost all NPP is released back to the atmospheric pool by either heterotrophic respiration or human interventions such as harvest. But since there is a time lag between the respired and fixed CO2, in the absence of significant disturbances, CO2 remaining in the terrestrial ecosystem will surpass the rate of returning CO2 to the atmosphere, increasing by such CO2 land uptake (Prentice et al., 2001). In addition, the oceanic pool forms a major sink for CO2. CO2 absorbed by the ocean is approximately 50 times greater than that found in the atmosphere (Prentice et al., 2001). Hence, in the absence of human disturbances, carbon is naturally sequestered by the terrestrial and aquatic reservoirs (Lal, undated). Figure 2 illustrates the natural carbon cycle, before human intervention. Today, humans are altering this system through excessive burning of fossil fuels and through land use change or more specifically deforestation (Schlesinger & Bernhardt, 2013) (figure 3).

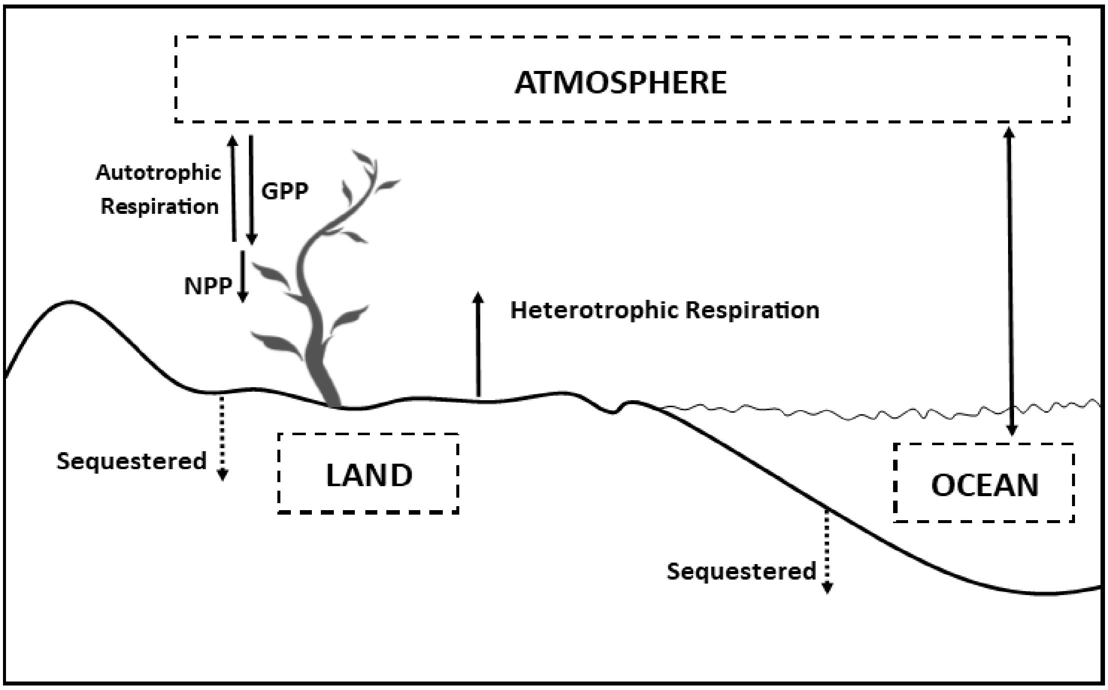


Figure 2. Natural carbon cycle

About half the emissions from fossil fuel burning are absorbed by the terrestrial biosphere or dissolved in the ocean. Thus, continuous anthropogenic disturbances of either the terrestrial biosphere or the ocean will ultimately induce a change in the functionality of these natural CO2 sinks (Prentice et al., 2001).

Moreover, emissions from agricultural activities such as livestock breeding, aggravate the global warming potential by adding CO_2, CH_4 and N_2O to the atmospheric GHG budget (Pulselli & Marchi, 2015). Knowing its strong impact on climate change, actions must be taken to reduce the increasing rate of atmospheric CO_2 (Lal, undated). This is done by accounting for the effects of human caused perturbations on the carbon cycle and by adding Carbon as a fourth major nexus player.

b. Sources of Emissions

Human disturbances are continuously causing an increase in GHG emissions, contributing to global warming. Although Carbon dioxide is the major global warming contributor, accounting for 75% of GHG emissions (IPCC, 2014), other GHG, like methane and nitrous oxide, substantially increase global warming. These emissions result from various activities of which burning fossil fuels and deforestation make the largest shares.

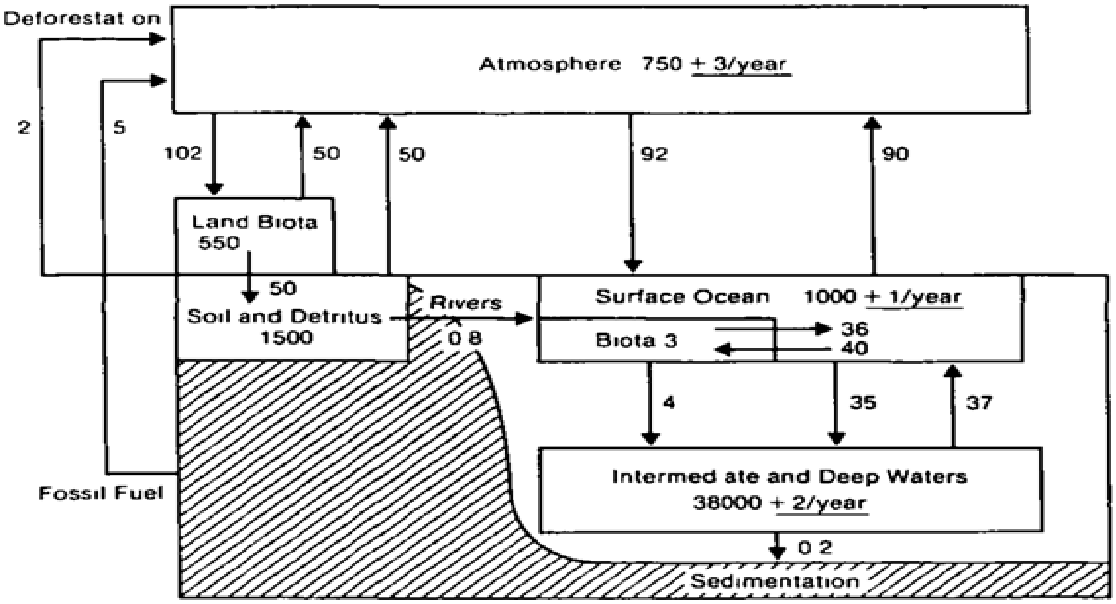


Figure 3. The carbon cycle after human intervention

In this model we will account for emissions from the agriculture and energy sectors. According to the Food and Agricultural Organization (FAO) (Tubiello et al., 2014), emissions from agricultural processes originate from various sub-categories of which the following are included in the methodology:

- Applied fertilizers
- Manure managed and deposited on pasture (untreated)
- Livestock raising (enteric fermentation)
- Land use change (deforestation)
- Rice cultivation
- Burning Savannahs

The IPCC presented in its guidelines for national greenhouse gas inventories, a detailed methodology to estimate these emissions (De Klein et al., 2006; Ipcc, 2006) (appendix C).

The model also accounts for emissions from the energy sector resulting from fossil extraction, refining and production as well as emissions from energy used for water, domestic and agricultural purposes. These emissions perturbate the carbon pools by increasing inputs to the atmospheric carbon budget and hence contributing to climate change. CO_2 emission factors vary according to energy source as well as technology used. IPCC reported in one of its special report on renewable energy sources and climate change mitigation, aggregated values of greenhouse gas emissions (Edenhofer et al., 2011).

5. Population

Population is a main nexus driver, for its growth increases the demand for water, energy and food. As population is expected to reach 9.7 billion by 2050 (UN, 2015), understanding and targeting the challenges that are likely to arise is key to sustaining our natural resources. This can be done by responding to population needs while securing our resources. For instance, a shift in diet is recommended if it reduces water and energy requirements while still providing the population with all its nutritional needs. This model accounts for domestic energy and water demands in the most optimum way while ensuring that population achieves its nutritional demands (figure 1).

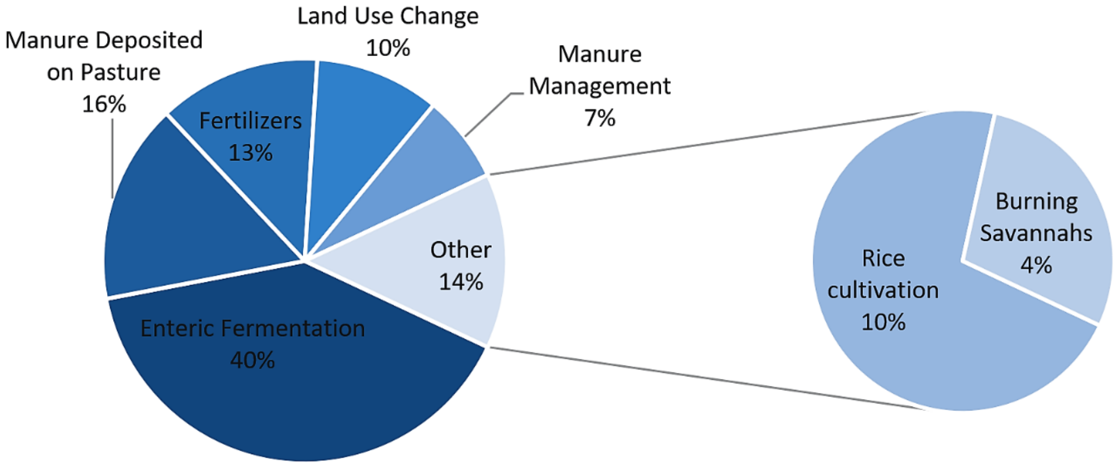


Figure 4. GHG emissions from agriculture

6. *Land*

In their model, Mortada et al. attributed a land cost for crop cultivation. To highlight the competition on land resources, our model also accounts for land costs associated with energy production. (Schechtman, 2011) grouped energy sources, according to their land use intensity, into three categories with biofuels belonging to the most land intensive category. A review of land footprint related to various energy sources was presented in (UNCCD & IRENA, 2017) and will be used later on in our case study.

C. Model Formulation

Here we define the model decision variables, objective functions (O.F) and constraints used to secure water, energy and food resources. Figure 5 presents a simplified version of the model framework. User inputs related to population, natural and technical influencing factors as well as resource availability, are processed according to objective functions and constraints. Regardless of the objective function, the model calculates demands for food and its related components as well as energy and water while accounting for carbon emissions. The model will ultimately find the most optimum way for resources production and trade while respecting imposed limits. Figure 6 shows a more detailed model flowchart.

The main components introduced by Mortada et al. remain unchanged as our model builds on the previously developed model. As discussed earlier, the model is deemed to be governed in space and time. Spatially, the model has fine and coarse resolution to provide results from district to regional scales. Temporally, the model deals with different time scales relating to parameters expressed in various time units. For example, precipitation is expressed as monthly averages whereas irrigation requirements are addressed on a weekly or daily basis. These scales also apply to the newly added parameters, as energy availability is space and time specific depending on climatic conditions as well as on existing energy resources within the borders of the area under study.

1. Model Decision Variables

Table 3 summarizes the previously introduced decision variables relating to crop and food. Energy related decision variables will be added, and feed, livestock and water will be explicitly expressed in our model.

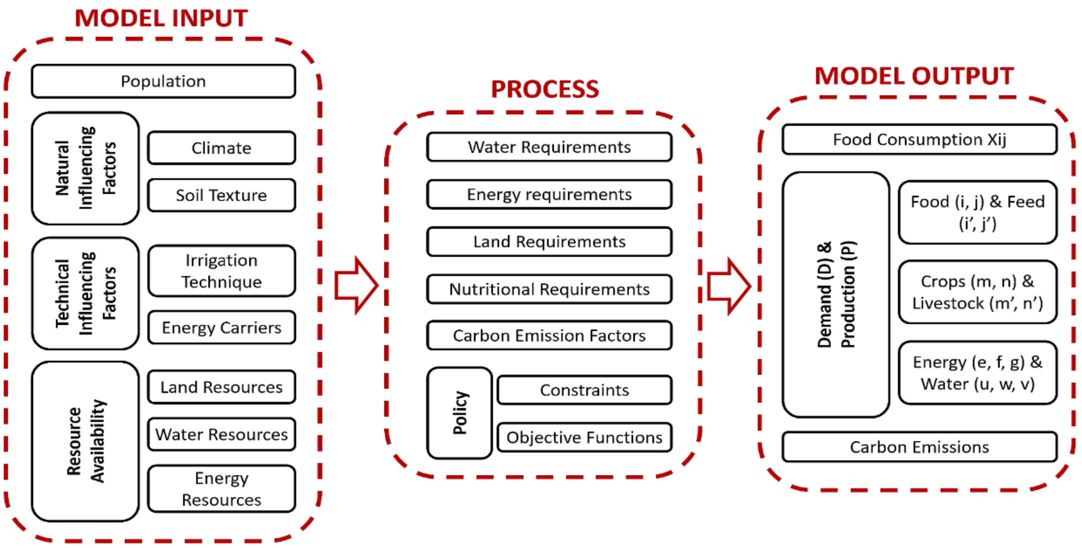


Figure 5. Simple model framework

a. Feed Consumption Decision Variables

$D_{i'j'}$, $P_{i'j'}$, $IMP_{i'j'}$ and $EXP_{i'j'}$ are respectively demand, production, import and export quantities of feed items (i', j') per year in (ton/year). Given that i' ∈ $\{1;\ 2;\ \ldots;\ I'\}$ is the index of feed groups, I' is the total number of feed groups, j'∈ $\{1;\ 2;\ \ldots;\ J'\}$ is the index of feed items belonging to feed group i' and J'(i') is the total number of feed items in group i'.

b. Livestock Policy Decision Variables

$D_{m'n'}$, $P_{m'n'}$, $IMP_{m'n'}$ and $EXP_{m'n'}$ are respectively national domestic demand, production, import and export quantities of livestock (m'; n') per year in (head/year). Given that m' ∈ $\{1;\ 2;\ \ldots;\ M'\}$ is the index of livestock groups, M' is the total number of livestock groups, n' ∈ $\{1;\ 2;\ \ldots;\ N'\}$ is the index of livestock type belonging to livestock group m' and N'(m') is the total number of animals in group m'.

c. Water Decision Variables

$P_{u,v,w}$ is a primary decision variable and represents the production of water from source u $\in \{1;\ 2;\ \ldots;\ U\}$ for use v or having quality v $\in \{1;\ 2;\ \ldots;\ V\}$, using technology w $\in \{1;\ 2;\ \ldots;\ W\}$, expressed in ($m^3$/year). D_u and D_v are respectively demand of water from source u and demand of water for use v, expressed in (m^3/year). It is worth mentioning that water trade is not expressed in our model.

Table 3. Mortada et al. decision variables

Decision Variable	Unit	Definition
X_{ij}	g/day/capita	Food consumption variables, corresponding to food item j belonging to food group i
D_{ij}, P_{ij}, IMP_{ij}, EXP_{ij}	ton/year	Food policy variables: domestic demand D_{ij}, production P_{ij}, import IMP_{ij} and export EXP_{ij} , corresponding to food item j belonging to food group i
Pmn, Dmn, IMPmn, EXPmn	ton/year	Crop policy variables: production P_{mn}, domestic demand D_{mn}, import IMP_{mn} and export EXP_{mn} , corresponding to crop n belonging to crop group m
P_{mnd}	ton/year	Crop production variable: production quantity corresponding to crop item n belonging to crop group m grown in district d
P_{mndrsq}	ton/year	Crop production variable: production quantity corresponding to crop item n belonging to crop group m grown in district d having a climate r and a soil s using irrigation technique q

d. Energy Decision Variables

P_{efg} is the production quantity of energy form $g \in \{1;\ 2;\ \ldots;\ G\}$ derived from source $e \in \{1;\ 2;\ \ldots;\ E\}$ using technology $f \in \{1;\ 2;\ \ldots;\ F\}$ expressed in varying units for every e and g. D_e, P_e, IMP_e, EXP_e are respectively demand, production, import and export of energy source *e*. D_g, P_g, IMP_g, EXP_g are respectively demand, production, import and export of energy form g.

2. Model Objective Functions

The problem may be tackled using different objective functions tailored to address a single sector or a combination of two or more sectors. Objective functions focusing on the scarcest resource in the area under study might also be defined.

a. First Approach: Optimize Water Security

This approach favors items with lower water requirements. Equation 1 illustrates this minimization function

$$
\begin{aligned}
Minimize \quad & \sum_{e=1}^{E}\sum_{f=1}^{F}\sum_{g=1}^{G} P_{efg} \times EWR_{efg} + \sum_{i=1}^{I}\sum_{j=1}^{J} P_{ij} \times FWR_{ij} \\
& + \sum_{m'=1}^{M'}\sum_{n'=1}^{N'} livestock\ population_{m'n'} \times LWR_{m'n'} \\
& + \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{q=1}^{Q} P_{mndrsq} \times \frac{BWF_{mndrsq}}{Irrigation\ Efficiency_q}
\end{aligned}
\qquad 1)
$$

Where EWR_{efg} , FWR_{ij} , $LWR_{m'n'}$ are respectively water requirements for energy carrier g derived from energy source e using technology f, water requirements for food (i, j) and for livestock (m’, n’). BWF_{mndrsq} , as defined by Mortada et al., is the blue water footprint for crop (m, n) cultivated in district d having a climate r and a soil s and using irrigation technique q and is obtained by subtracting Green water from CWR_{mn}.

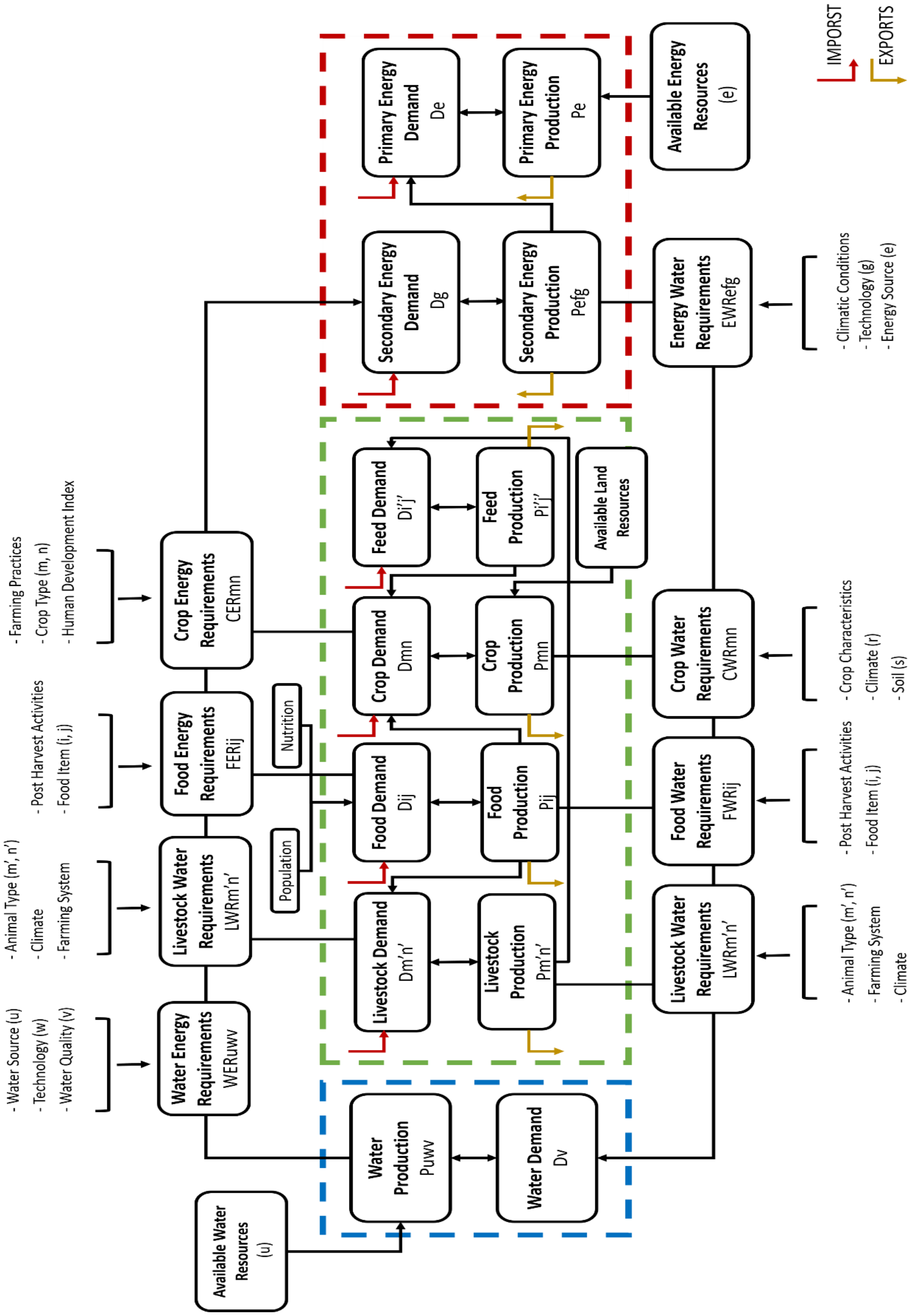


Figure 6. Detailed model flowchart

b. Second Approach: Optimize Energy Security

Similar to optimizing water security, a function aiming at optimizing energy security was developed.

$$\begin{aligned} Minimize \quad & \sum_{u=1}^{U}\sum_{v=1}^{V}\sum_{w=1}^{W} P_{uvw} \times WER_{uvw} + \sum_{i=1}^{I}\sum_{j=1}^{J} P_{ij} \times FER_{ij} \\ & + \sum_{m=1}^{M}\sum_{n=1}^{N} P_{mn} \times CER_{mn} + \sum_{m'=1}^{M'}\sum_{n'=1}^{N'} P_{m'n'} \times LER_{m'n'} \\ & + P_{fertilizers} \times Fertilizers\ Energy\ Requirements \end{aligned} \qquad 2)$$

Where WER_{uvw} , FER_{ij} , CER_{mn} and $LER_{m'n'}$ are respectively water energy requirements, food energy requirements, crop energy requirements and livestock energy requirements. $P_{fertilizers}$ is the quantity of synthetic and organic fertilizers applied.

c. Third Approach: Minimize Total Carbon Consumption

The third approach aims at limiting carbon emissions from the agriculture and energy sectors by restricting the transgression of its corresponding planetary boundary. As such, this function favors renewable energy for its low emission factors and it also favors less energy intensive items.

$$\begin{aligned} Minimize \quad & Energy\ Emissions_{efg} + Livestock\ Emissions_{m'n'} \\ & + Fertilizers\ Emissions + Land\ Use\ Change\ Emissions \\ & + Rice\ Cultivation\ Emissions \\ & + Burning\ Savannahs\ Emissions \end{aligned} \qquad 3)$$

All terms in equation 3 are detailed in chapter two and appendix C.

3. Model Constraints

Table 4 summarizes the previously defined model constraints by Mortada et al. which will be used unmodified in our model. It is worth mentioning that Mortada et al. also used a wide range of constraints to cover food preferences and socioeconomic constraints which are not covered in this paper.

The following set of equations present the newly added constraints. Equation 18 was derived from Mortada et al. and modified to account for the additional model components.

a. Balance Constraints

i. Feed Demand Constraints

$$D_{i'j'} = \frac{\sum_{m'=1}^{M'} \sum_{n'=1}^{N'} \left(X_{i'j',m'n'} * Livestock\ population_{m'n'} \right)}{\left(1 - waste\ factor_{\ i'j'}\right)\left(1 - loss\ ratio_{i'j'}\right)} \qquad \forall\, i' \,\&\, j' \quad (4)$$

where $X_{i'j',m'n'}$ is the quantity of feed (i’, j’) required for livestock (m’, n’) in ton per head per year; $loss\ ratio_{i'j'}$ and $waste\ factor_{\ i'j'}$ are losses occurring when converting crops to feed.

A feed balance constraint is added, assuming the storage change is zero

$$P_{i'j'} + IMP_{i'j'} - EXP_{i'j'} = D_{i'j'} \qquad \forall\, i' \,\&\, j' \quad (5)$$

ii. Crop-Food, Crop-Feed and Livestock-Food Relating Constraints

Mortada et al., computed the domestic demand on crop (m, n), (D_{mn}), needed for food production (P_{ij}) by introducing matrix $A = [a_{m\,n,i\,j}]$ where $a_{m\,n,i\,j}$ is the amount of crop (m, n) needed to produce a unit weight of food item (i, j). In our model, feed production ($P_{i'j'}$) will also be linked to (D_{mn}) by using matrix $A' = [a_{m\,n,i'\,j'}]$ where $a'_{m\,n,i'\,j'}$ is the amount of crop (m, n) needed to produce a unit weight of feed (i', j') and is determined according to FAO's technical conversion factors for agricultural commodities (FAO, 1972).

$$(D_{mn}) = A \times (P_{ij}) + A' \times (P_{i'j'}) \qquad \forall\, m, n, i, j, i' \& j \quad (6)$$

Similar to (D_{mn}), livestock demand ($D_{m'n'}$) will be computed using matrix $B = [b_{m'n',i\,j}]$ linking animal based food items to their livestock origin, where $b_{m'n',i\,j}$ is the number of heads of livestock (m', n') needed to produce a unit weight of food item (i, j).

$$(D_{m'n'}) = B \times (P_{ij}) \qquad \forall\, m', n', i \,\&\, j \quad (7)$$

The livestock balance constraint is expressed as follows:

$$P_{m'n'} + IMP_{m'n'} - EXP_{m'n'} = D_{m'n'} \qquad \forall\, m' \,\&\, n' \quad (8)$$

iii. Water Demand Constraints

Total water demand is calculated by summing water demands for the agriculture, energy and domestic sectors each requiring a unique water quality v (D_v):

$$Total\ water\ demand = \sum_{v=1}^{V} D_v \qquad \forall\, v \tag{9}$$

Knowing that water trade is not allowed in our model, the water balance equation is the following:

$$Total\ water\ demand = Total\ water\ production$$

$$= \sum_{u=1}^{U}\sum_{v=1}^{V}\sum_{w=1}^{W} P_{uvw} \qquad \forall\, u, v\ \&\ w \qquad 10)$$

Finally, when computing water demand from source u (D_u), we must account for technology-specific losses by applying the following equation:

$$D_u = \sum_{v=1}^{V}\sum_{w=1}^{W} P_{uvw} \times (1 + loss\ factor_{\ w}) \qquad \forall\, v\ \&\ w \tag{11}$$

where $loss\ factor_{\ w}$ represents the losses occurring when producing water using technology w, expressed in %.

iv. Energy Demand Constraints

In this model, energy production and demand will be computed on two levels:

- Primary energy level (e)
- Secondary energy level, represented by energy carrier (g)

Energy demand at the primary level (De) is calculated by accounting for energy losses occurring when converting primary energy to secondary energy (g), using technology (f)

$$D_e = \sum_{f=1}^{F}\sum_{g=1}^{G} [\, P_{efg} \times \frac{1}{Conversion\ Factor_{efg}}] \qquad \forall\, e, f\ \&\ g \tag{12}$$

where $Conversion\ Factor_{efg}$ links primary energy demand (D_e) with the production of energy carrier (g) and is affected by the technology employed (f) and the primary energy source (e).

Energy balance at the primary level is added as follows:

$$P_e + IMP_e - EXP_e = D_e \qquad \forall\, e \quad (13)$$

Moving to the secondary level, we introduce two balance constraints:

- For every energy carrier (g), the summation of energy production from various primary sources (e) is equal to the total production of secondary energy (g)

$$P_g = \sum_{e=1}^{E}\sum_{f=1}^{F} P_{efg} \qquad \forall\, e, f\ \&\ g \quad (14)$$

- Energy balance at the secondary level is also added as a constraint:

$$P_g + IMP_g - EXP_g = D_g \qquad \forall\, g \quad (15)$$

Where (D_g) is calculated by summing energy demands from all WEF sectors.

b. Resource Constraints

i. Land Constraints

Just like crop production, energy production has a land cost which will be expressed using the following equation:

$$Land\ for\ Energy = \sum_{e=1}^{E}\sum_{f=1}^{F}\sum_{g=1}^{G} Land\ for\ Energy_{efg} \times P_{efg} \qquad \forall\ e, f\ \&\ g \quad (16)$$

where $Land\ for\ Energy_{efg}$ is expressed in ha per quantity of secondary energy (g) produced using technology (f).

Furthermore, a constraint will be added to ensure that land used for energy and crop production does not exceed the total available land in the region under study:

$$Land\ for\ energy + TCL \ \leq TAL \qquad (17)$$

ii. Water and Energy Constraints

In the model, the demand for water from source u (D_u) is limited by water availability from source u.

$$D_u \ \leq \text{Available water from source u} \qquad \forall\ u \quad (18)$$

Likewise, to guarantee that energy production from source (e) does not exceed available energy (e) we introduce the following constraint:

$$P_e \ \leq \text{Available energy from source e} \qquad \forall\ e \quad (19)$$

c. Planetary Boundary Constraint

As mentioned in section 2.2.4.2, the model accounts for CO_2 emissions from the agriculture and energy sector. Hence, total CO_2 emissions are computed as per equation (32), in ton CO_2/year, and should not exceed the planetary boundary of 1.61 ton/capita/year set by (O’Neill et al., 2018):

$$Total\ CO_2\ emissions = Agriculture\ Emissions + Energy\ Emissions$$

$$\leq 1.61 \times \text{population} \qquad 20)$$

where

$$\begin{aligned} Agriculture\ Emissions \\ &= Livestock\ Emissions + Fertilizers\ Emissions \\ &+ Land\ Use\ Change\ Emissions \end{aligned} \qquad 21)$$

and

$$Energy\ Emissions = \sum_{e=1}^{E}\sum_{f=1}^{F}\sum_{g=1}^{G} P_{efg} \times Emission\ Factor_{efg} \qquad (22)$$

Where $Emission\ Factor_{efg}$ is expressed in ton CO_2 per unit of energy carrier (g) produced from energy source (e) using technology (f).

Table 4. Mortada et al. constraints

Type	Constraint
Balance Constraints	$D_{ij} = \frac{X_{ij} * population * 365.25}{10^6 * \ (1 - waste\ factor_{\ ij})(1 - loss\ ratio_{ij})} \quad \forall\ i\ \&\ j$ 23) $P_{ij}\ + IMP_{ij}\ -\ EXP_{ij}\ =\ D_{ij} \quad \forall\ i\ \&\ j$ 24) $P_{mn}\ + IMP_{mn}\ -\ EXP_{mn}\ =\ D_{mn} \quad \forall\ m\ \&\ n$ 25) $P_{mn} = \sum_{d=1}^{D} P_{mnd} \quad \forall\ m\ \&\ n$ 26) $P_{mnd} = \sum_{r=1}^{R} \sum_{s=1}^{S} \sum_{q=1}^{Q} P_{mndrsq} \quad \forall\ m, n\ \&\ d$ 27)
Nutritional Constraints	$Calorie\ intake_{av} = \frac{\sum[Calorie\ intake\ by\ Age\ Group \times Age\ Group\ Count]}{Population}$ 28) $L_k \leq \sum_{i=1}^{I} \sum_{j=1}^{J(i)} \frac{NTR_{ijk}}{100} * \left(Edible\ portion\ of\ X_{ij}\right) \leq U_k \quad \forall\ k\ \epsilon\ 1; 2; \ldots.; K = 16$ 29) $Min\ intake_{\ i} < \sum_{j=1}^{J(i)} X_{ij} < Max\ intake_{\ i} \quad \forall\ i\ \epsilon\ food\ groups\ covered\ by\ AHA$ 30) $Diet\ energy\ density = \left(\sum_{i=1}^{I} \sum_{j=1}^{J(i)} \frac{NTR_{ij(k=1)}}{100}\ *\ X_{ij} \right) / \left(\sum_{i=1}^{I} \sum_{j=1}^{J(i)} X_{ij} \right)$ 31)
Resource Constraints	$\frac{P_{mndrsq}}{PYIELD_{mn}}\ =\ CL_{mndrsq} \quad \forall\ m, n, d, r, s\ \&\ q$ 32) $\sum_{m=1}^{M} \sum_{n=1}^{N(m)} \sum_{q=1}^{Q} CL_{mndrsq}\ \leq CL_{drs} \quad \forall\ d, r\ \&\ s$ 33) $\sum_{d=1}^{D} \sum_{r=1}^{R} \sum_{s=1}^{S} CL_{drs}\ = TCL$ 34)

To account for CO_2 emissions from land use change, the model should first determine whether any forestland is converted to cropland. This can simply be done by using the following if statement:

If (F >0, F, 0) where F = forestland+ land for energy +TCL – TAL with forestland expressed as a percentage of TAL.

For simplification, and since we are using LP, we added two decision variables to the model which are Z and α by introducing a set of constraints replacing the if function.

$$Z \geq 0$$

$$Z \geq F$$

$$Z \leq M\alpha$$

$$Z \leq F + M(1 - \alpha)$$

Where M is a very large positive number and α is a binary integer variable ∈ (0;1) such that:

$$\alpha = \begin{cases} 1, & if\ F \geq 0 \quad\quad \equiv we\ have\ deforestation \\ 0, & if\ otherwise \ \equiv no\ deforestation \end{cases}$$

Thus, emissions from land use change can then be computed as follows:

$$Land\ Use\ Change\ Emissions = Z \times 302$$

Where 302 is the amount of CO_2 lost in ton CO_2/ha/year when converting forestland to cropland (EPA, 2018).

d. Non Negativity Constraint

All decision variables are non-negative.

CHAPTER III

VALIDATION WITH HYPOTHETICAL CASE STUDY

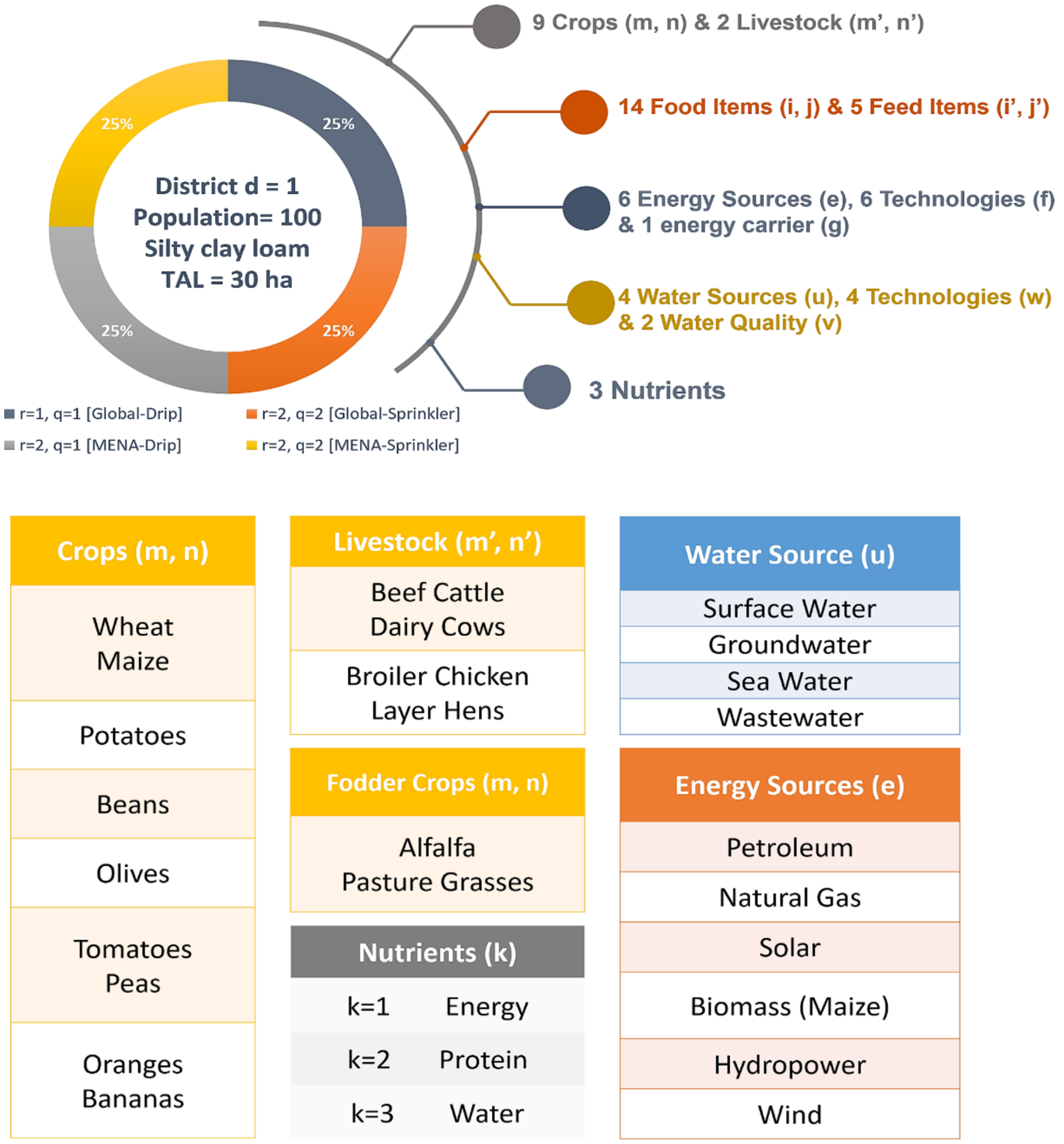
A. Case Study Description

The model was validated using a generic case study composed of limited variables. To run the model, we used Excel Premium Solver platform.

The study area is a small sized district with a total population of 100 inhabitants, composed of two equally distributed climatic regions (r), region 1 (r_1, global averages were used) and region 2 (r_2, data from the MENA region was used). A unified soil type (s=silty clay loam) was assumed for both regions and two irrigation techniques were employed, q_1 = sprinkler and q_2 = drip with 90% and 75% efficiencies respectively. We have only considered three nutrients for simplicity, total water, total calories and protein intakes, as shown in figure 7. Lists of crops, livestock and fodder crops are presented in figure 7, as well as energy and water sources. Detailed lists are presented in appendix D.

It is worth mentioning that Mortada et al. calculated crop water requirements for each climatic region r using CROPWAT model, whereas in our model we will use averages by summing the blue and green water components of the crop WF obtained from (Mekonnen & Hoekstra, 2011), to represent the CWR_{mn} , in m^3/ton of product.

It is also noteworthy that land resources, comprising used and unexploited arable land, will be used as outlined and categorized in Table 5. For simplification, pastureland will be added to cropland, forming total available land for cultivation which will be equal to total available land, assuming any available land is suitable for cultivation or energy production. Assuming 30 ha of total available land (TAL), forestland will be set to be 5% of (TAL) (1.5 ha).



Crops (m, n)
Wheat Maize
Potatoes
Beans
Olives
Tomatoes Peas
Oranges Bananas

Livestock (m', n')
Beef Cattle Dairy Cows
Broiler Chicken Layer Hens

Fodder Crops (m, n)
Alfalfa Pasture Grasses

Nutrients (k)	
k=1	Energy
k=2	Protein
k=3	Water

Water Source (u)
Surface Water
Groundwater
Sea Water
Wastewater

Energy Sources (e)
Petroleum
Natural Gas
Solar
Biomass (Maize)
Hydropower
Wind

Figure 7. Case study description

All constraints will be integrated in this case study to address the three objective functions detailed in chapter two.

Table 5. Arable land classification

Land Form	Definition
Cropland	Land allocated for crops cultivation[a]
Pastureland	Land allocated for livestock grazing[a]
Forestland	Land covered by trees and not used for other purposes[a]
Total Available Land	The total of areas under cropland, pastureland and forestland

B. Results and Sensitivity Analysis

In this section, we report the results of various scenarios tested under multiple conditions and policies. The tested scenarios are illustrated in table 6. Three objective functions were tested:

- O.F 1: minimizing total water consumption;
- O.F 2: minimizing total electricity consumption; and
- O.F 3: minimizing CO_2 emissions.

Table 6. Tested Scenarios

	Baseline Scenario	Scenario 1: Food Variety Scenario	Scenario 2: Trade Policy Scenario	Energy Policy Scenario		Scenario 5: Land Scenario
				Scenario 3	Scenario 4	
Available Water	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant
Food Variety	Not Imposed	Imposed	Imposed	Not Imposed	Not Imposed	Not Imposed
Trade	Not Allowed	Not Allowed	Allowed	Limited	Limited	Limited
Available Energy	Abundant Fossil & Renewables	Abundant Fossil & Renewables	Abundant Fossil & Renewables	70% Renewables	100% Renewables	Abundant Fossil & Renewables
Available Land (ha)	30	30	30	30	30	30 - 0

1. Baseline Scenario

We first introduce the baseline scenario, by assuming abundant resources, so production is expected to meet demand with no trade being allowed (exports and imports are set to zero). With 30 ha of available land, equally distributed among two climatic regions along with abundant energy and water resources, we obtained the results summarized in table 7.

Table 7. Baseline scenario summary results

		O.F 1	**O.F 2**	**O.F 3**
Food Consumption X_{ij} (g/capita/day)	Flour of maize	270	611	138
	Potatoes	1,991	0	813
	Beans [dry]	22.89	47.69	250
	Oranges	0	0	1,299
	Peas	91.81	166	0
	Water, tap, drinking	2,000	3,000	2,000
Resources	Total water consumed (m^3/year)	**14,688**	25,963	39,292
	Total electricity consumed (KWh/year)	1,083,636	**1,064,335**	1,092,279
	Total land used (ha/year)	8.93	9.63	19.18
	Total CO_2 emissions (ton CO_2 eq /year)	157	151	**129**

As shown in table 7, the model produced selective food items because we did not impose food variety or food preferences constraints/limitations on X_{ij} , so the model will try to satisfy the nutritional constraints by minimizing the use of resources and hence by favoring the least energy and water intensive food items. Only 5 out of 13 food items were produced under this scenario. Moreover, no animal source foods were produced when animal-based food items were not forced into the model, and thus no feed was produced. This demonstrates the inefficiency of animal-based food items in terms of water and energy requirements.

When testing O.F 1, the model produced food items with the best combination of nutritional values and water consumption instead of solely producing least water intensive items. For instance, tomatoes require less water for irrigation (63 m^3/ton) compared to maize (81 m^3/ton), yet the model favors the production of maize because it has 20 times more energy (361 Kcal/100g) compared to tomatoes (18 Kcal/100g). Similar observations were noted when testing O.F 2, where production of food items was not solely based on least energy intensive items (per unit weight). Although O.F 3 minimizes CO_2 emissions, we observe an increase in energy consumption which is reasonable because CO_2 emissions, as explained in chapter II, are not only from energy but also from agriculture including applied fertilizers which are crop and land dependent.

As water resources are abundant here, the model fully gets its water needs from surface water under the three objective functions, because it requires less energy and hence emits less CO_2 compared to other resources.

When minimizing water consumption (O.F 1), the model produces all energy needed from wind for it has zero water cost compared to other energy sources. Whereas under O.F 3, the model exhausts energy from hydropower before producing energy from wind because hydropower has the lower CO_2 emissions compared to wind (figure 8).

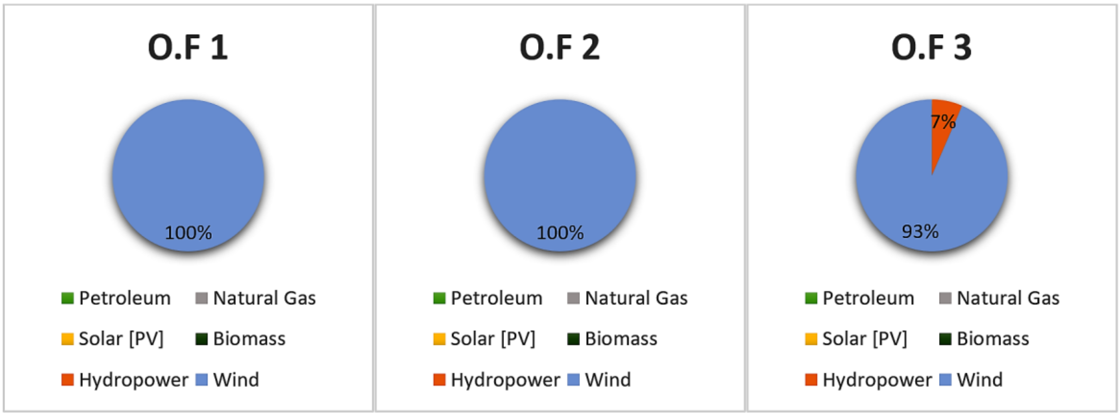


Figure 8. Energy consumption under baseline scenario

2. Scenario 1: Food Variety Scenario

Scenario 1 was formed by adding a constraint on average consumption variables (X_{ij}) to the previous scenario, to ensure that for any food item (i, j), X_{ij} will be at least 30 percent of its global average consumption obtained from FAOSTAT global food balance sheets (FAOSTAT, 2017).

$$X_{ij} \geq 0.3 \times Average\ Consumption\ of\ Food\ Item\ (i, j) \qquad \forall\ i\ \&\ j$$

Although we imposed an additional constraint to ensure food variety, the model sticks to producing the lower limit imposed on inefficient water and energy food items, while considerably exceeding that of efficient food items in terms of water and energy as shown in table 8. Unlike the baseline scenario, feed is being produced for raising livestock which appeared since animal-based food items are part of the optimum food basket in this case. Crops are cultivated in climatic regions where less water is needed.

Total water consumed under the three objective functions slightly differs and the model fulfills its water demand from surface water, for its abundant (200,000 m^3).

Similar to the baseline scenario, the model produces all its energy demand from wind under O.F 1 and O.F 2, whereas it exhausts hydropower energy before producing energy from wind under O.F 3.

Table 8. Scenario 1 summary results

		O.F 1	**O.F 2**	**O.F 3**
Food Consumption X_{ij} (g/capita/day)	Flour of wheat	125	125	125
	Flour of maize	184	482.7	58
	Potatoes	1,629	65.53	1,124
	Beans [dry]	4.78	4.78	144
	Olive oil, virgin	0.77	0.77	0.77
	Tomatoes	39.49	39.49	39.49
	Peas	1.59	1.59	1.59
	Oranges	23.76	23.76	746
	Bananas	23.55	23.55	23.55
	Beef and veal, boneless	17.87	17.87	17.87
	Chicken meat	28.75	28.75	28.75
	Cow milk, whole, fresh	173	173	173
	Chicken eggs, with shell	17.62	17.62	17.62
	Water, tap, drinking	2,000	2,805	2,000
Resources	Total water consumed (m^3/year)	**149,310**	157,746	164,393
	Total electricity consumed (KWh/year)	1,235,961	**1,219,816**	1,243,147
	Total land used (ha/year)	21.96	21.49	28.45
	Total CO_2 emissions (ton CO_2 eq /year)	314	326	**295**

By comparing findings of both scenarios, we can clearly tell that ensuring food variety comes with extra energy, water, CO_2 emissions and land costs. For the same objective function O.F 1, water consumed in scenario 1 is 10 times that consumed under the baseline scenario. Moreover, a 20% increase in electricity consumed occurs when food variety is imposed, and land used as well as CO_2 emissions are doubled.

The major change occurring in scenario 1, is the addition of animal source foods to the food basket. To have a better explanation, we performed another run, where we only imposed a limit on vegetal food. The results were very similar to those obtained under the baseline scenario. This indicates that the increase in resources is due to livestock production. Our results come in line with previous findings showing that shifting diets to reduce consumption of animal-based foods, contribute to sustainable use of resources and climate change mitigation (Ranganathan et al., 2016).

3. Scenario 2: Trade Policy Scenario

In scenario 2, full trade of resources is allowed. Since no limitations on imports were imposed, the model, under O.F 1, will not produce any crops because all crops have water requirements. Similarly, the model will not produce feed nor raise livestock because these activities are associated with significant water requirements. Instead of producing food, the model will import food items and will only produce food from imported crops if no water is needed for processing. It is worth mentioning that the model also relies on electricity imports to satisfy energy demands. Similar results were observed using O.F 2.

So, under scenario 2, crops are imported, feed is neither imported nor produced for we don’t raise livestock and all food items are imported unless they don’t have a cost when converted from crops to consumable items, in this case the model can choose either to import these items or to produce them from imported crops. Water, regardless the scenario, will always be produced, because water trade is not allowed, whereas energy is fully imported. In this scenario, we did not test for O.F 3 because the model already reduces CO_2 emissions to zero in O.F 1 and O.F 2 which shows that O.F 3 has multiple optimal solutions (table 9).

Table 9. Scenario 2 summary results

		O.F 1	**O.F 2**
Food Consumption X_{ij} (g/capita/day)	Flour of wheat	125	125
	Flour of maize	34.31	34.31
	Potatoes	1,701	65.53
	Beans [dry]	4.78	122
	Olive oil, virgin	56.24	140
	Tomatoes	39.49	39.49
	Peas	1.59	1.59
	Oranges	23.76	23.76
	Bananas	23.55	23.55
	Beef and veal, boneless	17.87	17.87
	Chicken meat	28.75	28.75
	Cow milk, whole, fresh	173	173
	Chicken eggs, with shell	17.62	17.62
	Water, tap, drinking	2,000	2,841
Resources	Total water consumed (m^3/year)	5,565	5,601
	Total electricity consumed (KWh/year)	1,028,038	1,005,534
	Total land used (ha/year)	0	0
	Total CO_2 emissions (ton CO_2 eq /year)	0	0

After testing the two extreme trade cases, baseline with closed borders and scenario 2 allowing full trade of resources, we can clearly see that ensuring self-sufficiency is associated with extra use and exploitation of resources. As a compromise, we will allow trade with maximum 40% imports in the remaining scenarios.

A better way to analyze results is by referring to figures 9 to 12, where findings of the three tested scenarios under the three objective functions were combined. These graphs are revealing in several ways. First, we can observe how achieving a self-sufficiency status is associated with high cost in terms of resources. Moreover, these graphs illustrate the increase in resource consumption when food variety is to be maintained.

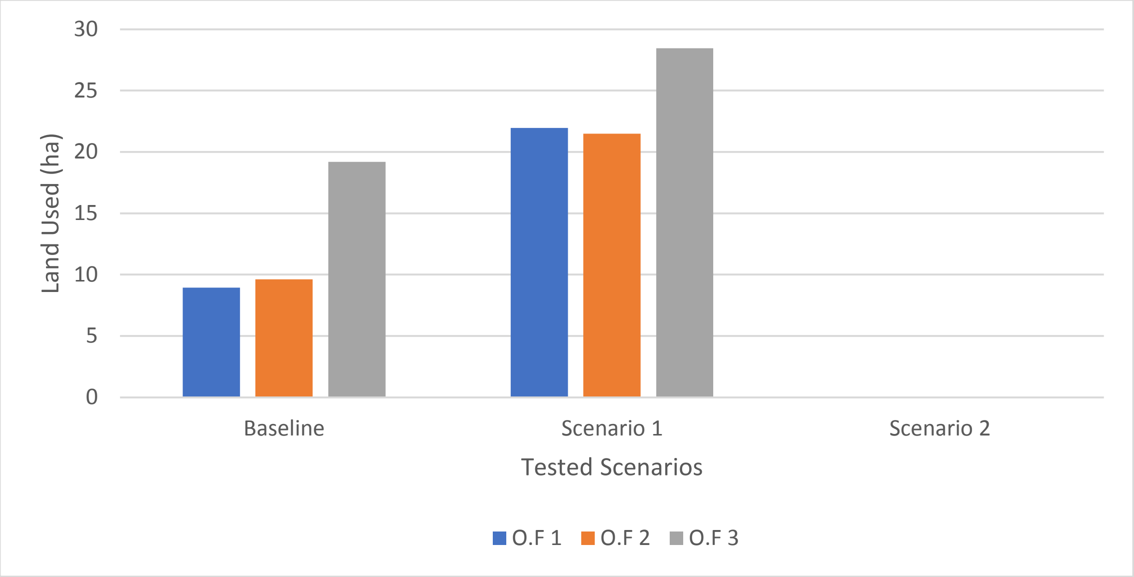


Figure 9. Land used in different scenarios under various objective functions

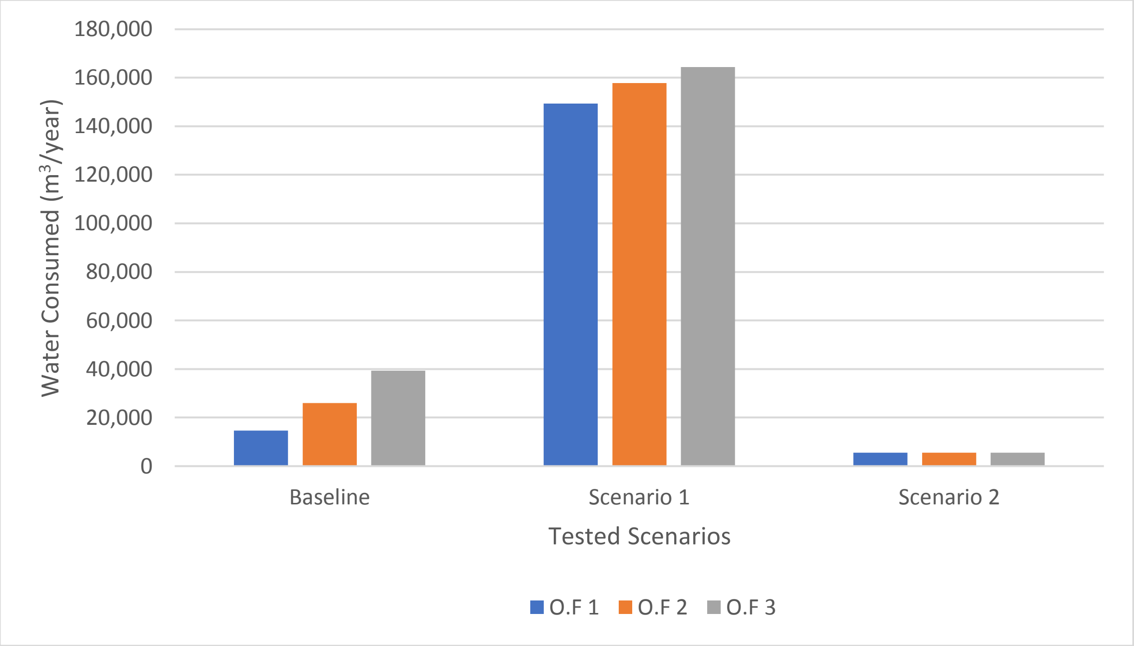


Figure 10. Water consumed in different scenarios under various objective functions

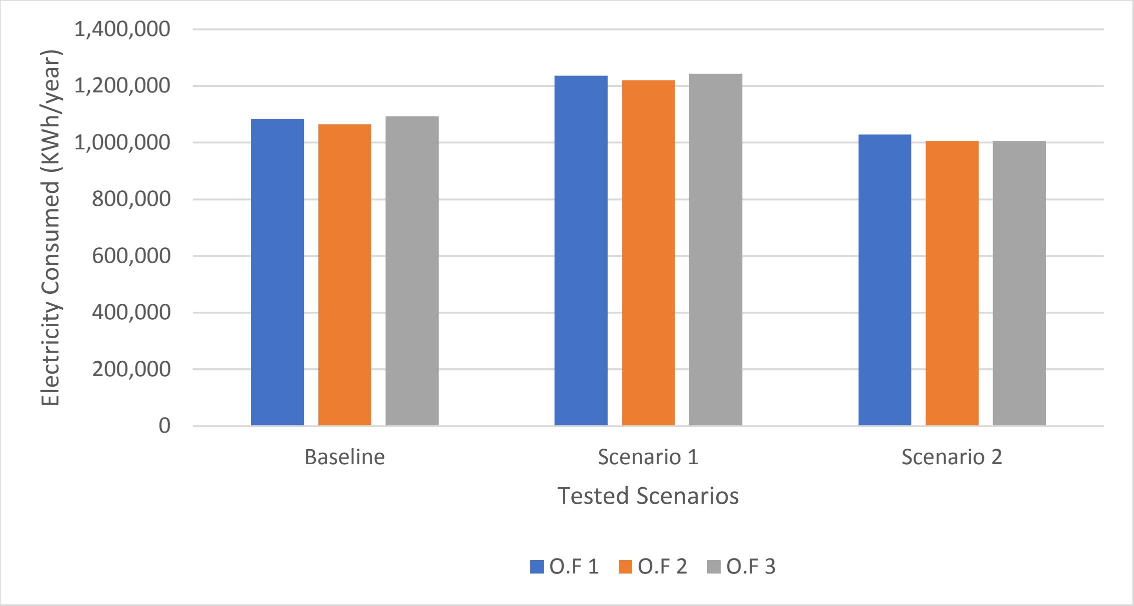


Figure 11. Electricity consumed in different scenarios under various objective functions

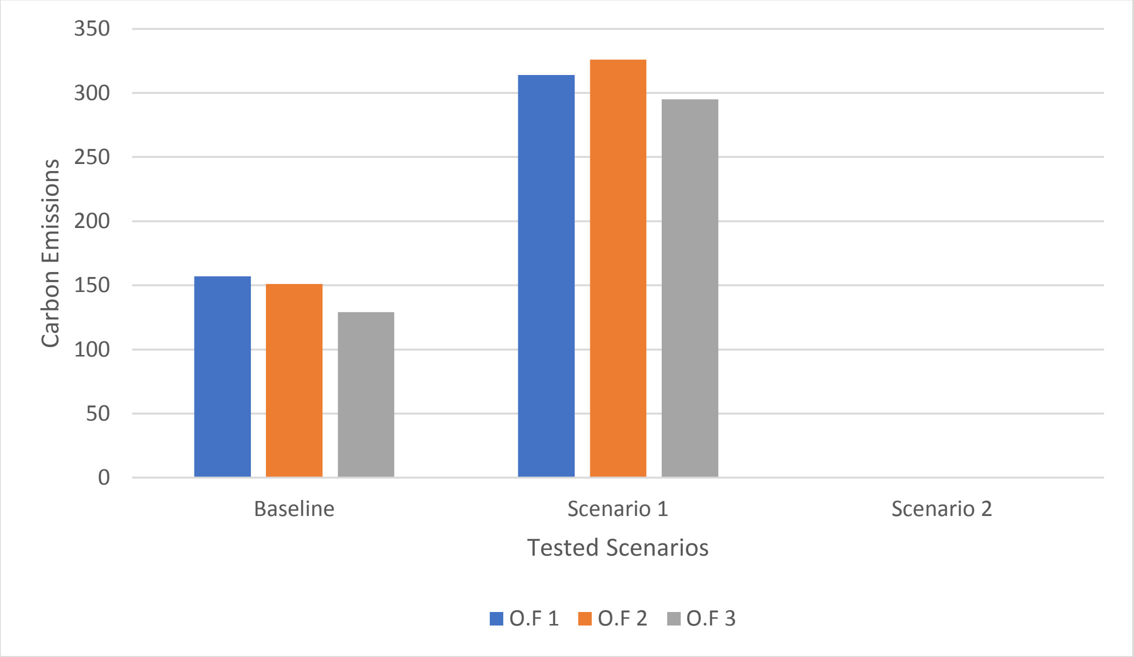


Figure 12. Carbon emissions in different scenarios under various objective functions

4. Scenario 3 & 4: Energy Policy Scenarios

In Scenarios 3 and 4, trade is allowed with imports not to exceed 40% of demand and food variety constraint is relaxed. Similar to previous scenarios, the same objective functions will be tested. To test the model response to energy variations, we will present the following two cases:

- Case 1: where energy needs will be satisfied using 30% fossil energy and 70% renewable energy
- Case 2: where energy demand will only be satisfied from renewable energy sources.

When comparing the two cases, under O.F 2, we see a slight change in energy and water consumptions while major differences in CO_2 and land used are observed. The results are summarized in table 10. Figure 13 shows the distribution of energy resources used in both cases.

The results show that for the same amount of electricity produced, if we are only using renewables, land is doubled, and CO_2 emissions are reduced approximately 9 times. This highlights the competition on land when countries are switching to clean energy. It also shows how using renewable energy drastically reduces CO_2 emissions. These results support earlier findings in the literature (UNCCD & IRENA, 2017).

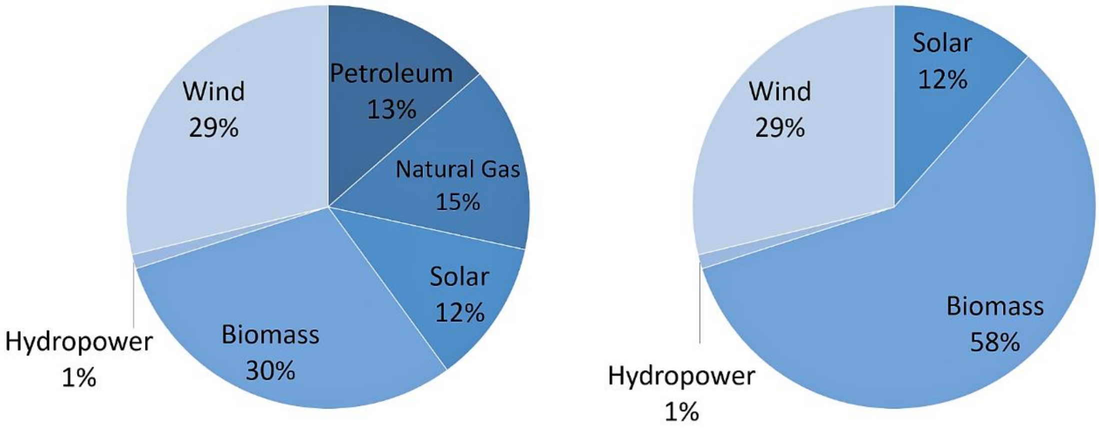


Figure 13. Energy distribution under scenarios 3 and 4

Table 10. Scenarios 3 and 4 summary results under O.F 2

Case	**Water Consumed** (m^3/year)	**Energy Consumed** (KWh/year)	**Land for Energy** (ha)	**CO_2 Emitted** (Kg CO_2/capita/year)
1	21,383	1,030,807	4.43	1,249
2	26,379	1,030,858	8.51	135

5. Scenario 5: Land Scenario

By performing sensitivity analysis on land resources under O.F 1, we obtained the same X_{ij} when land ranged between 3 and 15 ha (figure 17). This shows that produced crops are the most land and water efficient among the available food items in this case study. While X_{ij} remained unchanged, we observed an increase in CO_2 emissions from 88.5 kg of CO_2/capita/year to 139 Kg of CO_2/ capita/year when land availability increased from 3 to 13 ha (figure 16), because when land became available, the model produced all its energy needs from wind for it has zero water requirements. Hence, under 13 ha the model produced all energy whereas under 3 ha the model produced 60% only of needed energy which decreased CO_2 emissions.

When O.F 2 was tested, CO_2 emissions reached its limit value of 1610 kg of CO_2/capita/year when land decreased to 3 ha due to deforestation (figure 16). We also examined a decrease in water consumption when we reduced land from 15 to 3 ha (figure 14), and this comes in accordance with the conclusion reached when we tested for O.F 1, which indicates that less water intensive food items are those with lowest land requirements in this case. Unlike O.F 1, variations in X_{ij} were observed, where maize production increased while potatoes and beans productions decreased when land became scarce (figure 18)

Testing O.F 3, while gradually decreasing land availability and preserving water and energy resources availability, shows a decrease in water consumption from 25,000 m^3/year to 7,000 m^3/year under 15 and 3 ha respectively (figure 14). As available land decreases, the model produces less land demanding food items (X_{ij}) which happen to be less water demanding but require more fertilizers (figure 19), increasing by such CO_2 emissions from 70.83 kg of CO_2/capita/year to 78.37 kg of CO_2/capita/year (figure 16). This justifies the increase in water consumption with land increase observed in figure 14 under O.F 3. The increase in electricity consumed observed when increasing land availability (figure 15) also contributes to CO_2 emissions. It is worth mentioning that below 3 ha, the model becomes infeasible and above 15 ha no changes are observed. This indicates that when land becomes limiting, CO_2 emissions increase due to deforestation and fertilizers use.

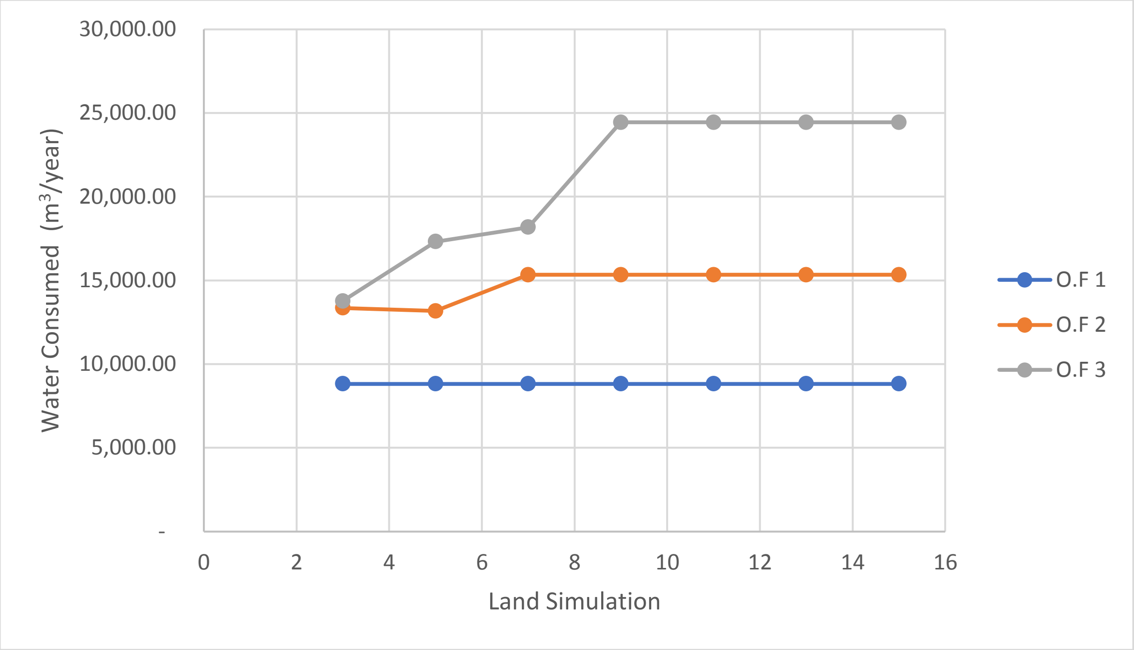


Figure 14. Water consumed under O.F 1, 2 and 3 With respect to land variation

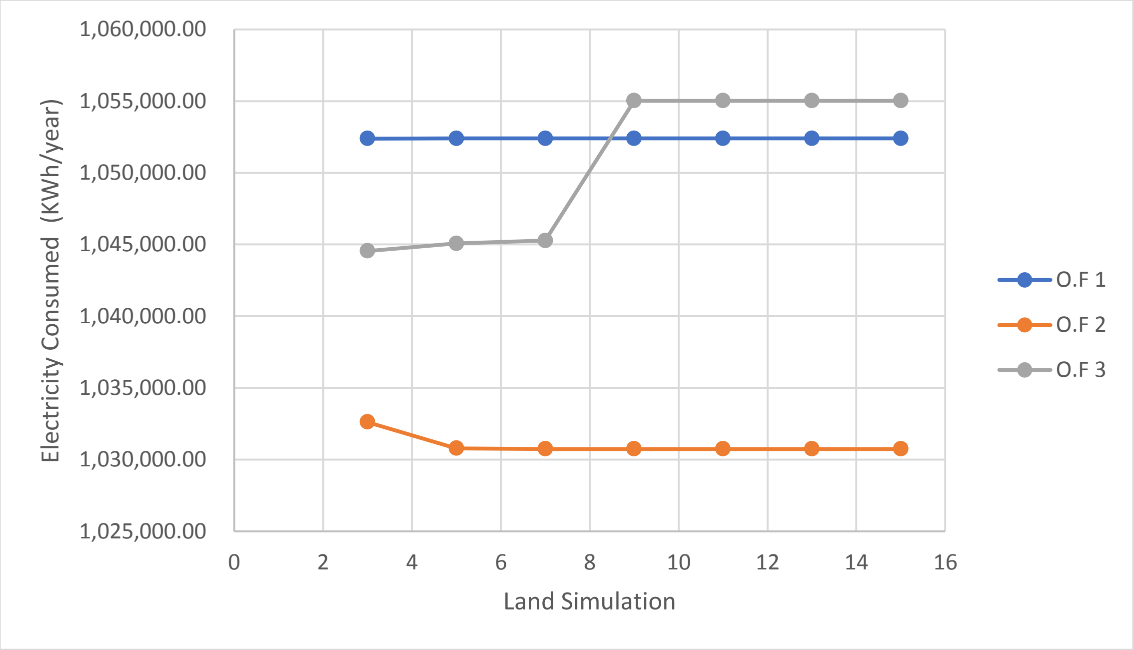


Figure 15. Electricity consumed under O.F 1, 2 and 3 with respect to land variation

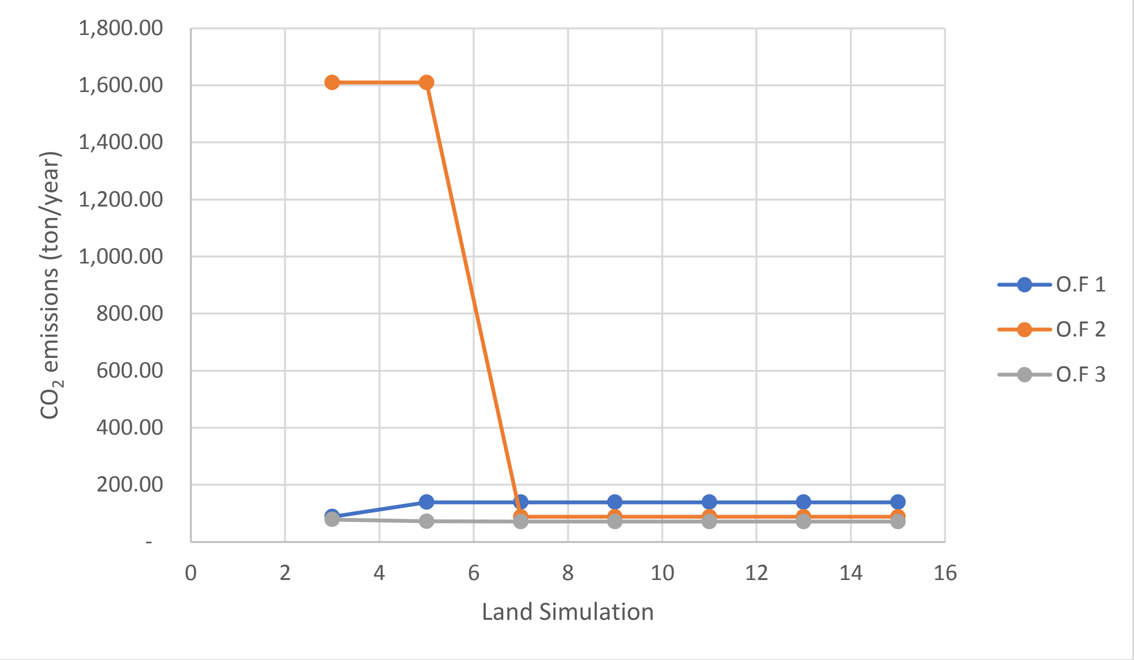


Figure 16. CO_2 emissions under O.F 1, 2 and 3 with respect to land variation

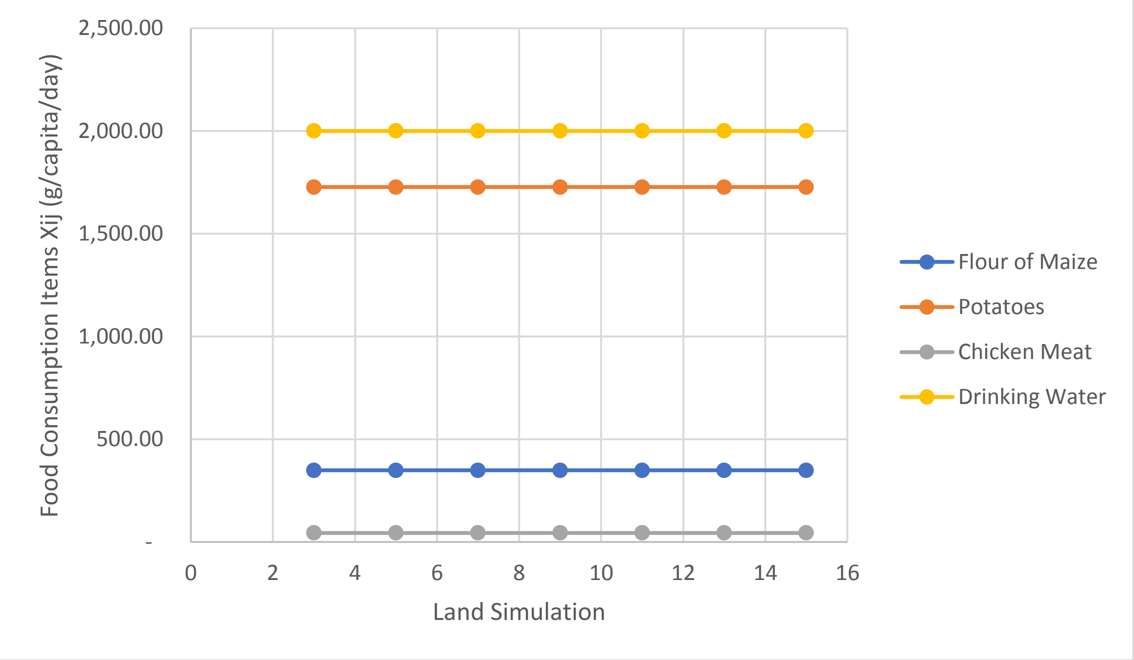


Figure 17. X_{ij} under O.F 1 with respect to land variation

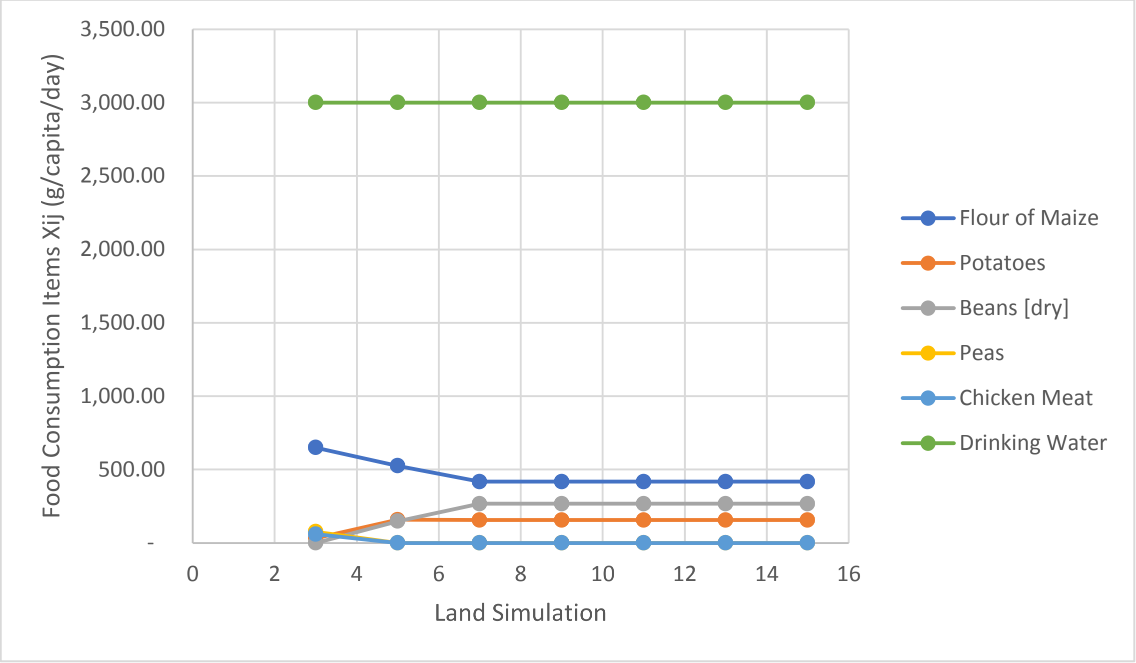


Figure 18. X_{ij} under O.F 2 with respect to land variation

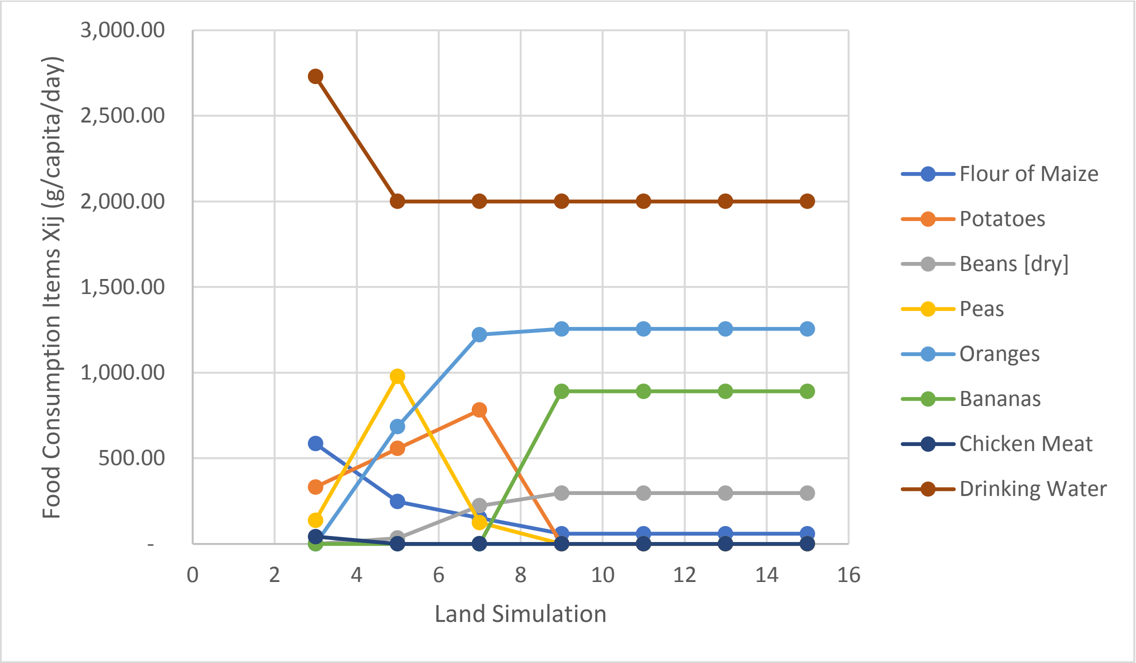


Figure 19. X_{ij} under O.F 3 with Respect to Land Variation

C. Conclusions and Recommendations

The presented model achieved its targets as a comprehensive nexus tool that allows policy makers to make optimum resource allocation and use under various policy and constraints. The model was designed to fit a wide range of applications with varying user-inputs. It was validated using a hypothetical case study customized to demonstrate the effectiveness of the model in solving conflicts among water, energy and food sectors within the imposed resource, environmental and technological constraints.

The results showed that consuming less animal source foods can drastically reduce the use of resources as well as the amount of CO_2 emissions. The results also revealed that relying on renewables can, in cases where land is limited, induce an insecure food status. Moreover, our findings indicate that ensuring a self-sufficiency status is associated with additional resource consumption.

Given that our findings are based solely on resources availability, closer inspection must be exercised before generalizing the results obtained. For instance, the model does not account for economics, so we cannot decide whether to rely on importation rather than production since no monetary cost was attributed to any activity at this stage. An additional downside regarding our methodology is extensive data collection, which is a common limitation among WEF tools. This recurring limitation was identified as a nexus gap by (Kaddoura & El Khatib, 2017) who reviewed existing modelling tools and pinpointed their capabilities and limitations. Another possible source of error is disregarding the suitability of land for cultivation or energy production. This can be easily done when a real region is under study by accounting for wind speed, solar radiation and soil fertility in each land area.

All these limitations can be addressed easily since the model is scalable and can be tailored to solve specific cases by defining additional set of variables and equations to be adapted to specific conditions. Although we used a unified unit for energy production (KWh) in the case study, the model allows the use of more than one energy unit and form as highlighted in the model description section. It is noteworthy that the model can also be used to secure a self-sufficiency status within the region under study by using the SSR function previously discussed in Mortada et al.

This study enhanced our understanding of the interlinkages among the nexus sectors and can serve as a solid base for future research. Further improvements might be accounting for the role of economics, considering food waste as an energy source and accounting for carbon capture and sequestration.

BIBLIOGRAPHY

Abdulbaki, D., Al-Hindi, M., Yassine, A., & Abou Najm, M. (2017). An optimization model for the allocation of water resources. *Journal of Cleaner Production, 164*, 994-1006. doi:https://doi.org/10.1016/j.jclepro.2017.07.024

Al-Ansari, T. (2015). *The development of the energy, water and food nexus systems model.* (PHD), Imperial College London. Retrieved from http://hdl.handle.net/10044/1/33377

Al-Karaghouli, A., & L. Kazmerski, L. (2013). *Energy Consumption and Water Production Cost of Conventional and Renewable-Energy-Powered Desalination Processes* (Vol. 24).

Allouche, J., Middleton, C., & Gyawali, D. (2015). *Technical Veil, Hidden Politics: Interrogating the Power Linkages behind the Nexus* (Vol. 8).

Ang, B. W., Choong, W. L., & Ng, T. S. (2015). Energy security: Definitions, dimensions and indexes. *Renewable and Sustainable Energy Reviews, 42*, 1077-1093. doi:https://doi.org/10.1016/j.rser.2014.10.064

Baba, A., Tayfur, G., Gunduz, O., W. F. Howard, K., Friedel, M., & Chambel, A. (2011). *Climate Change and its Effects on Water Resources*.

Barton, B. (2011). *The Routledge Handbook of Energy Security, Benjamin K.Sovacool Routledge, Abingdon (2011), 436 pp, ISBN: 978 0 415 59117 1* (Vol. 39).

Bauer, D., Philbrick, M., & Vallario, B. (2014). The Water-Energy Nexus: Challenges and Opportunities.

Bizikova, L., Roy, D., Swanson, D. A., Venema, H. D., & McCandless, M. (2013). The Water-Energy-Food Security Nexus: Towards A Practical Planning and Decision Support Framework for Landscape Investment and Risk Management

Brouwer, F., Avgerinopoulos, G., Fazekas, D., Laspidou, C., Mercure, J.-F., Pollitt, H., Ramos, E. P., & Howells, M. (2018). Energy modelling and the Nexus concept. *Energy Strategy Reviews, 19*, 1-6. doi:https://doi.org/10.1016/j.esr.2017.10.005

Calzadilla, A., Zhu, T., Rehdanz, K., Tol, R. S. J., & Ringler, C. (2014). Climate change and agriculture: Impacts and adaptation options in South Africa. *Water Resources and Economics, 5*, 24-48. doi:https://doi.org/10.1016/j.wre.2014.03.001

Chapagain, A., & Hoekstra, A. (2003). *Virtual Water Flows Between Nations in Relation to Trade in Livestock and Livestock Products*.

Compton, M., Willis, S., Rezaie, B., & Humes, K. (2018). Food processing industry energy and water consumption in the Pacific northwest. *Innovative Food Science & Emerging Technologies, 47*, 371-383. doi:https://doi.org/10.1016/j.ifset.2018.04.001

Daher, B. T., & Mohtar, R. H. (2015). Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. *Water International, 40*(5-6), 748-771. doi:10.1080/02508060.2015.1074148

De Klein, C., Novoa, R. S. A., Ogle, S., Smith, K., Rochette, P., Wirth, T. C., McConkey, B. G., Mosier, A., & Rypdal, K. (2006). *N2O Emissions from Managed Soils, and CO2 Emissions from Lime and Urea Application* (Vol. 4).

Edenhofer, O., Madruga, R. P., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., & Stechow, C. (2011).

Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change.

El-Gafy, I. (2017). Water–food–energy nexus index: analysis of water–energy–food nexus of crop's production system applying the indicators approach. *Applied Water Science, 7*(6), 2857-2868. doi:10.1007/s13201-017-0551-3

Endo, A., Tsurita, I., Burnett, K., & Orencio, P. M. (2017). A review of the current state of research on the water, energy, and food nexus. *Journal of Hydrology: Regional Studies, 11*, 20-30. doi:https://doi.org/10.1016/j.ejrh.2015.11.010

EPA. (2018). Greenhouse Gases Equivalencies Calculator - Calculations and References. Retrieved from https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

Fanzo, J., Davis, C., McLaren, R., & Choufani, J. (2018). The effect of climate change across food systems: Implications for nutrition outcomes. *Global Food Security, 18*, 12-19. doi:https://doi.org/10.1016/j.gfs.2018.06.001

FAO. (1972). *Technical conversion factors for agricultural commodities*. Retrieved from

FAO. (1995). World livestock production systems.

FAO. (2011a). "Energy-Smart" Food for People and Climate.

FAO. (2011b). *Global livestock production systems*. Retrieved from http://www.fao.org/docrep/014/i2414e/i2414e.pdf

FAO. (2014a). Sources of Meat. Retrieved from http://www.fao.org/ag/againfo/themes/en/meat/backgr_sources.html

FAO. (2014b). Walking the Nexus Talk: Assessing the Water-Energy-Food Nexus in the Context of the Sustainable Energy for All Initiative. 150.

FAOSTAT. (2017). Food Balance Sheets. Retrieved from http://www.fao.org/faostat/en/#data/FBS

Gerbens-Leenes, W., Hoekstra, A., & Meer, T. H. (2008a). *Water Footprint of Bio-energy and Other Primary Energy Carriers*.

Gerbens-Leenes, W., Hoekstra, A., & Meer, T. H. (2008b). *The Water Footprint of Energy Consumption : an Assessment of Water Requirements of Primary Energy Carriers* (Vol. 4).

Gleick, P. H. (1994). Water and Energy. *Annual Review of Energy and the Environment, 19*(1), 267-299. doi:10.1146/annurev.eg.19.110194.001411

Hoekstra, A. (2003). *Virtual Water Trade: Proceedings of the International Expert Meeting on Virtual Water Trade*.

Hoekstra, A., Chapagain, A., Aldaya, M., & Mekonnen, M. (2011). *The Water Footprint Assessment Manual*.

Hoff, H. (2011). *Understanding the Nexus. Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus*. Retrieved from

Houghton, R. A. (1991). Tropical deforestation and atmospheric carbon dioxide. *Climatic Change, 19*(1), 99-118. doi:10.1007/BF00142217

IEA. (2018). Energy security.

Intharak, N., Julay, J. H., Nakanishi, S., Matsumoto, T., Sahid, E., Ormeno, A. A. G., & Aponte, A. A. (2007). *A Quest For Energy Security in the 21st Century*.

IPCC. (1996). *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual* Retrieved from

Ipcc. (2006). *Emissions From Livestock and Manure Management*.

IPCC. (2007). *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* Retrieved from

IPCC. (2014). *Climate change 2014: Mitigation of Climate Change*. Retrieved from https://www.ipcc.ch/report/ar5/wg3/

IRENA. (2015). *Renewable energy in the water, energy & food nexus* Retrieved from http://www.irena.org/publications/2015/Jan/Renewable-Energy-in-the-Water-Energy--Food-Nexus

Kaddoura, S., & El Khatib, S. (2017). Review of water-energy-food Nexus tools to improve the Nexus modelling approach for integrated policy making. *Environmental Science & Policy, 77*, 114-121. doi:https://doi.org/10.1016/j.envsci.2017.07.007

Karabulut, A. A., Crenna, E., Sala, S., & Udias, A. (2018). A proposal for integration of the ecosystem-water-food-land-energy (EWFLE) nexus concept into life cycle assessment: A synthesis matrix system for food security. *Journal of Cleaner Production, 172*, 3874-3889. doi:https://doi.org/10.1016/j.jclepro.2017.05.092

Khaligh, A., & Onar, O. C. (2018). 23 - Energy Sources. In M. H. Rashid (Ed.), *Power Electronics Handbook (Fourth Edition)* (pp. 725-765): Butterworth-Heinemann.

Kirby, R. M., Bartram, J., & Carr, R. (2003). Water in food production and processing: quantity and quality concerns. *Food Control, 14*(5), 283-299. doi:https://doi.org/10.1016/S0956-7135(02)00090-7

Lal, R. (undated). Soil Carbon Sequestration. *SOLAW Background Thematic Report.* Retrieved from http://www.fao.org/fileadmin/templates/solaw/files/thematic_reports/TR_04b_web.pdf

Laponche, B., & Tillerson, K. (2001). *The green paper: « Towards a European strategy for the security of energy supply »*.

Liu, J., Mao, G., Hoekstra, A. Y., Wang, H., Wang, J., Zheng, C., van Vliet, M. T. H., Wu, M., Ruddell, B., & Yan, J. (2018). Managing the energy-water-food nexus for sustainable development. *Applied Energy, 210*, 377-381. doi:https://doi.org/10.1016/j.apenergy.2017.10.064

Matthews, N. (2016). People and Fresh Water Ecosystems: Pressures, Responses and Resilience. *Aquatic Procedia, 6*, 99-105. doi:https://doi.org/10.1016/j.aqpro.2016.06.012

Mekonnen, M., & Hoekstra, A. (2010). *The green, blue and grey water footprint of farm animals and animal products*.

Mekonnen, M., & Hoekstra, A. (2011). *The green, blue and grey water footprint of crops and derived crop products* (Vol. 8).

Monforti, F., Dallemand, J., Pinedo Pascua, I., Motola, V., Banja, M., Scarlat, N., Medarac, H., Castellazzi, L., Labanca, N., Bertoldi, P., Pennington, D., Goralczyk, M., Schau, E., Saouter, E., Sala, S., Notarnicola, B., Tassielli, G., & Renzulli, P. (2015). *Energy use in the EU food sector: State of play and opportunities for improvement*.

Mortada, S., Abou Najm, M., Yassine, A., El Fadel, M., & Alamiddine, I. (2018). Towards sustainable water-food nexus: An optimization approach. *Journal of Cleaner Production, 178*, 408-418. doi:https://doi.org/10.1016/j.jclepro.2018.01.020

O'Neill, D. W., Fanning, A. L., Lamb, W. F., & Steinberger, J. K. (2018). A good life for all within planetary boundaries. *Nature Sustainability, 1*(2), 88-95. doi:10.1038/s41893-018-0021-4

Parikh, J. K., & Syed, S. (1988). Energy use in the post-harvest food (PHF) system of developing countries. *Energy in Agriculture, 6*(4), 325-351. doi:https://doi.org/10.1016/0167-5826(88)90005-8

Parthemore, C. (2010). *Sustaining Security How Natural Resources Influence National Security*. Retrieved from

Paustian, K., H Ravindranath, N., & Van Amstel, A. (2006). *Agriculture, Forestry and Other Land Use (AFOLU)* (Vol. 4).

Pimentel, D. (1980). *Handbook of energy utilization in agriculture. [Collection of available data]*.

Plappally, A. K., & Lienhard V, J. H. (2012). Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renewable and Sustainable Energy Reviews, 16*(7), 4818-4848. doi:https://doi.org/10.1016/j.rser.2012.05.022

Prentice, I., Farquhar, G., Fasham, M., Goulden, M. L., Heimann, M., Jaramillo, V., Kheshgi, H., Le Quéré, C., Scholes, R., Wallace, D. W. R., & al, e. (2001). *The carbon cycle and atmospheric carbon dioxide*.

Pulselli, F. M., & Marchi, M. (2015). Global Warming Potential and the Net Carbon Balance☆ *Reference Module in Earth Systems and Environmental Sciences*: Elsevier.

Ranganathan, J., Vennard, D., Waite, R., Searchinger, T., Dumas, P., & Lipinski, B. (2016). *Shifting Diets: Toward a Sustainable Food Future*.

Rasul, G., & Sharma, B. (2016). The nexus approach to water–energy–food security: an option for adaptation to climate change. *Climate Policy, 16*(6), 682-702. doi:10.1080/14693062.2015.1029865

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S. I., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., & Schellnhuber, H. (2009). *Planetary Boundaries: Exploring the Safe Operating Space for Humanity [Internet]* (Vol. 14).

Rossi, S., Tubiello, F. N., Prosperi, P., Salvatore, M., Jacobs, H., Biancalani, R., House, J. I., & Boschetti, L. (2016). FAOSTAT estimates of greenhouse gas emissions from biomass and peat fires. *Climatic Change, 135*(3), 699-711. doi:10.1007/s10584-015-1584-y

Schechtman, J. A., Clinton. (2011). Alternative Energy Sources and Land Use.

Schlesinger, W. H., & Bernhardt, E. S. (2013). Chapter 11 - The Global Carbon Cycle. In W. H. Schlesinger & E. S. Bernhardt (Eds.), *Biogeochemistry (Third Edition)* (pp. 419-444). Boston: Academic Press.

SEI. (2018). WEAP. Retrieved from https://www.weap21.org/index.asp?NewLang=EN

Smith, H. (1944). *Livestock feeds and feeding*

Tubiello, F., Salvatore, M., Danica Condor Golec, R., Ferrara, A., Rossi, S., Biancalani, R., Federici, S., Jacobs, H., & Flammini, A. (2014). *Agriculture, Forestry and Other Land Use Emissions by Sources and Removals by Sinks: 1990-2011 Analysis*.

UN. (2015). The 2015 Revision of the UN's World Population Projections. *Population and Development Review, 41*(3), 557-561. doi:doi:10.1111/j.1728-4457.2015.00082.x

UN. (2017). Global Climate, Land, Energy & Water Strategies. Retrieved from https://unite.un.org/sites/unite.un.org/files/app-globalclews-v-1-0/landingpage.html

UN. (2018). Water. Retrieved from http://www.un.org/en/sections/issues-depth/water/

UNCCD, & IRENA. (2017). *Energy and land use*. Retrieved from

United Nations Educational, S. a. C. O. (2018). *Sustainable Development Goal 6 Synthesis Report 2018 on Water and Sanitation*. Retrieved from New York:

Winzer, C. (2012). Conceptualizing energy security. *Energy Policy, 46*, 36-48. doi:https://doi.org/10.1016/j.enpol.2012.02.067

Woods, J., Williams, A., Hughes, J. K., Black, M., & Murphy, R. (2010). Energy and the food system. *Philosophical Transactions of the Royal Society B: Biological Sciences, 365*(1554), 2991.

WWAP. (2012). *Managing Water under Uncertainty and Risk* Retrieved from http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/wwdr/wwdr4-2012/

WWAP. (2014). *The United Nations World Water Development Report 2014: Water and Energy*. Retrieved from Paris:

WWAP. (2015). *The United Nations World Water Development Report 2015: Water for a Sustainable World*. Retrieved from Paris:

Zhang, C., Chen, X., Li, Y., Ding, W., & Fu, G. (2018). Water-energy-food nexus: Concepts, questions and methodologies. *Journal of Cleaner Production, 195*, 625-639. doi:https://doi.org/10.1016/j.jclepro.2018.05.194

Zou, C., Zhao, Q., Zhang, G., & Xiong, B. (2016). Energy revolution: From a fossil energy era to a new energy era. *Natural Gas Industry B, 3*(1), 1-11. doi:https://doi.org/10.1016/j.ngib.2016.02.001

APPENDIX A- GLOBAL AVERAGE WATER FOOTPRINT OF CROPS AND DERIVED CROP ITEMS

(Mekonnen & Hoekstra, 2010) quantified global blue, green and grey water footprints of 126 crop and their derived food items.

Crop and Crop Products	**Global average water footprint** (m^3 ton^{-1})			
	Green	Blue	Grey	Total
Wheat	1277	342	207	1827
Wheat flour	1292	347	210	1849
Wheat bread	1124	301	183	1608
Dry pasta	1292	347	210	1849
Wheat pellets	1423	382	231	2036
Wheat, starch	1004	269	163	1436
Wheat gluten	2928	785	476	4189
Rice, paddy	1146	341	187	1673
Rice, husked (brown)	1488	443	242	2172
Rice, broken	1710	509	278	2497
Rice flour	1800	535	293	2628
Rice groats and meal	1527	454	249	2230
Barley	1213	79	131	1423
Barley, rolled or flaked grains	1685	110	182	1977
Malt, not roasted	1662	108	180	1950
Malt, roasted	2078	135	225	2437
Beer made from malt	254	16	27	298
Maize (corn)	947	81	194	1222
Maize (corn) flour	971	83	199	1253

Maize (corn) groats and meal	837	72	171	1081
Maize (corn), hulled, pearled, sliced or kibbled	1018	87	209	1314
Maize (corn) starch	1295	111	265	1671
Maize (corn) oil	1996	171	409	2575
Rye	1419	25	99	1544
Rye flour	1774	32	124	1930
Oats	1479	181	128	1788
Oat groats and meal	2098	257	182	2536
Oats, rolled or flaked grains	1998	245	173	2416
Millet	4306	57	115	4478
Sorghum	2857	103	87	3048
Buckwheat	2769	144	229	3142
Potatoes	191	33	63	287
Tapioca of potatoes	955	165	317	1436
Potato flour and meal	955	165	317	1436
Potato flakes	694	120	230	1044
Potato starch	1005	173	333	1512
Sweet potatoes	324	5	53	383
Manioc (cassava)	550	0	13	564
Tapioca of cassava	2750	1	66	2818
Flour of cassava	1833	1	44	1878
Dried cassava	1571	1	38	1610
Manioc (cassava) starch	2200	1	53	2254
Taro (coco yam)	587	3	15	606
Yams	341	0	1	343
Sugar cane	139	57	13	210
Raw sugar, cane	1107	455	104	1666
Refined sugar	1184	487	111	1782

Fructose, chemically pure	1184	487	111	1782
Cane molasses	350	144	33	527
Sugar beet	82	26	25	132
Raw sugar, beet	535	167	162	865
Beans, dry	3945	125	983	5053
Broad beans, horse beans, dry	1317	205	496	2018
Peas, dry	1453	33	493	1979
Chick peas	2972	224	981	4177
Cow peas, dry	6841	10	55	6906
Pigeon peas	4739	72	683	5494
Lentils	4324	489	1060	5874
Cashew nuts	12 853	921	444	14 218
Chestnuts	2432	174	144	2750
Almonds, with shell	4632	1908	1507	8047
Almonds, shelled or peeled	9264	3816	3015	16 095
Walnuts, with shell	2805	1299	814	4918
Walnuts, shelled or peeled	5293	2451	1536	9280
Pistachios	3095	7602	666	11 363
Kola nuts	23 345	26	19	23 391
Hazelnuts, with shell	3813	1090	354	5258
Hazelnuts, shelled or peeled	7627	2180	709	10 515
Areca nuts	10 621	139	406	11 165
Soya beans	2037	70	37	2145
Soya sauce	582	20	11	613
Soya paste	543	19	10	572
Soya curd	2397	83	44	2523
Soy milk	3574	123	65	3763
Soya bean flour and meals	2397	83	44	2523
Soybean oil, refined	3980	137	73	4190

Soybean oilcake	1690	58	31	1779
Groundnuts in shell	2469	150	163	2782
Groundnuts shelled	3526	214	234	3974
Groundnut oil , refined	6681	405	442	7529
Groundnut oilcake	1317	80	87	1484
Coconuts	2669	2	16	2687
Copra	2079	1	12	2093
Coconut (husked)	1247	1	7	1256
Coconut (copra) oil , refined	4461	3	27	4490
Coconut/copra oilcake	829	1	5	834
Coconut (coir) fiber, processed	2433	2	15	2449
Oil palm	1057	0	40	1098
Palm nuts and kernels	2762	1	105	2868
Palm oil, refined	4787	1	182	4971
Palm kernel/babassu oil, refined	5202	1	198	5401
Palm nut/kernel oilcake	802	0	31	833
Olives	2470	499	45	3015
Olive oil, virgin	11 826	2388	217	14 431
Olive oil, refined	12 067	2437	221	14 726
Castor oil seeds	8423	1175	298	9896
Castor oil	21 058	2938	744	24 740
Sunflower seeds	3017	148	201	3366
Sunflower seed oil, refined	6088	299	405	6792
Sunflower seed oilcake	1215	60	81	1356
Rapeseed	1703	231	336	2271
Rape oil, refined	3226	438	636	4301
Rape seed oilcake	837	114	165	1115
Safflower seeds	6000	938	283	7221
Sesame seed	8460	509	403	9371

Sesame oil	19 674	1183	936	21 793
Mustard seeds	2463	1	345	2809
Poppy seeds	1723	0	464	2188
Melon seed	5087	56	41	5184
Seed cotton	2282	1306	440	4029
Cotton seeds	755	432	146	1332
Cotton lint	5163	2955	996	9113
Cotton linters	1474	844	284	2602
Cotton-seed oil, refined	2242	1283	432	3957
Cotton seed oilcake	487	279	94	860
Cotton, not carded or combed	5163	2955	996	9113
Cotton yarn waste (including thread waste)	950	544	183	1677
Garneted stock of cotton	1426	816	275	2517
Cotton, carded or combed	5359	3067	1034	9460
Cotton fabric, finished textile	5384	3253	1344	9982
Linseed	4730	268	170	5168
Linseed oil, refined	8618	488	310	9415
Linseed oilcake	2816	160	101	3077
Hempseed	3257	12	417	3685
Cabbages and other brassicas	181	26	73	280
Artichokes	478	242	98	818
Asparagus	1524	119	507	2150
Lettuce	133	28	77	237
Spinach	118	14	160	292
Tomatoes	108	63	43	214
Tomato juice unfermented & not spirited	135	79	53	267
Tomato juice, concentrated	539	316	213	1069

Tomato paste	431	253	171	855
Tomato ketchup	270	158	107	534
Tomato puree	360	211	142	713
Peeled tomatoes	135	79	53	267
Tomato, dried	2157	1265	853	4276
Cauliflowers and broccoli	189	21	75	285
Brussels sprouts	189	21	75	285
Pumpkins, squash and gourds	228	24	84	336
Cucumbers and gherkins	206	42	105	353
Eggplants (aubergines)	234	33	95	362
Chillies and peppers, green	240	42	97	379
Onions (incl. shallots), green	176	44	51	272
Onions, dry	192	88	65	345
Garlic	337	81	170	589
Garlic powder	1297	313	655	2265
Beans, green	320	54	188	561
Peas, green	382	63	150	595
String beans	301	104	143	547
Carrots and turnips	106	28	61	195
Okra	474	36	65	576
Maize, green	455	157	88	700
Carobs	4557	334	703	5594
Bananas	660	97	33	790
Plantains	1570	27	6	1602
Oranges	401	110	49	560
Orange juice	729	199	90	1018
Tangerines, mandarins, clement	479	118	152	748
Lemons and limes	432	152	58	642
Grapefruit	367	85	54	506

Apples, fresh	561	133	127	822
Apples, dried	4678	1111	1058	6847
Apple juice unfermented & not spirited	780	185	176	1141
Pears	645	94	183	922
Apricots	694	502	92	1287
Sour cherries	1098	213	99	1411
Cherries	961	531	112	1604
Peaches and nectarines	583	188	139	910
Plums and sloes	1570	188	422	2180
Strawberries	201	109	37	347
Raspberries	293	53	67	413
Gooseberries	487	8	31	526
Currants	457	19	23	499
Blueberries	341	334	170	845
Cranberries	91	108	77	276
Grapes	425	97	87	608
Grapes, dried	1700	386	347	2433
Grapefruit juice	490	114	71	675
Grape wines, sparkling	607	138	124	869
Watermelons	147	25	63	235
Figs	1527	1595	228	3350
Mangoes, mangosteens, guavas	1314	362	124	1800
Avocados	849	283	849	1981
Pineapples	215	9	31	255
Pineapple juice	1075	45	153	1273
Dates	930	1250	98	2277
Cashew apple	3638	34	121	3793
Kiwi fruit	307	168	38	514

Papayas	399	40	21	460
Coffee, green	15 249	116	532	15 897
Coffee, roasted	18 153	139	633	18 925
Cocoa beans	19 745	4	179	19 928
Cocoa paste	24 015	5	218	24 238
Cocoa butter, fat and oil	33 626	7	305	33 938
Cocoa powder	15 492	3	141	15 636
Chocolate	16 805	198	193	17 196
Green and black tea	7232	898	726	8856
Hop cones	2382	269	1414	4065
Hop extract	9528	1077	5654	16 259
Pepper of the genus Piper	6540	467	604	7611
Chillies and peppers, dry	5869	1125	371	7365
Vanilla beans	86 392	39 048	1065	12 6505
Cinnamon (canella)	14 853	41	632	15 526
Cloves	59 834	30	1341	61 205
Nutmeg, mace and cardamoms	30 683	2623	1014	34 319
Anise, badian, fennel, coriander	5369	1865	1046	8280
Coriander seeds	5369	1865	1046	8280
Ginger	1525	40	92	1657
Peppermint	206	63	19	288
Flax fiber and tow	2637	443	401	3481
Flax fiber, otherwise processed but not spun	2866	481	436	3783
Flax tow and waste	581	98	88	767
Hemp fiber and tow	1824	–	624	2447
True hemp fiber processed (but not spun)	2026	–	693	2719
Jute and other textile bast fibers	2356	33	217	2605

Ramie	3712	201	595	4507
Sisal	6112	708	222	7041
Sisal textile fibers processed but not spun	6791	787	246	7824
Agave fibers	6434	9	106	6549
Manila fiber (Abaca)	19 376	246	766	20 388
Abaca fiber, processed but not spun	21 529	273	851	22 654
Tobacco, unmanufactured	2021	205	700	2925
Natural rubber	12 964	361	422	13 748

APPENDIX B- LIVESTOCK DRINKING AND SERVICE WATER REQUIREMENTS

It has not escaped our notice that (Mekonnen & Hoekstra, 2010) used three farming systems rather than focusing on the main two systems defined by FAO.

Animal	**Drinking Water Requirements** (Liter per day)			**Service Water Requirements** (Liter per day)		
	Grazing	Mixed	Industrial	Grazing	Mixed	Industrial
Beef Cattle	20	27	33	4.3	7	9.8
Dairy Cattle	40	55	70	5	13.5	22
Broiler Chicken	0.18	0.18	0.18	0.09	0.09	0.09
Laying Hens	0.18	0.18	0.18	0.09	0.09	0.09
Pig	8	11	13	10	29	48
Sheep	6	6	7.5	1.3	1.3	5
Goat	3.5	3.5	3.8	1.3	1.3	5
Horse	45	45	45	5	5	5

APPENDIX C- EMISSIONS FROM AGRICULTURE

1. Emissions from Applied Fertilizers

N_2O emissions from synthetic and organic fertilizers are estimated using the following equation:

$$(N_2O)_{fertilizers} = (FSN + FON) \times EF_1 \times \frac{44}{28}$$

Where, $(N_2O)_{\text{fertilizers}}$ is in Kg of N_2O/year, F_{SN} and F_{ON} are respectively the amount of synthetic and organic fertilizers applied in (Kg N/year) and EF_1 is the N_2O-N emission factor (= 0.01 KgN_2O-Ninput)

2. Emissions from Manure Managed and Deposited on Pasture

a. Emissions from manure management

CH_4 is produced from the decomposition of manure during its storage and treatment. It is simply calculated by knowing the temperature of the region under study, the livestock category and its corresponding emission factor.

In addition, N_2O is produced directly and indirectly during the storage and treatment of manure. Direct N_2O emissions occur from nitrification and denitrification whereas indirect emissions result from volatilization and leaching. In this paper, we will only account for the direct emissions using the set of equations below:

$$N_2O_{direct} = Nex_{(T)} \times MS_{(T,S)} \times EF_{3(s)} \times \frac{44}{28}$$

Where N_2O_{direct} is the direct N_2O emissions in Kg of N_2O/animal/year, $MS_{(T,S)}$ is the fraction of N excreted by animal category T and managed using management system S, $EF_{3(S)}$ is the emission factor for direct N_2O emissions from manure management system (S) in Kg N_2O-N/Kg N and $Nex_{(T)}$ is the yearly average excretion per head in Kg N/animal/year and is calculated as follow:

$$Nex_{(T)} = N_{rate\ (T)} \times \frac{TAM}{1000} \times 365$$

Where $N_{rate(T)}$ is yearly N excretion for animal category T and TAM is the typical animal mass in Kg/animal

b. Emissions from manure deposited on pasture

Manure deposited on pasture or known as untreated manure are also a source of N_2O. To estimate the amount of N_2O emitted from untreated manure, we will be using the following equation:

$$N_2O - N_{PRP} = F_{PRP,CPP} \times EF_{3PRP,CPP}$$

3. Emissions from Enteric Fermentation

Enteric fermentation is the process through which methane emissions are released from livestock raising. The amount of methane produced vary according to animal and feed type. To quantify methane emissions, default emission factors set by the IPCC can be used.

4. Emissions from Land Use Change

Clearing forests affects carbon exchange between land and the atmosphere by reducing carbon stock in the former and increasing atmospheric carbon. Seven types of land use change were assessed by (Houghton, 1991). In this paper, carbon emissions released from converting forests to croplands will add to the carbon emissions budget. To estimate carbon emitted per hectare of deforested land, yearly carbon emissions from (EPA, 2018) will be used.

$$Annual\ Carbon\ emitted\ from\ deforestation = \\ 302\ t\ CO_2/\ ha\ of\ deforested\ area.$$

5. Emissions from burning Savannahs

To estimate the emissions from biomass burning, including Savannahs, the following generic equation was developed by the IPCC (Rossi et al., 2016).

$$(E_x)_{savannahs} = A \times M \times C \times EF_x$$

Where E_x is the GHG emissions of gas x with x being N_2O or CH_4, A is the burned area, M is the mass of fuel available for combustion, C is the combustion factor and EF_x is the emission factor for gas x.

6. Emissions from rice cultivation

To calculate the annual methane emissions from rice cultivation, the following equation can be used (IPCC, 1996):

$$(E_{CH4})_{rice\ cultivation} = A \times EF \times 10^{-12}$$

Where $(E_{CH4})_{\text{rice cultivation}}$ is the estimated annual emission of methane from rice cultivation, A is the harvested area in m^2/year and EF is the methane emission factor during a cropping season, expressed in g/m^2

APPENDIX D- CASE STUDY

Table D1. Crop list

Group Rank	Group Name	Item Rank	Item Name
m=1	Cereals	n=1	Wheat
		n=2	Maize
m=2	Roots and tubers	n=1	Potatoes
m=3	Pulses [legumes]	n=1	Beans [dry]
m=4	Oil crops	n=1	Olives
m=5	Vegetables	n=1	Tomatoes
		n=2	Peas
m=6	Fruits	n=1	Oranges
		n=2	Bananas
m=7	Fodder	n=1	Alfalfa for Forage + Silage
		n=2	Grasses nes, grazing pasture

Table D2. Livestock list

Group Rank	Group Name	Item Rank	Item Name
m'=1	Cattle	n'=1	Beef Cattle
		n'=2	Dairy Cows
m'=2	Poultry	n'=1	Broilers
		n'=2	Laying hens

Table D3. Feed list

Group Rank	Group Name	Item Rank	Item Name
i'=1	Concentrates	j'=1	Wheat
		j'=2	Grain corn
i'=2	Roughages	j'=1	Grazing pasture
		j'=2	Dry hay
		j'=3	Silage

Table D4. Food list

Group Rank	**Group Name**	**Item Rank**	**Item Name**
i=1	Cereals	j=1	Flour of wheat
		j=2	Flour of maize
i=2	Roots and tubers	j=1	Potatoes
i=3	Pulses [legumes]	j=1	Beans [dry]
i=4	Vegetable oils	j=1	Olive oil, virgin
i=5	Vegetables	j=1	Tomatoes
		j=2	Peas
i=6	Fruits	j=1	Oranges
		j=2	Bananas
i=7	Meat	j=1	Beef and veal, Boneless
		j=2	Chicken meat
i=8	Dairy	j=1	Cow milk, whole, fresh
		j=2	Chicken eggs, with shell

Table D5. Nutrients List with their concentrations per 100 grams of food

Nutrient Rank **Nutrient Name** **Nutrient Unit**		**k=1** **Water** (g)	**k=2** **Energy** (Kcal)	**k=3** **Protein** (g)
Food Items	Flour of wheat	11.92	364	10.33
	Flour of maize	10.91	361	6.93
	Potatoes	81.58	69	1.68
	Beans [dry]	11.32	333	23.36
	Olive oil, virgin	0	884	0
	Tomatoes	94.52	18	0.88
	Peas	78.86	81	5.42
	Oranges	86.75	47	0.94
	Bananas	74.91	89	1.09
	Beef and veal, Boneless	61.94	254	17.17
	Chicken meat	75.46	119	21.39
	Cow milk, whole, fresh	88.13	61	3.15
	Chicken eggs, with shell	87.57	52	10.9

Table D6. Water requirements for crops

Crop Item Name	**Water Requirements**			
	Climatic Region [r=1]		Climatic Region [r=2]	
	Blue	Green	Blue	Green
Wheat	342	1277	1564	308
Maize	81	947	616	255
Potatoes	33	191	59	183
Beans [dry]	125	3945	2264	430
Olives	499	2470	2782	1135
Tomatoes	63	108	64	93
Peas	63	382	1303	223
Oranges	110	401	231	363
Bananas	97	660	376	298
Alfalfa for Forage + Silage	27	207	27	207
Grasses nes, grazing pasture	27	207	27	207

Table D7. Water requirements for Livestock

Animal Type	**Livestock Water Requirements ($LWR_{m'n'}$)** (m^3/year)
Beef Cattle	32.4
Dairy Cows	43.0229
Broiler Chicken	0.0294
Laying Hens	0.2002

Derived from (Mekonnen & Hoekstra, 2010). Since feed requirements will add to crop demand, water from feed will be subtracted from livestock water requirements to avoid double accounting.

Table D8. Water requirements for food processing

Food Item Name	**Processing Water Requirements** (m^3/ton)
Flour of wheat	22
Flour of maize	31
Potatoes	0
Beans [dry]	0
Olive oil, virgin	11416
Tomatoes	0
Peas	0
Oranges	0
Bananas	0
Beef and veal, Boneless	15377
Chicken meat	4325
Cow milk, whole, fresh	978
Chicken eggs, with shell	3265

Table D9. Energy requirements for crops

Crop Item Name	**Energy Requirements** (KWh/ton)
Wheat	1989.43
Maize	1094.42
Potatoes	603.95
Beans [dry]	2141.77
Olives	2008.49
Tomatoes	805.95
Peas	666.66
Oranges	536.42
Bananas	1261.98
Alfalfa for Forage + Silage	479.24
Grasses nes, grazing pasture	0.00

Table D10. Energy requirements for livestock

Animal Name	**Energy Requirements** (KWh/head)
Beef Cattle	312.53
Dairy Cattle	17195.71
Broiler Chicken	0.62
Laying Hens	15.14

Table D11. Energy requirements for food processing

Food Item Name	**Processing Energy Requirements** (KWh/ton)
Flour of wheat	562.51
Flour of maize	562.51
Potatoes	0.00
Beans [dry]	0.00
Olive oil, virgin	223.16
Tomatoes	0.00
Peas	0.00
Oranges	0.00
Bananas	0.00
Beef and veal, Boneless	1401.64
Chicken meat	1401.64
Cow milk, whole, fresh	411.43
Chicken eggs, with shell	0

Table D12. Energy requirements for water (Plappally & Lienhard V, 2012)

Water Source (u)	**Technology (w)**	**Output Water Quality (v)**	**WER_{uvw}** (KWh/m^3)
Surface	Horizontal Pumping	Drinking	0.005/Km
Ground	Horizontal and Vertical Pumping	Drinking	0.45/m
Sea	MSF	Drinking	23.415
Waste	Membrane Bioreactor	Irrigation	0.65875

We assumed 10 m groundwater depth and 2 Km distance from water source to city.